

# En route to safer roads

How road structure and road classification  
can affect road safety



Atze Dijkstra

# EN ROUTE TO SAFER ROADS

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can affect road safety

Atze Dijkstra

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**EN ROUTE TO SAFER ROADS**

HOW ROAD STRUCTURE AND ROAD CLASSIFICATION  
CAN AFFECT ROAD SAFETY

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## Preface

In the eighties I conducted a literature survey on the interaction between urban planning, road design and road safety. Many years later, I again broached this topic as part of the 'Safer Transportation Network Planning' project (a co-operation between the SWOV and a Canadian Insurance company). In both projects it appeared to be difficult to show a (quantitative) relationship between the planning level and the crashes at an operational level. Also the relationship between road network structure and road safety was difficult quantifying. Furthermore, the Dutch concept of Sustainable Safety requires that the fastest route should coincide with the safest route, another aspect demanding further research. In order to elaborate the issues regarding urban planning, road network structure, route choice, and road safety, I proposed a long-term study 'Route choice in road networks'. In this project I thought it would be possible to quantify the interactions between these factors by using a simulation model. This would lead me and my fellow colleagues at the SWOV into the world of micro simulation. The study was initially (in the year 2002) going to be carried out by one of my junior colleagues. However, that colleague quite unexpectedly decided to leave SWOV. I had to try and find a replacement, preferably a PhD student. Finding one in the short term was not possible. To compound the problem, my research theme 'Road design and road safety' was nearing the end of its four year term and a replacement research subject had not yet started. Combining the two 'vacancies' (both researcher and subject), resulted in the decision to do the project myself, and thereby taking the first steps towards my PhD project. A review of professors active in the field covered by my project, led me to Martin van Maarseveen as the most promising supervisor. Despite the only relatively large distance between the university in Enschede and the SWOV institute in Leidschendam, a good working relationship was soon established. Although it took some time to get used to each other, we ended up co-operating well. Martin is very diplomatic and provides input in a very subtle way. This requires listening carefully!

The study started with an inventory of models that could be useful for our approach. Luc Wismans (consultant at Goudappel Coffeng) was very helpful in providing us with information about this topic. The next step was to choose a micro simulation model. Ronnie Poorterman (consultant at Grontmij) was the first in offering us the S-Paramics model for research purposes. Hans Drolenga (at first as an MSc student, later on as a researcher) managed to make that model appropriate for our study; resulting in our first

joint TRB paper. Vincent Kars has gradually improved the application that transforms the output from the model into different types of safety indicators.

I would also like to acknowledge and thank the many researchers that have worked on parts of the study: Charles Goldenbeld, Robert Louwerse, Peter Morsink, Paula Marchesini (at first as an MSc student), Wendy Weijermars, Frits Bijleveld, and Jacques Commandeur. Also the following (MSc and BSc) students were involved: Marcel Bus, Leander Hepp, Alex Smits, and last but not least, Tjesco Gerts. Marijke Tros patiently carried me through the many layout issues. The individual and combined efforts of these colleagues have resulted in the overall success of this study.

My thanks also go to Rob Eenink, my departmental manager. Due to his insight and belief in the importance of micro-simulation models for research purposes, he could support me practically and keep me alert all through the study.

Almost thirty years after graduating as an engineer, and being a researcher from that time on, I will finally be an 'official' researcher. Fortunately my employer facilitated this work to a large extent, through which 'family life' did not suffer too much. Fortunately the family gradually got used to a husband/father working on a PhD thesis. However, the time to spend on our holidays was reduced considerably, something I hope to make up for in the coming years.

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## 1. Subject description

The subject of this study is about the influence of network structure and road classification on road safety. Road safety, or unsafety, is usually expressed as the number of crashes or casualties. It is not evident how one can relate what happens at street level to the decisions regarding network design and the elaboration of this design. Traffic circulation can be regarded as the link between these two levels. Behind traffic circulation is the individual who decides to travel from a point of origin to a destination, using a particular route. The route is the starting point for this study. That is because network structure and road classification are important preconditions for traffic circulation and route choice, while the intersecting routes will determine the crash locations. This study will therefore focus on the effects of changing route choices on road safety. The changes in route choice may be the result of:

1. (intended) changes in the structure of the road network
2. a change in traffic circulation, e.g. on account of an alteration of a traffic signal system or of congestion on the main roads
3. instructions to car drivers through navigation systems or route guidance signs

*These changes, adaptations and instructions aim to improve the traffic and transport system as a whole. This study is undertaken to find the effect of the changes/instructions enumerated above on the safety of all road users in the road network. This study will show whether an improvement can be attained and how it can be attained.*

An alternative aim could be to improve road safety of individual car drivers. This could be an aim of systems giving individual instructions. A navigation system, for example, could advise a car driver to follow the route being the safest one for him or her. However, this advice could make the route in question less safe for other road users following or crossing that route. This study does not aim to improve individual route choice, but rather to contribute (SWOV, 2009a; p. 4) to road safety of all road users. For the benefit of their safety, it would be worthwhile to find out the effect of a continuing growth in the use of systems that give individual advice. Finally, this study focuses on urbanized regional areas because of the complex and still growing traffic and road safety problems in these areas.

The topic of this study was inspired by the functional requirements of Sustainable Safety (CROW, 1997), in particular:

1. Realization of residential areas, connected to a maximum extent
2. Minimum part of the journey along unsafe roads
3. Journeys as short as possible
4. Shortest and safest route should coincide

Requirements 1 to 3 are meant to reduce exposition (it is safer to spend less time and to cover shorter distances in traffic), and to let road users follow road types which are safer both for themselves and for other users of those roads and their environment. The fourth requirement combines the second and the third one.

Would it be possible to determine whether these requirements can be fulfilled in case of:

- one trip
- all trips between one origin and destination, using different routes
- all trips with various origins and destinations, partially using the same route
- all trips in a road network

For answering these questions, one needs a method that can represent several safety aspects of trips and routes. Existing methods only show the safety of either intersections or road sections. New methods will have to be developed for answering the aforementioned questions.

## **1.1. Research questions**

The new methods should be able to show the results of the improvements for road safety and for traffic flow. The methods should preferably be able to predict the results before the improvements will actually be implemented. From this problem statement, the following research questions are derived:

1. *Which indicators for road safety are suitable for determining the safety of routes?*

The common indicator for road safety is the number of recorded victims. This indicator is used by the national government for setting goals regarding the level of road safety in the future. The effect of each road (safety) measure should be determined in terms of this indicator. For small-scale measures, this will be hardly possible, because the number of crashes with injury is too small and these numbers fluctuate too much. To enable an evaluation, other indicators are required. These indicators must be related to crash frequency or seriousness of a crash (e.g. fatal injury). The effect of a road hump, for

example, is derived from the speed reduction near the hump. In general, this reduction is an indication of the seriousness of crashes. A vehicle changing its route will marginally change the safety of both 'new' route and 'old' route. This cannot be expressed into numbers of victims. This is also the case for trips with different origins and destinations and for more than one vehicle. For this reason an indicator is needed which will show the relationship with the number of crashes and/or victims and, secondly, which will show the changing route choice. This study chooses an indicator following from a micro-simulation of traffic movements in a regional network. The way vehicles 'meet' each other is an indicator for safety.

2. *What are the consequences for the distribution of traffic over the network if the fastest routes will coincide with the safest routes?*

According to Sustainable Safety, the safest route should coincide with the fastest route. To realize this aim, the use of the road network has to be changed. The level of safety of each road section or route before these changes will presumably differ from the safety level after these changes. After all, more vehicles on a route will influence the safety level of that route, in the same way as a different distribution of traffic will change the safety level of an intersection. The changes in route choice and the resulting safety levels can be analyzed by means of a dynamic simulation model. This report will explain the use of such a model, and subsequently interpret the results.

3. *How can car drivers be persuaded to use the safest routes? Which tools are effective?*

Literature shows a great many methods and tools to influence route choice. Partly, the effects of these methods and tools can also be found in literature: in some cases by means of an evaluation study or otherwise by a modelling study. The most promising methods and tools are put into a simulation model. On a network level, the model will show the effects on traffic flow and road safety.

In a simulation model it is rather easy to let vehicles change their routes. In reality, car drivers will have to be persuaded to do so. This study discusses both the knowledge gained from literature concerning this reluctance and the way in which this knowledge can be applied in simulation models.

4. *What are the total effects of a changing traffic distribution on road safety and traffic flow, both for selected routes and for the road network as a whole?*

The main question of this study is how influencing route choice will affect both traffic distribution will affect both traffic circulation (and flows) and

road safety on selected routes and on the network as a whole. This study does not comprise field experiments. The reported effects are solely based on knowledge from literature and from applying a micro-simulation model. The effects found are mainly of a theoretical nature. However, the output from the simulation model was related to recorded crash data. The interpretation of the results will clarify to which level the effects will be realized in practice.

## 1.2. Subjects of this study

The four research questions in the previous *Section 1.1* relate to the following five main research areas:

- Road networks
- Use of the road network
- Routes and route choice
- Influencing route choice
- Safety aspects of the four previous areas

These main research areas have been subdivided into eight subjects of this study. A first description of these subjects will be given hereafter. Further elaboration will be given in *Chapters 2 to 10*.

*Chapter 11* will show the overall concept of finding safety effects from different variables that, on the one hand, operate on different spatial levels and, on the other hand, are very much related to each other.

Finally, the conclusions and recommendations of this study are given in *Chapter 12*.

The following limitation of the present study has to be mentioned: it does not discuss the interactions between spatial planning and urban planning (or the spatial distribution of activities) on the one hand, and traffic, transport and road infrastructure on the other. When relevant, some aspects of this interaction will be mentioned, however, only as a condition or an input.

This study does not deal with the environmental effects of traffic and transport.

### 1. *Characteristics of transportation networks and road networks; influence on both the generation of traffic and the circulation of traffic in the road network*

On the level of transportation networks and road networks, the structure of networks is a main issue. The structure is a combination of form, mesh, position related to the surroundings, and the density of the intersections. By and large the structure is a constant factor, which can only be changed in the long term, usually at high costs. Both the spacing of origins and destinations

over an area and the road structure will influence the distribution of traffic over the road network, as is shown in *Chapter 2*. The changing influence of the spatial distribution of activities and/or of the road environment (development along a road, protected areas, interactions with vulnerable road users and users of the public space), could change the traffic distribution to such an extent, that the road structure needs to be adapted.

2. *Road network structure and road classification: their influence on traffic circulation and its road safety aspects*

Road classification can be changed more simply and quickly than road structure: a traffic sign may even be sufficient to adapt the (formal) traffic function of a road. *Chapter 3* describes how the factors road classification, traffic design, traffic regulations, and traffic distribution are interdependent. Understanding this interdependence is necessary in order to find out in which way and to which extent; it would be possible to influence these factors. The motivation for influencing these factors is based on the aim to improve road safety. This means that the road safety aspects of these factors have to be understood as well. Data about the number of crashes and victims, for a certain time period and given the amount of traffic, are needed for all of these factors. These kinds of data are not always available, either on account of a lack of evaluation studies or on account of methodological problems.

Sustainable Safety has set requirements to road classification and to the design of road sections and intersections. These requirements aim to avoid large differences between road users regarding speed, mass and direction. These requirements can be checked for existing (parts of) road networks as well as for networks in the planning stage.

3. *Route choice in road networks; options to influence route choice*

In *Chapter 4* dealing with the important subject of route choice in road networks, only the existing knowledge will play a role. The chapter focuses on the fundamentals of route choice, starting with the theories being formulated. Subsequently literature on route choice will be reviewed according to a set of research questions. These questions deal with: the underlying decision process, differences between car drivers regarding their route choice, important variables for influencing route choice, characteristics of these variables, interdependency of these variables, in which context (spatial and temporal) they are valid, whether they will be useful for redirecting route choice, and finally, the size of the effect of this redirecting.



*Chapter 4* does not treat road safety aspects of route choice. Car drivers apparently do not give priority to road safety when choosing a route. That is why road safety is treated differently: namely as a characteristic of the collective route choice, resulting from empirical data.

4. *Road safety aspects of road network structure and road classification; results from modelling studies and evaluation studies*

On the level of road networks, a change in road structure or road classification usually results in a different traffic circulation. Even departure times or transport modes can be influenced by these changes. The changes and their effects can be very complicated. That is why these kinds of relationships are mostly studied by using traffic and transport models. *Chapter 5* describes some modelling studies, especially studies focusing on road safety too. Traffic and transport models comprise a large number of presumptions and simplifications. Do these kinds of models, nonetheless, accurately describe reality? Do they predict future situations in a reliable way?

In addition to modelling studies, *Chapter 5* describes evaluation studies and pilot studies. The studies contain real-life data indispensable for validating models.

5. *Detecting the effects on road safety by changes in route choice; methodological issues and review of different types of studies*

It is very difficult to get data about route choice, changes in route choice and the resulting changes in road safety. Direct observations, through questionnaires or registration plate surveys, are both time-consuming and labour-intensive. It is almost impossible to undertake such observations on the level of a whole region or even of a smaller area like a city. Moreover, direct observations only refer to the existing situation and do not predict future situations. More insight can be obtained by using traffic and transport models, which are only reliable when sufficient observations are used for calibration.

Crashes do not happen in traffic models. This has been excluded by the programmer. In what other way would it be possible to get to know more about the safety aspects of route choice when using traffic models? Somehow, an indication should be given of road safety aspects, such as the absolute or relative safety level and the changes in these levels. To be sure that these indicators really represent road safety they need to be related directly or indirectly to the traditional safety indicator: the number of road crashes or the crash risk.

In *Chapter 6*, some methodological issues are discussed and a number of methods are described, which are potentially useful for showing safety effects in a micro-simulation model. A few promising methods are elaborated upon: a method showing whether the characteristics of the chosen routes fit certain safety requirements as well as methods to be used in micro-simulation modelling.

6. *More detailed analysis of road safety indicators; simulated conflicts and recorded crashes*

The best-known safety indicator in micro-simulation models is the 'conflict' situation – a situation in which two vehicles are approaching each other and where, if no action were taken, a crash would occur. These conflict situations can be detected in the simulation model, without necessarily referring to any actual observed conflicts, let alone recorded crashes. *Chapter 7* examines the quantitative relationship between the detected conflicts at junctions in the model and the recorded crashes at the same locations in reality. The methods chosen for detecting conflicts and for selecting crashes are explained. A micro-simulation model was constructed for a regional road network. The conflicts in this network were detected, and the recorded crashes were selected.

This analysis is only focussed on car crashes. Crashes involving other road users are not taken into consideration. This is because of the limitations of the micro-simulation model used in this study.

7. *More detailed analysis of road safety indicators; simulated conflicts, route characteristics and route criteria*

*Chapter 8* focuses on the design of a method enabling the planner to find out the safety effects of existing route choice, and changes in route choice. A description of road safety can be made by constructing a so-called 'route diagram' for each route. This diagram can be checked according to a series of criteria, each representing requirements for a Sustainably-Safe route choice. Each criterion of the route diagram contributes to the entire safety level of a route by the number of 'demerit points' scored by the criterion. The criteria are described, and are tested in a micro-simulation of alternative routes in a regional road network.

8. *Changing route choice for more safety; adapting road structure.*

The ultimate goal of this study is to show that, and how, three factors are interacting: road structure/road classification at the starting point, route choice as an intermediate factor, and thirdly the resulting factor of road

safety. Road structure and road classification can be influenced by spatial and infrastructural measures while route choice can be influenced by traffic management. The resulting traffic unsafety should be as low as possible. Safety can additionally be improved by taking (mitigating) traffic measures. *Chapter 9* is meant to show the effect of road structure and classification on road safety. Both road structure and classifications can be varied systematically in a micro-simulation model. Whether a structure is good for road safety can be shown through the output variables of the simulation model.

The simulation model is applied (*Chapter 10*) to the area between Noordwijk, Katwijk, Leiden and The Hague. This area was subjected to a network analysis, which gave some clues for adapting the road network.

## 2. Characteristics of transportation networks and road networks

On the level of transportation networks and road networks, the structure of a network is a main issue. The structure is a combination of the following factors:

- form (or typology, e.g. a triangular, circular or square structure)
- mesh
- position related to the surroundings
- density of the intersections

A variation in factors will result in many different structures, each having a characteristic interaction with the use of it. The structure is either historically grown or completely designed.

The structure of a network may be positioned on the 'supply side' of the infrastructure. Mostly the structure is a constant factor, which can only be changed in the long run, usually at high costs. In newly built areas, a structure could be chosen which would result in an optimal road safety situation. In practice, however, urban planning concepts will determine the choice for a structure, and safety concepts will not (Poppe et al., 1994). In some cases, urban planning concepts also work out favourably for road safety purposes (Vahl & Giskes, 1990).

Both the spacing of origins and destinations over an area and the road structure have an influence on the distribution of traffic over the road network. The changing influence of the spatial distribution of activities and/or of the road environment (development along a road, protected areas, interactions with vulnerable road users and users of the public space), could change the traffic distribution to such an extent, that the road structure needs to be adapted.

This *Chapter 2* will focus on the supply side but will also show the resulting effects on the use of the infrastructure, the demand side.

In a description of a network structure, two factors are very important: the spatial distribution of origins and destinations as well as the size of the urbanized areas. This study distinguishes four levels of urbanized areas:

- region
- city or pan-urban
- district or part of a city
- neighbourhood

A *region* comprises a main city, a few middle-sized cities and a number of villages. The urban areas in a region are usually strongly related to each other. Regions can have different sizes and different numbers of inhabitants. The resemblance is in the coherence of the areas in a region. A *city* is a well-defined type of area. Cities can differ very much in size and number of inhabitants. Still the mechanism of what makes an area to act as a city is universal. The term 'pan-urban' is mostly used to express that all activities of a completely urbanized area are incorporated: sometimes a few cities are so close to each other that they are almost like one city. A *part of a city or district* is a level at which important components of a city can function on their own, like a residential area or a central business district. At the level of the *neighbourhood*, activities will mostly be of the same nature (working or housing). However, at this level the influence of the surrounding areas is noticeable.

Since the regional level and the city level are very important for this study, these levels should get most of the attention, although the available literature does not meet this need. More literature can be found regarding the pan-urban level, and still more about the district and neighbourhood levels. Despite these restrictions, each level is described as well as possible.

In many cases, the available information about network structures lacks relevant data about road safety. So for this reason only network structures will be discussed of which a link to road safety is known.

Several authors have paid attention to the structure of road networks. Important systematic explorations regarding characteristics and effects of different structures were reported in the sixties and seventies by Holroyd (1966, 1968), Jansen & Bovy (1974a, 1974b, 1975). Later on Bolt (1983), Vaughan (1987), Wright et al. (1995) and Marshall (2005) increased knowledge about this subject. These studies rarely focus on the regional level, however. This level only appears to have become relevant for planning and design purposes recently. The provinces have their '*streekplannen*' (regional plans), but these are mainly aimed at making spatial planning choices (directing functions to areas, like housing, working and recreation). These plans do not relate to road network structures. The Netherlands does not have a governmental layer responsible for the regional road network. The provinces are the road authority of only a few, mostly unconnected, roads. So the regional network does not have an 'owner'. The importance of this network level, however, has grown because the number of regional trips has increased and is still increasing. This was already made clear by Jansen & Van Vuren (1985) who concluded that the number of internal car trips in a city declined by thirty percent while, at the same time, the external car trips

between cities and the surrounding areas doubled. Groenendijk et al. (2004) found that during 1992 - 2002 the number of regional trips grew faster than local and external (to and from outside the region) trips. Thus, it is clear that the regional level is becoming more relevant. The existing literature does, however, not provide much knowledge about this level.

## **2.1. Literature review**

### **2.1.1. Regional level**

Since 2005, regional structures and regional transport have been studied more and more. Regarding regional transport, Limtanakool et al. (2005) define four indicators for the interactions between cities:

- strength, which is the intensity of interaction between areas
- connectivity, which is the intensity of connections between areas, regardless of the strength of these connections
- symmetry, which is direction of the interaction: equally important or directed towards one of the areas
- hierarchy, which is the relatively dominant position of a city in relation to the surrounding cities

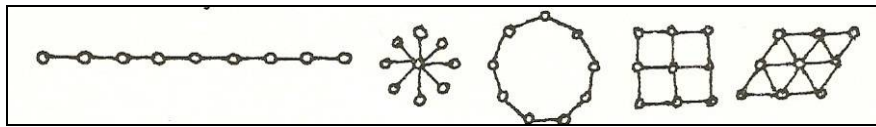
From 1992 - 2002, the position of cities within the Randstad changed (Limtanakool et al.). The position of The Hague and Rotterdam grew less than the position of Amsterdam and Utrecht. The symmetry for both The Hague and Rotterdam increased during that period, while the symmetry for Utrecht declined. The rest of the indicators did not change much. More detailed figures are needed to find out how the indicators changed in regional parts of the Randstad.

The authors do not elaborate upon the characteristics and functioning of a road network on the regional level.

### **2.1.2. Regional and pan-urban level**

Bolt (1983) investigated the transportation aspects of different types of network structures. He defines five basic structures:

- linear
- star
- circle
- square
- triangle



**Figure 2.1.** Basic structures according to Bolt (1983)

Figure 2.1 shows these basic structures. Each structure connects nine 'places' (nodes) through links having the same length. Bolt assessed these structures regarding four aspects:

- capital cost
- recurring cost
- frequency
- centrality

*Capital costs* are costs proportional to the length of a link. In this case, all links have the same length, so the capital costs are proportional to the number of links. The *recurring costs* are related to the distance travelled (number of vehicle kilometres). *Frequency* results from the number of trips between the places and does not depend from the trip lengths. *Centrality* is an indicator for the ratio between the distance travelled to and from the best and the worst accessible place. The scores for each structure were indexed (lowest score = 1.00). Within the linear structure, for instance, *capital cost* has the lowest score; the figure in Table 2.1 is therefore 1.00.

	Circle	Triangle	Square	Linear	Star
Capital cost	1.12	2.00	1.49	1.00	1.00
Recurring cost	1.43	1.00	1.14	1.91	1.02
Frequency	2.54	1.00	1.52	3.81	2.03
Centrality	1.00	1.80	1.50	1.80	1.88

**Table 2.1.** Indexed scores (lowest score = 1.00) for five structures on four aspects. Source: Bolt (1983)

The linear structure is showing less favourable scores for three aspects. The star structure scores best on these three aspects (taken together). However, it scores worst on centrality because all trips have to pass the centre. The rest of the structures are in between these two extremes. The square (grid) structure does not have extreme scores for any of the aspects. If we assume each aspect to be as important (all having the same weight), the square structure scores very well. The star structure and linear structure show a better result (related to the square structure) if we attach more importance to capital costs. These

two structures keep scoring worse for frequency (related to the square structure).

### 2.1.3. Pan-urban level

Jansen & Bovy (1974b) worked on the issue of the average number of arms of intersections in a transport network. They used data from six middle-sized cities in the Netherlands. For each of the cities the average number appears to be three arms. Subsequently they checked how many road sections border a 'region' (an area having no streets). It appears that on average a 'region' is bordered by six road sections. Vaughan (1987) used these results in his comprehensive study regarding characteristics of road networks and traffic circulation.

Holroyd (1966, 1968) and Holroyd & Miller (1966) have performed theoretical analyses to find the effects of different structures (circular and square structures) on the circulation of traffic. These structures are on a pan-urban level. Holroyd uses different combinations of network structures and routing systems within these structures. His approach was continued and extended by Vaughan (1987) and Wright et al. (1995).

An important variable used by Vaughan (1987) is the 'route factor': dividing the average distance via the routing system by the average direct distance. A direct route from origin to destination has a route factor which equals 1. Both Vaughan and Holroyd (1966) discuss the characteristics of twelve structures in circular areas; see *Figure 2.2*.

In each of the twelve areas in *Figure 2.2*, the same origin-destination pair is related to the routing system in that particular area. In three of the structures, the routing system provides for two alternative routes: external ring / radial, internal ring / radial, and radial - arc / radial. The author chooses the shortest one of these two routes.

The lowest average route factor (about 1.1) can be found in structures with triangular roads as well as in structures with routes through both ring roads and radial roads. Other structures (radial, external ring, internal ring) have route factors up to 1.4. The grid and hexagonal structures are in between.

Vaughan does not use the route factor for selecting an optimal structure. He thinks that traffic distribution is a more important factor to find an optimal structure. He analyses the given twelve structures regarding traffic volumes, number of crossing routes and distance travelled. Three structures have a good score for these factors: radial - arc / radial, radial / arc and rectangular. The radial - arc / radial structure shows higher traffic volumes in the central area than the grid structure. However, it shows 17 percent shorter distances and just as many crossing routes. The radial - arc structure shows almost no



traffic in the central area and thirty percent fewer crossing routes than radial - arc / radial; but the distance travelled is 10 percent longer.

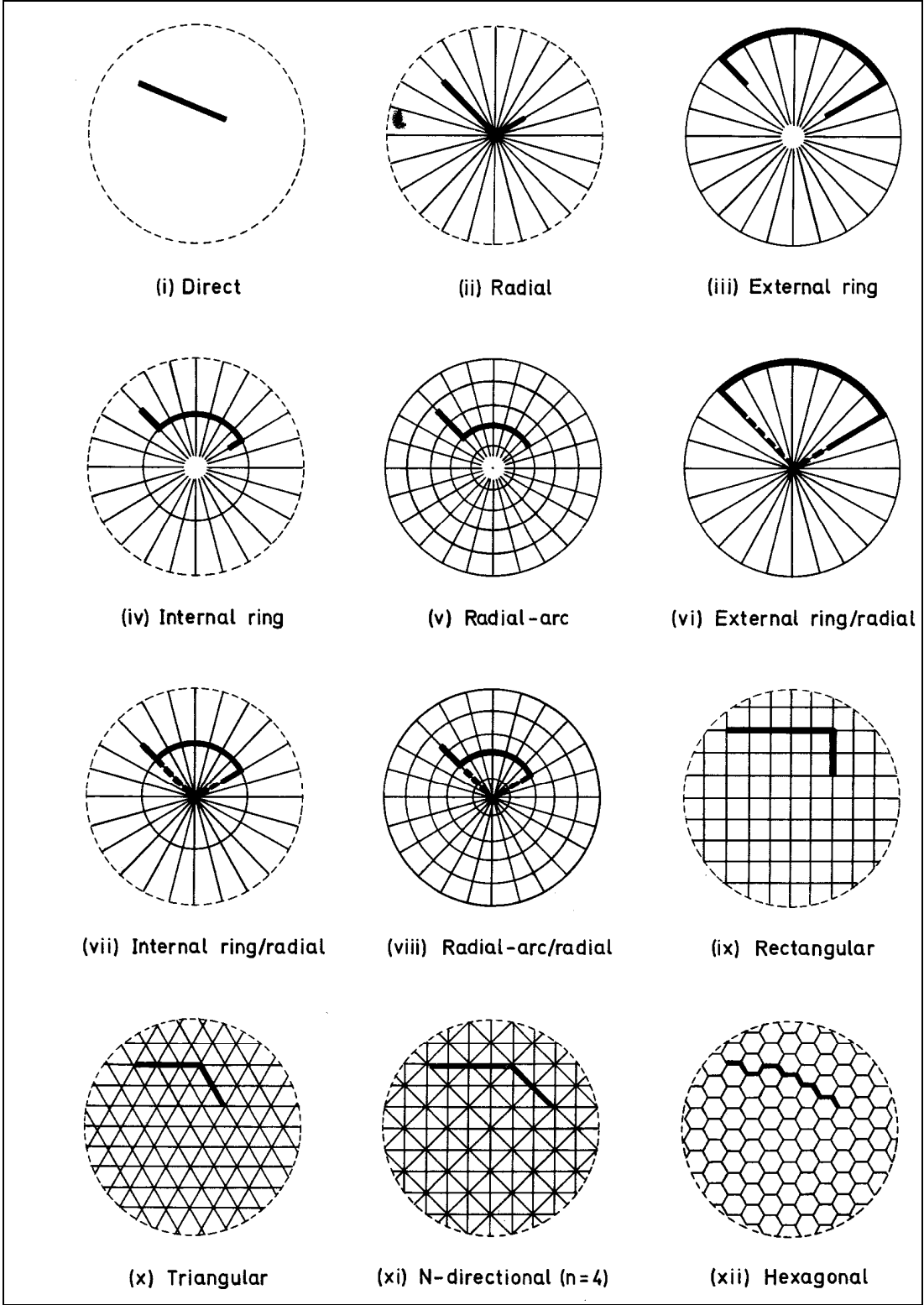


Figure 2.2. Twelve structures in circular areas by Holroyd (1966)

In addition, Vaughan (1987) analyzed spiral structures; some of the spiral structures score very well for the aforementioned factors. Hidber (2001) considers a spiral structure as a rolled up linear structure: the spiral structure has the advantages of the linear structure, while at the same time it has a very compact form. In practice, spiral structures are hardly applied.

Vaughan also analysed the rectangular structures, described by Holroyd (1968). Holroyd takes a rectangular structure in which housing and working areas are distributed uniformly and independently. Part of the trips between home and work will not cross each other, and the other part will cross. The latter part can be calculated. When all routes would cross, the result equals to 1, and if crossing does not occur the result equals 0. The theoretical minimum, calculated by Holroyd (1968) equals 0.125. This means that in a road network at least one eighth of the trips will cross each other. Holroyd & Miller (1966) showed that the minimum value is 0.125 in a circular city. In a rectangular city (Vaughan, 1987; p. 258) this value equals 0.222.

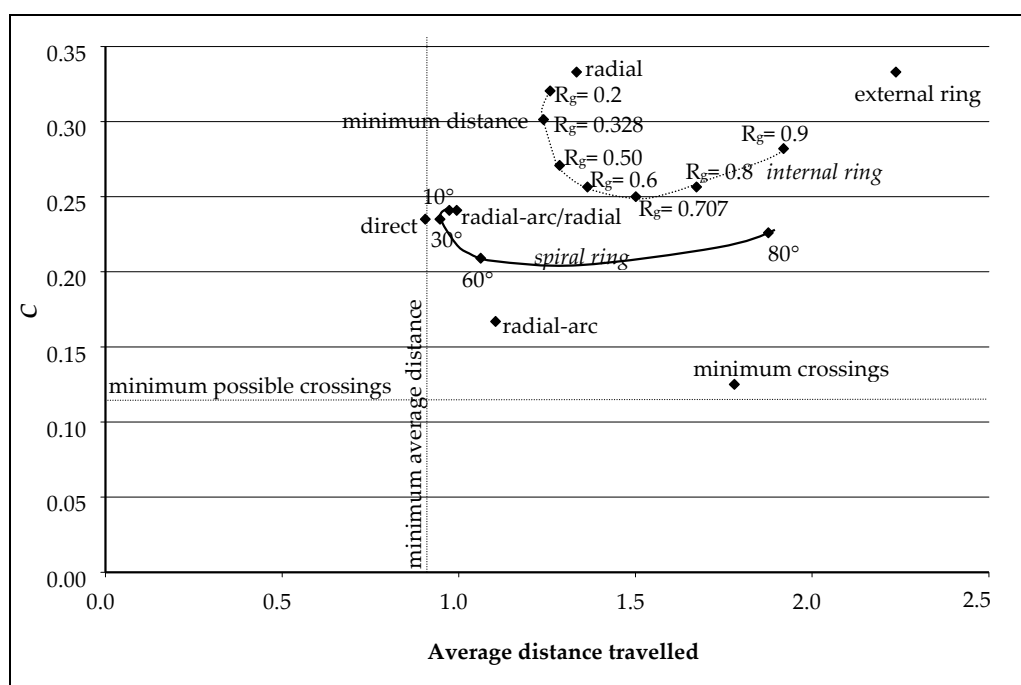
Subsequently Holroyd (1968) calculated the expected number of crossing routes per pair of routes, given a rectangular structure, when the route choice is used as an input, e.g. vehicles turn right as much as possible or vehicles choose a turning point remote from the centre. The results of the calculations for five routing systems are laid down in *Table 2.2*. The system with a random choice has the highest value (0.222). The lowest value is 0.156, which can be attained by relieving the city centre.

Routing system	C
Random choice	0.222
Right-turning	0.222
East-west section remote from east-west axis	0.167
Turning-point remote from centre (rectangular distance)	0.156
Turning-point remote from centre (straight-line distance)	0.156

**Table 2.2.** The expected number of crossing routes per pair of routes C in a rectangular structure, varied by routing system. Source: Holroyd (1968)

Vaughan (1987) also examined the possibilities to reduce both the distance travelled and the number of crossing routes (C). This analysis was applied to 'Smeed's city', a theoretical city in which origins and destinations are uniformly distributed. For this city, different structures were evaluated regarding distance travelled and crossing routes (*Figure 2.3*). The circular structure with radial-arc (See also *Figure 2.2*) scores very well, better than the

spiral structures. The spiral structures, In their turn, score better than the ring structures. Vaughan stresses that these results are valid for roads all having the same characteristics (speed limit, capacity). It is obvious that these results are very much of a theoretical nature, because both the assumptions for a Smeed's city and the characteristics of the roads can hardly ever be found in actual practice. One can question whether this method can even be applied to a real network. It is possible to calculate the values for the distance travelled and for  $C$  in a real network. Subsequently, these values can be compared to the values of the theoretical structures. If the differences are high, it may be concluded that the real network needs improvement. This will be further discussed in *Chapter 5*.



**Figure 2.3.** Mean number of crossings per pair of routes ( $C$ ) and average distance travelled (based on data according to Vaughan, 1987; p. 302).

Hidber (2001) also analyses three theoretical structures: a square city with a grid structure, a circular city with radials and concentric circles, and a purely linear city. He splits these cities up into zones. The amount of traffic between the zones depends on four types of resistance: exponential, quadratic, and linear (inversely proportional to distance), and a type that is independent of distance (without any resistance). Hidber compares these types with regard to three criteria:

- accessibility (expressed as travel time of distance)
- amount of internal traffic (traffic which does not leave its zone)

- number of vehicle kilometres (sum of the amount of traffic between the zones times the distance)

The amount of internal traffic depends on the type of resistance.

The linear city appears to have the largest amount of internal traffic (which is favourable for potential pedestrian trips), lowest accessibility, and a high number of vehicle kilometres (as compared to the other city types). The square city as well as the circular city show a uniform distribution of traffic over the road network.

#### **2.1.4. Pan-urban, district, neighbourhood**

Snellen (2001) investigated relationships between city structure and activity patterns. The aim was to find whether the city structure could have an influence on the reduction of the number of car trips. The structures studied are located at three levels:

- pan-urban: ring, grid, radial
- district: ring, loop, radial, axial (a distributor connected to a main road), grid, tangential
- neighbourhood: loop/tree, loop, loop/grid, grid, tree

The influence of the urban form on travel patterns (concerning daily activities) appears to be small. A positive influence of fewer car trips is related to:

- poly nuclear, radial or axial district distributors
- neighbourhood distributors by way of loop/tree and loop/grid

The number of car trips is not likely to be reduced in case of:

- urban distributors by way of a ring
- district distributor by a loop or ring
- neighbourhood by loop

A large neighbourhood shopping centre, district sports facilities, a longer distance to the city centre, situation within the Randstad, and a lower degree of urbanization of a district do not contribute to car trip reduction either.

#### **2.1.5. Pan-urban, district**

Marshall (2005) reported about an extensive study of characteristics of road structures and routing systems within these structures. Routing systems or routing structures have three main properties:

- depth: the maximum distance to be travelled into an area
- continuity: the number of links that a route is made up of, e.g. a route with four links has a smaller continuity than a route, having the same length, with two links
- connectivity: the number of routes to which a given route connects

These properties can be calculated for each routing system.

#### 2.1.6. Traffic circulation system in general

The circulation system determines the distance travelled and the number of conflicts between vehicles. Wright et al. (1995) investigated fifteen circulation systems (see *Appendix A* for a description) with  $N$  nodes (having both origins and destinations). For each system they calculated the distance travelled and the number of conflicts ( $C$ ) (assuming  $N$  is very large). The conflicts consist of four types: intersecting, weaving, merging, diverging and shunting (rear-end) conflicts. Of these types, only intersecting and weaving conflicts are serious conflicts. *Table 2.3* shows the distance travelled and the number of serious conflicts for each of the fifteen circulation systems. The same variables are shown in *Figure 2.4*.

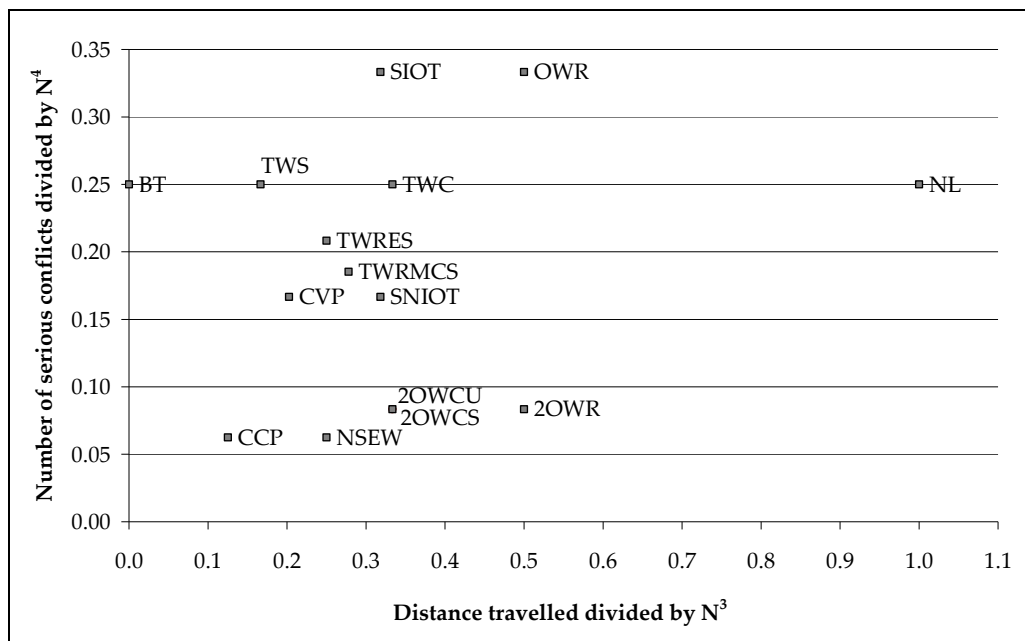
The systems at the *bottom left hand side* of *Figure 2.4* have favourable scores on both variables: the number of serious conflicts is relatively low and so is the distance travelled. Wright et al. (1995) stress the relevance of more variables when choosing a circulation system:

- adaptability: the system should have to fit existing structures on all levels
- robustness: the system should be able to handle the transport demand
- simplicity: simple systems are easier to understand
- compliance: drivers should be easily routed through the system

Systems 2OWCU, 2OWCS, NL, 2OWR and NSEW are not very robust. Systems 2OWCU, 2OWCS and NL can be applied within closed systems like conveyor systems in factories. Systems SIOT, SNIOT, TWC, TWS, OWR, 2OWR, TWRES, TWRMCS and BT can be implemented in both rectangular grids and ring-radial networks. Systems NSEW and CCP need a large road length.

	Abbreviation	Circulation system	Distance travelled divided by $N^3$	Number of serious conflicts divided by $N^4$
1	SIOT	Star, interlocking offside turns	0.318	0.333
2	SNIOT	Star, non interlocking offside turns	0.318	0.167
3	CVP	Convex polygon	0.203	0.167
4	TWC	Two-way corridor	0.333	0.250
5	TWS	Two-way spine	0.167	0.250
6	2OWCU	Two one-way corridors, uniform alignment	0.333	0.083
7	2OWCS	Two one-way corridors, symmetrical alignment	0.333	0.083
8	NL	Nested loops	1.000	0.250
9	OWR	One-way ring	0.500	0.333
10	2OWR	Two one-way rings	0.500	0.083
11	TWRES	Two-way ring, equal split	0.250	0.208
12	TWRMCS	Two-way ring, minimum crossing split	0.278	0.185
13	NSEW	NS-EW split	0.250	0.063
14	CCP	Concentric polygons	0.125	0.063
15	BT	Binary tree	0.000	0.250

**Table 2.3.** Distance travelled and number of serious (intersecting or weaving conflicts for fifteen circulation systems (Wright et al., 1995)



**Figure 2.4.** Distance travelled and number of serious conflicts for fifteen circulation systems (based on data by Wright et al., 1995)

## 2.2. Criteria for evaluating (road) networks

The findings from literature provide good suggestions for evaluating road networks, routing systems and circulation system. They make clear which kind of characteristics, classifications, variables and criteria can be used for a proper evaluation. The most important criteria are listed below.

### **Routing systems and distribution systems**

- depth: the maximum distance to be travelled into an area
- continuity: the number of links that a route is made up of, e.g. a route with four links has a smaller continuity than a route, having the same length, with two links
- connectivity: the number of routes to which a given route connects
- strength, which is the intensity of interaction between areas
- symmetry, which is the direction of the interaction: equally important or directed towards one of the areas
- hierarchy, which is the relatively dominant position of a city related to the surrounding cities
- traffic circulation system: limitations in driving directions, routing through the central area
- number of crossing vehicles: frequency of crossing
- number of serious conflicts: type of conflicts (intersecting, weaving, merging, diverging, rear-end)

### **Road networks and road structures**

- type of structure on different levels
- total length of all links: road length
- number of intersections
- average number of arms of intersections
- traffic volumes: road section level or network level
- adaptability: the system should have to fit existing structures on all levels
- robustness: the system should be able to handle the transport demand
- simplicity: simple systems are easier to understand
- compliance: drivers should be easily routed through the system

### **2.3. Summary**

A great variety of indicators and variables is available for describing, analyzing, and evaluating routing systems, distribution systems, road networks and road structures. Several authors have applied these indicators and variables to a great number of structures and systems, often on a theoretical basis, sometimes using data from actual practice.

Indicators based on the number of crossing or conflicting vehicles and the type of these conflicts are relevant if road structures need to be selected for attaining more road safety. Literature shows a number of indications about some road structures having a low number of crossing vehicles. On the other hand, these structures may result in larger distances travelled, which means more exposition to risk. In theory, some structures have a low number of crossings as well as small distances travelled. Wright et al. (1995) find this property for convex and concentric polygons, 'two one-way corridors' and a North/South - East/West split. Vaughan (1987) and Holroyd (1968) find this for circular structures with routing systems radial-arc/radial, radial/arc and rectangular. They also find rectangular structures with a routing system in which vehicles make turning movements remote from the centre, in order to relieve the city centre. These structures deserve more attention from researchers. In these kinds of structures, all roads are more or less of the same class (no hierarchy, same design). Adding a classification system will change the results mentioned above.



### **3. Road network structure and road classification**

Road classification is meaningful for both road authorities and road users. The road authority needs road classification for an efficient use of the road network and for setting priorities in allocating its budgets. The coherence of the road classes within a network, the road network structure, is also relevant for road classification. Network structure and road classification can assist the road user in choosing a safe and quick route. A characteristic design of a road class will also help the road user to be aware of the behaviour expected of him/her (recognisability), which other types of road users can be expected on the road, and what sort of behaviour can be expected from those other road users (predictability). To stimulate recognisability and predictability each road class needs its own characteristic design elements. Research on which elements are to be used is continuing. In addition, some design elements are required for enlarging the safety level of a road class, by regulating speed differentials and by mixing or separating different types of road users.

It is easier to change or adapt the road classification selected than it is to change the road structure. For example, putting up a road sign may be sufficient to change the (formal) road class. In principle, however, road classification comprises much more than the mere placement of road signs. Roads should be designed and all appropriate design elements should be introduced according to road class requirements. Road classes should be relatively positioned in the road network structure in order to optimize safety, flow and accessibility.

#### **3.1. Functionality of roads**

##### **3.1.1. Network structure**

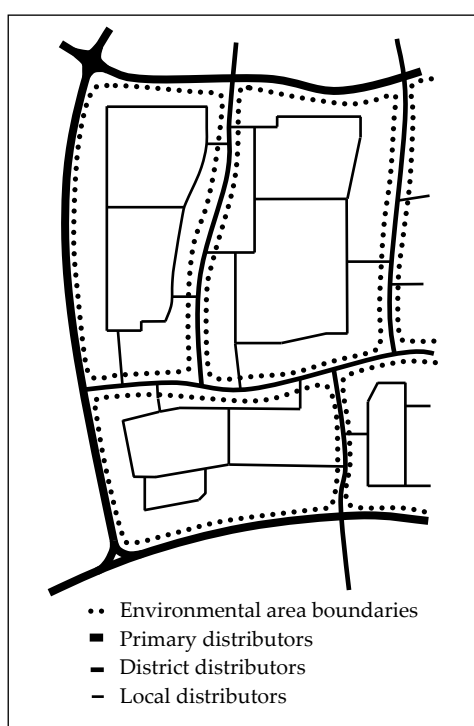
Determining the functionality of roads and of the road network, i.e. the network structure, precedes road classification. The network structure is dependent on the trips taken in an area and its surrounding areas. Trips are dependent on the size of these areas, and on the nature of the trip (home - work, home - shop etc.). Connections between areas will facilitate trip-taking. The capacity of these connections needs to be tuned to the expected traffic volumes. A connection designed for high motor vehicle volumes can only be built at high costs. Planning these kinds of connections requires much

attention to assure that the investments are used for the right purpose, and will be cost-effective. When planning a network structure, each type of connection is put into place. Subsequently, road classification adds factors to functionality regarding the road environment as well as the presence of different types of road users.

### 3.1.2. Roads and environmental areas

A good example of network structure in urban areas is the division in two types of areas: (main) roads and environmental areas (Minister of Transport, 1963; Goudappel & Perlot, 1965).

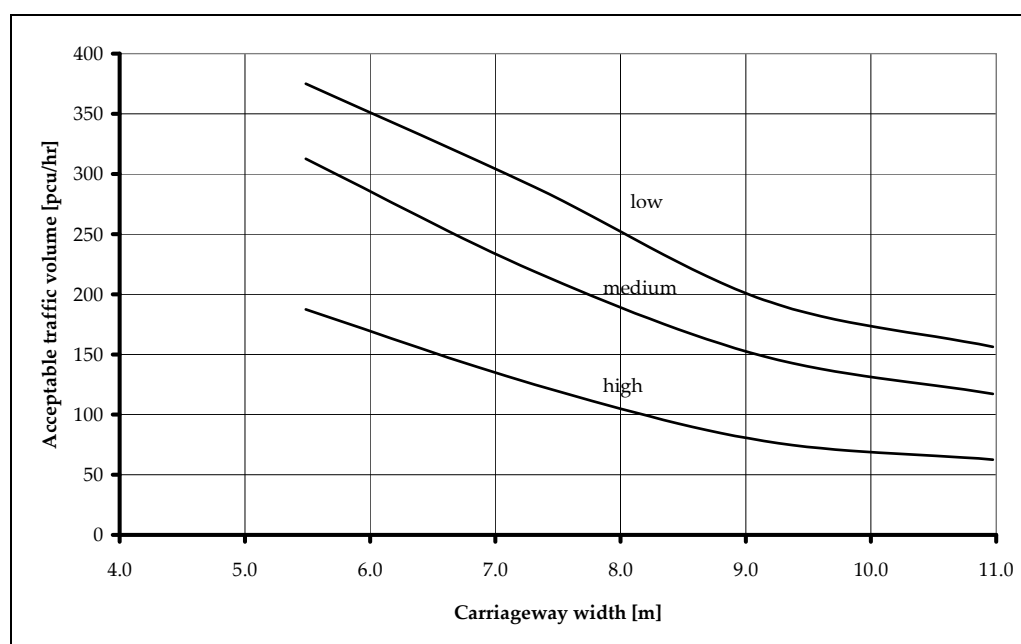
The Buchanan Commissions report *Traffic in Towns* (Ministry of Transport, 1963) has achieved fame far beyond the shores of the United Kingdom. The report describes all aspects of urban traffic problems and has a pan-urban approach.



**Figure 3.1.** Road classification according to Buchanan et al. (1963)

Buchanan et al. conclude that the increase in vehicular traffic is not to be halted and the road network will therefore have to be drastically modified. Rather than opting for a plan making extensive use of public transport like Le Corbusier (1987), they plump for large scale clearances to make way for new trunk roads.

Buchanan et al. also include so-called environmental areas in their plan, to take on the functions of the lower-traffic residential area (*Figure 3.1*). These environmental areas may not be too large lest the number of vehicles exceeds the environmental capacity. This is defined in the simplest of terms, the main criterion being the ease with which a street in the area can be crossed. This 'pedestrian delay' factor is however variable according to the number of vulnerable pedestrians (old people, children: the level of vulnerability) and the degree to which a street can be read, i.e. the degree to which the situation in the street can be seen at a glance: (parked cars, number of obscured exits, driveways etc.: the level of protection). This approach means that, for example, a street with an average level of protection, and a nine-metre wide carriageway may carry only 150 vehicles per hour (see *Figure 3.2*, medium degree of vulnerability). The variation in environmental capacity means that the actual size of an environmental area is heavily dependent on its physical location.

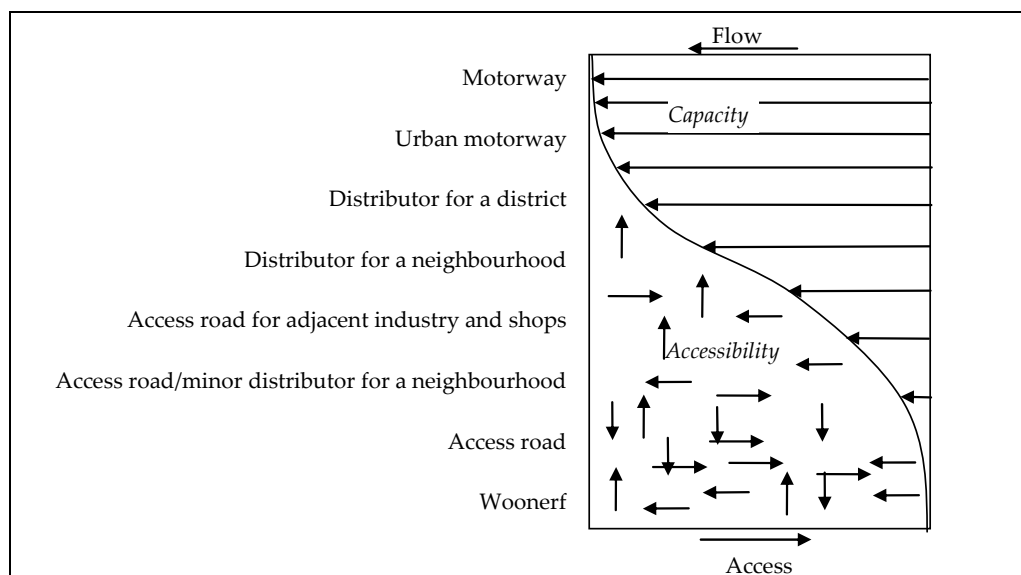


**Figure 3.2.** Acceptable traffic volumes varying with carriage width and degree of vulnerability (Buchanan et al., 1963: p. 205)

A classic Dutch study is '*Verkeer en Stad*', (*Traffic and the City*; Goudappel & Perlot, 1965). This slim volume contains an illustration that is probably the most copied in all the traffic safety literature (*Figure 3.3*). It shows the arrangement of roads and streets according to traffic volume and residential functions. *Figure 3.3* is meant to clarify that residential and flow functions bring about many 'disturbances' in longitudinal and transversal directions

(arrows in *Figure 3.3*). On motorways the flow function dominates, disturbances are scarce. Urban streets have both functions and therefore many disturbances will occur. On some urban main roads (e.g. shopping streets), the flow function can be as important as the residential function, whereas the flow function on residential streets is hardly existent. Between a motorway and a residential street, there is a sliding scale of a diminishing flow function while the residential function increases.

Under the heading 'urban traffic planning' the authors deal with such aspects as road classification, (from urban motorway to footpath), functionality of roads and residential areas, and equilibrium between supply and demand. The classification proposed by Goudappel & Perlot is still used or cited by many, thanks to that one illustration. However, the origin of the classification is unclear. In no edition of Goudappel & Perlot (1965), early or late, is its derivation or basis given.



**Figure 3.3.** Frequency of disturbances because of conflicting movements: from motorway (autosnelweg) to home zone (woonerf) (Goudappel & Perlot, 1965)

According to the authors, the design criteria for roads and streets are as follows (Goudappel & Perlot, 1965 p. 101):

1. All areas of the urban region must be equally accessible.
2. The weight and numbers of vehicles must be spread as evenly as possible; heavy concentrations of traffic must be avoided.
3. The roads should follow the pattern of origins and destinations (straight connections between origin and destination) as closely as

possible whereby traffic movement through areas not being part of a given route is avoided.

4. By ensuring that roads and junctions are of appropriate dimensions, a fluent and constant traffic flow should be made possible. Road classification is an important aid to this.
5. In considering future situations, special attention should be paid to achieving less traffic within an area, with the emphasis on time, rather than on distance.

Out of three possible traffic systems - radial, tangential (grid) and other, Goudappel & Perlot opt for the tangential system, with special regard to criterion 2. For inner cities, they prefer the ring or loop. The authors further lay down requirements for the positioning of housing. Houses must be easily accessible on the one hand and must be on a street primarily residential in nature on the other hand.

At the time of the publication of their report (the sixties) the authors propagated to tackle traffic problems at the pan-urban level. Obviously, they were very much influenced by Buchanan et al.

### **3.1.3. Mesh**

Van Minnen & Slop (1994) proposed a mesh of 10 km for distributors in rural areas. In that case the travel time from an origin to the nearest distributor would take 3 to 5 minutes at the most for 90 percent of the trips. This proposal was not adopted by CROW (1997). However, CROW did not offer any alternative. Therefore, the network structure of rural roads did not get a quantitative criterion regarding the mesh.

For urban residential areas, Van Minnen (1999) concludes that the size, varying from 65 to 80 ha (900 times 900 m<sup>2</sup> at the most), comes up to expectations. Criteria for his evaluation were trip length (within and outside the area), traffic volumes within the area, percentage of through-traffic, driving speeds of motorized vehicles, accessibility of facilities, and accessibility to public transport and to emergency services. In addition, the pedestrian delay factor was evaluated. Most of these criteria were evaluated by means of simple calculations as well as by data based on experiences from recently installed zone 30 areas.

In the former Swedish guidelines for network structure of urban roads (SCAFT, 1968), regional distributors have a mesh of 2,500 m, district distributors a mesh of at least 1,000 m and local distributors a mesh of at least 250 m. These values were primarily chosen from a safety point of view. A number of considerations were taken into account:

- sufficient space for entries and exits
- drivers should be able to anticipate the next intersection
- overtaking should be possible

In addition, hands-on experience played a role in choosing the mesh values. In more recent publications (TRÅD, 1982; SALA, 1999) the mesh values were not used anymore.

Ewing (2000) analysed a theoretical design of a road network, using the following variables:

- number of dwellings per area
- number of car trips per dwelling per day
- average trip length
- share of rush hour traffic
- capacity of a road (in number of vehicles per lane per hour)
- main roads with a maximum of four lanes, distributors with a maximum of two lanes (both road types are part of a grid)

The number of dwellings per area varies from 2.5 per ha to 124 per ha. The mesh of the main roads varies accordingly from 4,000 m to 81 m; in all cases, there is one distributor in between each pair of main roads. After the introduction of an elasticity factor the mesh becomes bigger for the high dwelling densities (from 81 m to 145 m). Subsequently, peak spreading is introduced as well as an adaptation of road capacity. Finally, the mesh for main roads becomes 3.107 m for low dwelling densities and 111 m for high dwelling densities (*Table 3.1*).

Density of dwellings (dwellings/ha)	Vehicle kilometres (mvhkm/km <sup>2</sup> /h)	One-way or two-way traffic	Mesh of main roads (m)	Mesh of distributors (m)
2.5	2,580	2	3,107	1,546
9.9	6,775	2	1,121	560
17.3	10,397	2	663	332
24.7	13,424	2	444	222
37.0	17,380	2	188	93
49.4	21,948	1	280	140
74.1	30,979	1	171	85
123.5	47,823	1	111	55

**Table 3.1.** Mesh values at varying dwelling densities adjusted for peak spreading and road capacity. From Ewing (2000)

The mesh values calculated by Ewing differ from the proposed values by SCAFT (1968). Ewing mainly assumes variations in the dwelling density, while SCAFT focuses on safety criteria regarding minimum lengths of road needed for drivers to anticipate and to overtake. SCAFT does not take the dwelling density into consideration.

### **3.1.4. Network structure through spatial distribution of (housing) clusters**

Clusters for housing, trading, shopping etc., differ in many ways. German guidelines for network structure and classification of connections (FGSV, 1988) divide clusters into four classes. Each class refers to the functionality of a cluster regarding government, court of justice, culture, different kinds of services:

- cluster having the highest functionality (e.g. a national capital)
- cluster having a medium functionality
- cluster having a basis functionality
- cluster having hardly any functionality

A so-called residential area is a cluster (not being assigned to a class) without any functionality. A cluster is not always an urban area; it can also be a recreational area or a transport centre (harbour, airport).

The classification above is a relative one: classes do not have strict limits, e.g. a minimum and maximum number of inhabitants or facilities. The functionality of all clusters in an area is listed. From that listing, the classification follows. So if one cluster is obviously the most important one, that cluster will be in class 1, while the cluster with hardly any functionality will enter class 4. The outcome of this classification may differ from the outcome in another area: in one area, the lower limit of class 2 may have another value than the lower limit of the same class in another area.

The clusters are connected according to their functionality, i.e. the number of persons and the amount of cargo to be transported will be facilitated by the connections (attraction and production for a given O-D matrix). FGSV (1988) defined six levels for these connections:

- I. large-scale, national
- II. pan-regional, regional
- III. inter-urban
- IV. distributor for a district
- V. distributor for a neighbourhood
- VI. local access

Figure 3.4 shows how clusters are connected. Similar classes have a direct connection, while clusters of different classes are connected by two connections not belonging to the same level, thus creating a hierarchy in connecting clusters.

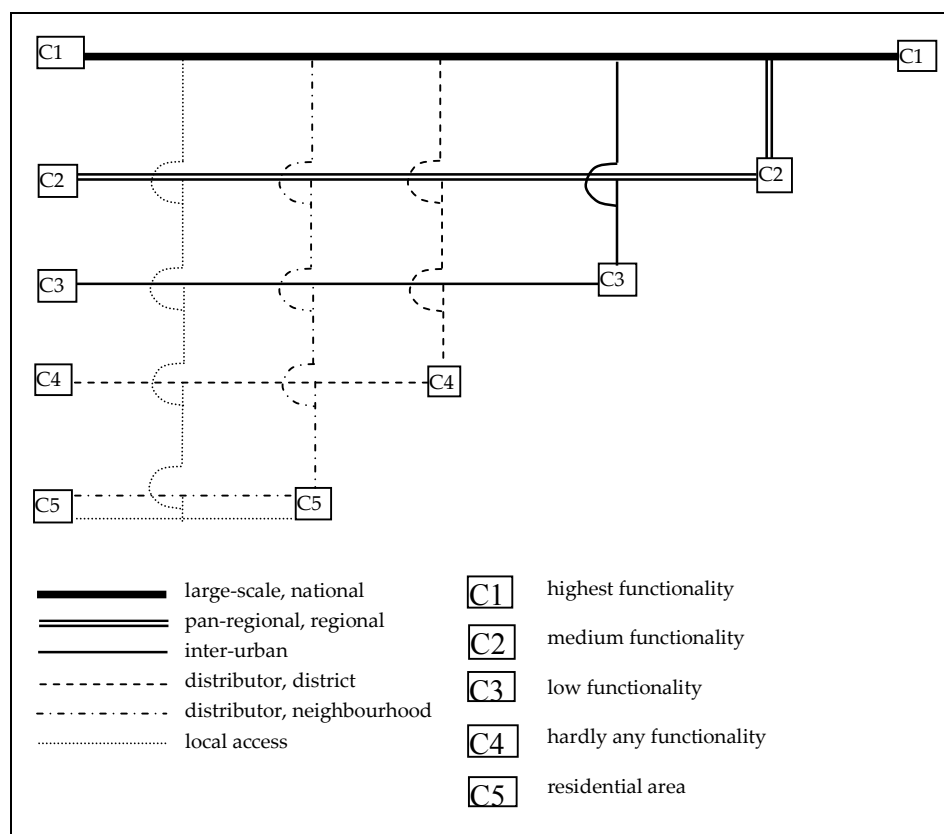


Figure 3.4. System of connections between cluster types

The 1988 guidelines (Leitfaden für die funktionale Gliederung des Straßennetzes RAS-N) were recently replaced by newer guidelines (Richtlinien für integrierte Netzgestaltung RIN) (FGSV, 2008). Gerlach (2007) provides an overview of the differences between the old and new guidelines. The classification of clusters with characteristic functionality remains. However, an additional functionality was added: the metropolis (read as Berlin). The number of connections remains six, but their nature is somewhat different. The lowest level IV disappears, and a new highest level is introduced: the continental connection (between countries). The numbering starts at level '0' and ends at level V.

RAS-N only applied to motorized traffic (in particular private cars), RIN also deals with public transport and bicycle traffic. RAS-N did not indicate a preference for the level of accessibility of clusters, in terms of intended travel



times for different types of connections. RIN does give these indications of travel time in minutes. Travelling by car to a cluster C3 should not take longer than 20 minutes, to a cluster C2 30 minutes, and to a cluster C1 60 minutes. Between two C3 clusters, the maximum travel time should be 25 minutes, between two C2 clusters 45 minutes and between two C1 clusters 180 minutes.

### 3.1.5. Road classification

The North American 'Blue Book' presented a road classification system for rural roads (in 1954); the first of this kind of classification systems. Weiner (2008) gives an overview of the development of the classification systems in the United States. Janssen (1974) proposed a road classification system that would contribute, at least theoretically, to more road safety. The formal road classification in the Netherlands was established by RONA (1992). Janssen (1991a) set up a road classification for urban roads; this system was not accepted however. Finally, a road classification system for all road types was introduced (CROW, 1997) according to the principles of Sustainable Safety (Koornstra et al., 1992). Infopunt DV (1999, 2000) elaborated this classification, particularly the design elements within road classes.

According to Janssen (1974), the aim of road classification is to relieve (simplify) the driving task is. Therefore, the 'recognisability'<sup>1)</sup> for road users should be enlarged. Road classification should meet the following requirements:

- within a class: consistency, continuity and little variation (uniformity) in design elements
- between classes: clear differences between design elements of each class
- number of classes: a limited number


RONA (1992) uses a classification system with four main classes for roads outside urban areas (rural areas); see *Table 3.2*. Each main class is divided up into two classes. One of these classes is taken as the standard class, the other one is a sub-standard class.

RONA's main classes are characterized by the number of carriageways, by the design speed, and by the types of intersections. Janssen (1988, 2005) shows the differences between these classes regarding their risk (number of crashes divided by the number of motor vehicle kilometres); see *Table 3.3*.

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<sup>1)</sup> The driver is easily able to understand which road type he is driving on.

Road user				Road designer										Description of road function
Road class	Possibly present		Traffic situation	Road type (name)	Road type	Road environment	Design speed	Cross-section		Intersection design		Design principle		
	Depending on road type	All vehicle types, as well as pedestrians	Oncoming vehicles					Crossing vehicles	Dual carriageway	Single carriageway	Grade-separated	At-grade	Grade-separated	
Main road network														
A				motorway	I	all situations	120							significant for long-distance traffic, connecting large cities, territories and countries, main transport artery
				motorway	II	urban	90							(part of) ring road for long-distance traffic, important distributor for a city or a region
B			1)	road for motorvehicles only	III	all situations	100				1)			long-distance traffic
				road for motorvehicles only	IV	urban	80							important distributor for a city or a region
Other road networks														
B			1)	road for motorvehicles only	III	all situations	100				1)			connecting important clusters in a region
				road for motorvehicles only	IV	all situations	100							important connection between clusters in a region
C				prohibited for slow moving vehicles	V	all situations	80							significant for medium-distance traffic or distributor for a region
				prohibited for slow moving vehicles	VI	all situations	60							mainly for local traffic
D				road for all vehicle types	VII	all situations	< 60							other roads (also service roads), mainly used as access road
				road for all vehicle types	VIII	all situations	-							access road

 present or applicable

1) grade-separated intersections may occur

 not present or not applicable

**Table 3.2.** Road classification system by RONA (1992)

	Road class	Year	
		1986	1998
Outside urban areas (rural area)	Autosnelweg (motorway)	0.07	0.06
	Autoweg (road only for fast motor vehicles)	0.11	0.08
	Weg met geslotenverklaring (road on which slow moving vehicles are not allowed)	0.30	0.22
	Weg voor alle verkeer (road for all traffic)	0.64	0.43
	Sum rural area	0.23	0.16
Urban area	Verkeersader (main road)	1.33	1.10
	Woonstraat (residential street)	0.74	0.57
	Sum urban area	1.16	0.94
	All road types	0.53	0.35

**Table 3.3.** Key safety indicators for rural RONA road classes and for urban road classes (adaptation by the author of Janssen, 1988 and 2005)

These differences appear to be quite large, the risk increases with the number of disturbances (from motorway to road for all traffic, and from residential street to main road). Many disturbances occur when through traffic mixes with local traffic, when slow moving vehicles mix with motor vehicles, when pedestrians cross a street, and when many vehicles overtake others on a road with a single carriageway.

The introduction of Sustainable Safety resulted in a new road classification system (Janssen, 1997; CROW, 1997):

- fewer road classes: three instead of eight classes in rural areas
- mono-functionality of each road class: a class is either intended for flowing or for offering access, in between there is a road class which connects the other two classes
- potentially serious conflicts are not allowed: e.g. frontal conflicts (on 80 kph roads) are prevented by separating (physically) vehicles driving in opposite directions
- 'essential' characteristics should enhance recognisability: number of carriageways, presence of an emergency lane, longitudinal marking

In urban areas road classification is a matter of splitting the area up into residential areas (access roads, preferably grouped within a zone 30) and areas for main roads (distributor roads).

### 3.2. Homogeneity of traffic within a road class

The term homogeneity comprises all available means:

- to restrict the differences in speeds, driving directions and masses
- to separate types of road users, in particular pedestrians and cyclist from motorized traffic
- to lower speeds if the previous means are either not present or not preferred

Several traffic measures are available for improving homogeneity. A physical separation is meant to prevent differences in driving directions, one lane for each direction will reduce driving speeds, bicycle paths and lanes will separate cyclists from motorized traffic, a roundabout will decrease speeds and reduce the number of serious conflicts at intersections, and a hump will reduce speeds at road sections. These kinds of traffic measures will most probably reduce the number of crashes, as is shown by Dijkstra (2003).

Guidelines (CROW, 1997) and recommendations (Infopunt DV, 1999 and 2000) were formulated to establish a specific set of design elements for each road class. Doumen & Weijermars (2009) conclude that the implementation of these guidelines and recommendations is still in progress.

#### **Design elements that stimulate recognisability as well as predictability**

Janssen (1974) states: "A road class will function efficiently if the road characteristics create the right expectations to the road user regarding his traffic behaviour (choice of route and manoeuvres) and the behaviour of the other road users." The term 'expectations' is too inexact to use in research. That is why mostly characteristics have been studied which drivers use when classifying roads (Noordzij, 1996). Other types of studies used human test subjects who were shown pictures of road images after which they had to tell which kind of behaviour would be appropriate (stated preference). In addition, human test subjects in a simulator were asked to respond to simulated traffic situations (Noordzij, 1996). Noordzij concludes that human test subjects who classify roads (usually by sorting photographs), mostly take the number of carriageways and the number of lanes as a clue. On the basis of recent simulator studies, Aarts & Davidse (2007) conclude that a more recognisable design (according to the design elements of Sustainable Safety) results in a safer behaviour: lower speeds and a position in the cross-section closer to the edge of the road than on the classic road types. However, the homogeneity of speeds did not improve.

### 3.3. Summary

The Germans have more than forty years of experience in structuring their road network. Sweden introduced a network structure (for urban areas) many years ago. And in the Netherlands, the network structure is not a foregone conclusion. The mesh of main roads in Dutch urban areas was clarified to some extent; the foundation is the result of a simulation study.

Road classification was introduced at an early stage of the large-scale car mobility. On the one hand, road classification is a way of planning and designing the different functions of roads, on the other hand it helps road users to make safe and quick trips. For a road authority, road classification is not necessarily the same as road classification for a road user. The road authority needs a classification relevant for the road functions and for the use of the road (as the authority would like it to be). This classification of the road authority results in a design for each road. The design, amongst other things, is a prerequisite for homogeneity within road classes. The road user on the other hand should be able to understand from the road characteristics and from actual traffic situations (recognisability) how to behave and what behaviour is to be expected from other road users (predictability). Road classification should assist the road user in this driving task. This assumption could be confirmed to some extent.

Road classification is meant to reconcile the aims of the road authority and the aims of the road user. In Sustainable Safety this reconciliation is included as the principles of recognisability/predictability and functionality/homogeneity.

The methods described above, to come to a network structure and to a road classification are typical methods of network design. The design principles and rules of thumb are mostly based on hands-on experience. The scientific foundation for this set of principles, requirements and rules is very frail. However, road classification is relevant to this study. To overcome the frailties in the existing methods, a new method will be described for classifying roads (*Chapter 9*). This method is partly based on the German guidelines.

## 4. Route choice in road networks

In the present study, route choice in road networks is a very important issue; in this chapter, only the existing knowledge will play a role. The research carried out in this respect will be explained in *Chapter 6*.

Studying the use of roads network could be limited to analysing the volumes of road sections for different periods. However, another type of information is required in order to find differences between the intended use and the actual use of roads and road classes. Therefore, a more relevant analysis unit will be the route: all road sections and intersections between origin and destination. Analysing a route will show whether the sequence of road categories meets the requirements of Sustainable Safety. Routes not fitting these requirements should be adapted or traffic should be advised not to use those routes.

Several measures are available for these purposes: roadside message signs, navigation systems, road closures. Their effects are only partially known, more knowledge is needed, particularly for routes on the regional level.

This chapter also deals with the question: what are the direct effects of route choice on road safety and what is the nature and size of these effects?

### 4.1. Route choice as part of Sustainable Safety

A Sustainably Safe traffic system comprises a set of requirements for road networks. For route choice, the most important requirement is whether the safest route coincides with the fastest route. Meeting this requirement could result in car traffic moving through residential areas because:

- residential areas are very safe
- routes through the areas are mostly short-cuts

That is why an additional requirement is set:

- a residential area may only be the origin or destination of a route
- the major part of the route should follow main roads (flow function)
- a minor part of the route may follow a distributor

To come to a route choice like this, the resistance (i.e. travel time) of a route through a residential area must be larger than a route along main roads and distributors. In addition, the route choice may be influenced by instructions at the roadside or within a vehicle, and possibly by the design of the road and its environment. A road network can only be sustainably safe if the traffic on the main roads keeps flowing. If not the resistance of the residential

areas for through traffic will be relatively lower than the resistance of the main roads.

Another important issue for a sustainably safe road network is road classification. The classification should correspond to the actual traffic circulation. This relates to the mesh of the distributor roads and main roads. Sustainable Safety (CROW, 1997) does not prescribe certain mesh values. Initially, the so-called travel time criterion (Van Minnen & Slop, 1994) was formulated. A driver, starting in a residential area, should reach a distributor with a few minutes. Drivers only need to be subjected to a low speed limit for a short while. This criterion sets a limit to the size of residential areas. Since the criterion could not be based on knowledge yet, the guidelines for road classification (CROW, 1997) do not encompass it. On the contrary, the guidelines require residential areas to be 'as large as possible'. This requirement will influence the mesh value. In actual practice, this value (in urban areas) mostly varies from 20 ha to 100 ha (Van Minnen, 1999; Krabbenbos et al., 2002).

## **4.2. Route choice in general**

The previous *Section 4.1* treated route choice from a safety point of view. The network structure, the mesh of main roads, the relative resistance of routes, information provided to drivers, are all means to let drivers choose the routes favourable to both safety and accessibility. In this section, the background of route choice is discussed. Many authors have studied route choice. The focus will be on the following questions:

- What are the reasons for choosing a route (how and why)?
- Which variables will affect route choice?
- How are these variables related to each other?

Literature shows that many researchers have been working on these questions and issues, as the following overview will confirm.

### **What are the reasons for choosing a route?**

Much elementary knowledge about route choice can be found in a study written by Bovy & Stern (1990). In their view, route choice is part of travel behaviour, and subsequently travel behaviour is part of spatial behaviour. Spatial behaviour is the result of "a mixture of cognitive and affective attitudes, emotions, perceptions, cognition and learning" (Bovy & Stern, 1990; p. 25). According to the authors, what is important to spatial behaviour is that a person will develop decision rules in order to make spatial choices.

Successive spatial choices of individuals and groups will result in behavioural processes that will finally determine spatial structure.

Travel behaviour stems from the series objective situation, personal perception, subjective situation, and personal decision. Four groups of factors influence this decision: physical environment, socio-demographic environment, normative environment and personal environment (Bovy & Stern, 1990). Personal environment filters the other three environments.

Route choice is an inseparable part of travel behaviour. The traveller, given his personal environment, will have to make a choice from the possibilities offered by the physical environment. A large number of alternative routes are potentially at his disposal. However, the traveller is not aware of all alternatives (cognition). His experience is relevant for this cognition. Not all of the available alternatives are useful for the intended trip, because of conditions regarding travel time and destination(s). Finally, the traveller makes a choice by weighing his own preferences as well as the physical aspects of the alternatives. During a trip new choices sometimes appear, by additional information about the alternatives for the rest of the trip.

These general notions about route choice will be elaborated below, using information from literature:

1. What is the structure of the underlying decision processes?
2. Which variables will affect route choice?
3. In which context are these variables valid (temporal and spatial)?
4. How do drivers receive traffic information? And does this information influence their route choice?
5. Which subdivision of the driver population is relevant?
6. What is the size of the effect?

Influencing route choice by navigation systems will be discussed separately (*Section 4.3*).

#### **4.2.1. What is the structure of the underlying decision processes?**

Andan & Faivre d'Archier (2001) have studied how car drivers choose their routes. The routes were part of regional trips, having a length of 50 to 200 km. The researchers prepared three scenarios, possibly resulting in a route change. A group of 30 car drivers taking these types of trips was selected. The drivers were confronted with three scenarios:

- adverse weather conditions: varying in seriousness
- traffic congestion: either starting at one third or at two thirds of the route length
- re-routing: a road closure at one third or at two thirds of the route length



Different strategies were stated to adapt route choice behaviour. In the first scenario, for example, three strategies were found:

- staying on the same route; relying on own skills
- reducing risk by changing routes or choosing another time of departure
- reducing risk by postponing the trip or letting a (more experienced) passenger drive

Relevant factors for route choice are dependent on the underlying decision process. The factors for the decision are:

- perception of the nature of the disruption
- possibilities to react
- skills to evaluate the risks

Contributing factors are:

- preferences of the driver
- skills and knowledge
- available resources: e.g. a map, a mobile phone
- conditions: time pressure, additional costs

The variability of route choice behaviour is smaller (or the adaptation is more stable) in the re-routing scenario compared to the other ones. Car drivers reacted in two ways.

1. Individual factors (attitude towards dealing with the altered situation, personal skills, preferences and knowledge) determine their choice, independent of the nature of the altered situation. Sometimes an adaptation is inevitable because of the circumstances.
2. A combination of both individual factors and circumstances determine their choice. This means that, when analysing route choice, both circumstances and individual factors should be considered.

## **Conclusions**

Quite a few car drivers make reasoned choices, by weighing the risks (of not adapting) and the advantages (of adapting). Personal preferences are less important than was assumed. What is also relevant is the context of the trip and the nature of the disturbances. Drivers are strongly motivated to get as much relevant information as possible. Some drivers deliberately choose motorways because up-to-date information is mostly provided on this type of road.

#### **4.2.2. Which variables affect route choice?**

Wachs (1967) interviewed several hundred car drivers about their route choices. They preferred routes having a small number of crossroads and driveways, minor congestion, less stress for the driver, more safety, and the shortest travel time. They preferred routes along commercial areas or, by contrast, routes along attractive scenery.

Ueberschaer (1969, 1971) describes an extensive questionnaire survey among 13,000 car drivers. He finds the following relevant factors for route choice: fastest route, shortest route, less congestion, well-designed road. Benshoof's (1970) study confirms these results. The preferences for route choice are, in descending order: fastest route (82%), less congestion (77%), less traffic than on alternative routes (71%), shortest route (60%). These preferences are also mentioned by Vaziri & Lam (1983).

Michaels (1965) made drivers choose between two parallel roads, having the same length. The one road was a toll road, the other one a rural main road. The choice for either of these roads depends on road type, driver's age, trip frequency, and (less) tension.

De Palma & Picard (2005) find as an additional variable: the aspired level of certainty about the expected arrival time (aversion to arrive late).

Goldenbeld et al. (2006) sent a questionnaire to 500 car drivers. They subsequently found that a driver who often travels to the same destination, changes routes more often.

A delay of at least 15 minutes induces the driver to choose an alternative route, and to use traffic information. Li et al. (2005) reported the characteristics of routes most preferred by drivers. Compared to other routes, these routes have a shorter length and travel time, have fewer idle stops, fewer signals at intersections, and have a larger share of motorway length. Zhang & Levinson (2008) find similar results.

None of the studies mentioned shows road safety to affect route choice in any significant way.

#### **Conclusions**

Travel time and trip length appear to be the most important factors in route choice. A less congested route is preferred as well as routes with a larger share of motorway length, less uncertainty about travel time, less tension, and fewer idle stops. A driver who often travels to the same destination, changes routes more often. Road safety does not appear to be an important factor in route choice.

#### **4.2.3. In which context are these variables valid (temporal and spatial)?**

Ueberschaer (1969, 1971) shows that the number of selected routes increases in accordance with trip length: two to three routes are usual given a trip length of 3 to 9km. The number of alternatives decreases at longer distances. The number of selected routes in a rural network is smaller than in an urban network; e.g. in a fringe and suburban area the number is smaller than in a central business district. The number of routes also depends on the volumes on the main network. Goldenbeld et al. (2006) studied route choice in an area sized 10 by 20km. The drivers in this survey could choose between three alternative routes to their destination. Some parts of the routes coincided. The majority of the drivers choose a route on the motorway. About 30 percent does not opt for an alternative route. The alternatives mostly consist of other road types, which in 25% of the cases is a regional main road. Two out of five drivers prefer a route or alternative route on roads not being main roads.

Li et al. (2005, 2006) studied trips from home to work. Two out of three drivers prefer only one route, the other ones use two routes (30%) or three routes (3%). They also found the share of motorway length on the preferred route is 54% while the share on the alternative route is 33%.

According to Ueberschaer (1969, 1971) car drivers see travel time and travel distance as the main reasons for their route choice. However, measurements of times and distances did not always appear to be consistent with the stated values. The reasons given by car drivers usually preferring motorways were more in accordance with actual measurements than reasons given by users of rural and urban roads. Zhang & Levinson (2008) also find that the observed trip length differs from the perceived trip length. Ueberschaer concluded from the answers to Benshoof's survey, that either route choice is an irrational process or car drivers do not 'measure' route characteristics accurately. This conclusion was relevant because, at that time, many traffic models used travel time as the main criterion for route choice. Benshoof (1970) suggested introducing a set of criteria, consisting of travel time, number of stops, traffic volumes in direction of travel, and distance. This set was also used by Ueberschaer (1969). Li et al. (2006) reported a difference between car drivers using only one preferred route and drivers using more routes. For the latter group, travel time, trip length, number of idle stops, number of trip chaining stops (stops with a specific purpose), and the variation in travel time exceed these of the group with only one route.

Michaels (1965) studied the differences between drivers choosing a rural main road and the ones choosing a toll road. The appreciation of the toll road, and the actual use of this road, is higher for drivers travelling both routes more often (from origin to destination). Measurements of the tension of the drivers showed 46% lower values for users of the toll road. Wachs (1967) showed that the preference for a route with less congestion, less tension, and along *pleasant scenery* is related to a longer trip length.

More than 50 percent of the respondents to the questionnaire used by Vaziri & Lam (1983), choose for a reduction in travel time and less congestion for the morning trip, and only choose for less travel time on the way back. About 30 percent does not opt for a time reduction.

Goldenbeld et al. (2006) show that a car driver prefers short travel times and trip lengths when making *commuter trips and business trips*. For other purposes travel time and trip length are less important; familiarity with a route is more important.

The *quality of urban planning aesthetics* makes a route more attractive for all purposes, according to Zhang & Levinson (2008). Commuter trips and trips with purposes 'event' and 'visit' are related to efficient routes. For these purposes, drivers choose a route they already know. The knowledge about a route prior to making a trip, explains route choice better than the perceived characteristics of a route. While the perceived characteristics explain route choice better than the objectively observed characteristics. According to the authors, route choice is, in the first place, a matter of prior knowledge, in the second place a matter of perceived characteristics, and finally, a matter of objective characteristics.

## **Conclusions**

The number of selected routes is related to the nature of the environment, rural or urban, and to the volumes on the main road network. Most car drivers use two or three alternative routes. Quite a few car drivers choose a route on the motorway. The preference for the motorway is also sizeable because of the low tension on this road type.

Car drivers mention travel time and trip length as main factors for their route choice in commuter trips. Yet, perceived travel time and trip length are not always in accordance with observed travel time and trip length. The number of stops and traffic volumes are related factors for route choice. The road environment (*urban planning aesthetics, scenery*) will also influence route choice. Prior knowledge about a route is of more importance for route choice than perceived route characteristics, which are in their turn, more important than objective characteristics.

#### **4.2.4. How do drivers receive traffic information? Moreover, does this information influence their route choice?**

Shirazi et al. (1988) interviewed commuters by phone. About 40 percent of these commuters sometimes change their routes, of which a quarter changes seldom, and a third often to very often. Congestion is the main motivation for changing. Indicative for this decision are radio information, experience, pressure to be in time, information on the Electronic Freeway Signs. Two thirds often to very often listen to radio information.

Three out of four of commuters obtain traffic information by listening to the radio before departure (Wenger et al., 1990). However, this information hardly has any influence on the decisions regarding the trip; travel mode (car or bus) and departure time are seldom changed. On average commuters decided to change their route before departure twice a month. Traffic information during the trip is dominant for changing routes, the observed traffic situation is of less importance. About a third of the commuters do not know whether their decision to change the route was right. The majority of the commuters get feedback about their choice more than five minutes after making the decision.

Spyridakis et al. (1991) conclude that recent traffic information, observed congestion, and time of day affect route choice. Time pressure and weather conditions have a smaller influence on route choice. Commuters actually changing their routes are influenced by all of these factors. More than half of the commuters would like to get traffic information before departure; the rest prefers receiving information just before entering the motorway. Traffic information sometimes or regularly influences departure time; it sometimes or regularly influences route choice before departure. The information before departure is obtained by radio or television. Half of the commuters change their routes while travelling, because of traffic information received by radio or electronic message signs. Radio information is most helpful, electronic message signs are less helpful.

Jou et al. (2005) interviewed car drivers along a motorway. The respondents mentioned radio, the Internet and variable message signs as a way of getting up-to-date traffic information. A substantial number of drivers (44%) use these media quite often or every time. One tenth does not take note of this kind of information.

Goldenbeld et al. (2006) reported that car drivers do not choose their preferred routes if information is available about a possible queue or if they can avoid congestion. For one third of the drivers, route choice depends on traffic information by radio, television or the Internet, prior to departure.

Only a small number use navigation systems. Along the way, more than half of the drivers (59%) use information sources; most of them use the radio or electronic message signs (DRIPs). Only 3 percent use a navigation systems.

### **Conclusions**

Prior to making a trip, a considerable number of car drivers take note of traffic information, mostly by radio, television and the Internet. This information influences the route choice or departure time for only a small number of drivers. Along the way, traffic information mostly originates from radio, own observation, electronic message signs, and sometimes from a navigation system. A substantial number of drivers change routes because of this information.

#### **4.2.5. Which subdivisions of the driver population are relevant?**

Wenger et al. (1990) divided commuters in four clusters, differing in flexibility regarding departure time, likelihood to change routes after receiving information before departure, searching for information before departure, and the level of tension on the preferred route. The four clusters are:

- Route changers (21%), those willing to change their commuting routes on or before entering the motorway
- Non-changers (23%), those unwilling to change departure times, transportation modes, or commuting routes
- Time and route changers (40%), those willing to change both departure time and commuting routes
- Pre-trip changers (16%), those willing to make time, mode or route changes before leaving the house but unwilling to change en route

### **Conclusions**

Commuters can be divided up into clusters differing in flexibility regarding departure times and levels of tension on the preferred route as well as likelihood to change routes on account of information along the way or information prior to departure.

#### **4.2.6. What is (the size of) the effect of traffic information?**

Kraan et al. (1999) evaluated the effect of installing seven additional variable messages signs along the southern part of the Amsterdam ring road (motorway A10). On this part of the road drivers can choose between two parallel routes (A10 and A9).

Kraan et al. defined congestion as a situation with driving speeds below 35 kph. Comparing the situation before and after implementation shows that both congestion and delays decreased. The standard deviations for both indicators were clearly reduced. The queue length differences between both routes could be related to the changes in route choice. A bigger difference in length will result in more drivers changing routes. If the difference is 5km, 10% of the drivers will change routes.

Jou et al. (2005) gave car drivers a choice between two routes, both on motorways. Traffic information allows drivers to change between these routes at four locations. The outcome shows that drivers tend to switch more often at the beginning of the route than at the end.

Bogenberger et al. (2006) presented situations to human test subjects who had to decide about the rest of their trip. The participants had to imagine driving on a motorway. Information was available about expected congestion, queue length, delays and the distance to the next exit. The participant passes through two scenarios.

In the first scenario, the congestion increases. During the first 'trip', there is no congestion. The participant is advised to exit the motorway in order to follow an alternative route. If he/she does not follow this advice, congestion will be worse during the next trip. The same advice will be given during the second trip. A participant, who also neglects this advice, gets the same advice during a third trip. Ignoring this again, will result in being stuck in a queue.

The second scenario is quite similar to the first one. However, congestion does not increase and traffic flows are undisturbed. In this second scenario, the advice is obviously not correct (because it is not necessary to exit the motorway). The results of the scenarios are laid down in *Table 4.1*.

In scenario 2, more than 50 percent of the participants (called obedient persons) have followed the advice. Afterwards they have negative feelings about this choice. They are annoyed that the advice was wrong. The feelings of this group about scenario 1 coincide with the feelings of the persons who did not follow the advice in scenario 2. Participants having an in-car navigation system state that they usually follow the advice of their systems. They subsequently take the alternative routes. They claim that their system guides them to their destination faster. A majority of the participants question the quality of the traffic information. A third think that the advice should always be followed.

		Scenario 2				
		Exits the motorway during the first trip	During the second trip	During the third trip	Does not exit the motorway (critical person)	TOTAL
Scenario 1	Exits the motorway during the first trip	97 (obedient persons)	4	0	3	104
	During the second trip	2	4	5	23	34
	During the third trip	0	2	0	15	17
	Does not exit the motorway (critical person)	1	1	2	5	9
	TOTAL	100	11	7	46	164

**Table 4.1.** Decision to exit the motorway according to scenarios and to trips (in numbers of human test subjects)

## Conclusions

A series of variable messages signs on an urban ring road showed some effect on route choice. The queue length differences between both routes could be related to the changes in route choice. A larger difference in length will result in more drivers changing routes

At the beginning of a route, more route changes are made than at the end.

In an experimental design, 50 percent of the participants follow the advice to exit the motorway, even if the advice is obviously not correct. Almost a third does not follow this advice, even in conditions confirming the correctness of the advice.

### 4.3. Navigation systems

DVS (2008) reports about a questionnaire survey amongst 202 car drivers using a navigation system. Most of the drivers (60%) in this survey drive at least 20,000 kilometres a year in their own car or in a company car. For commuting, almost 70 percent never uses the navigation system. The system is used for business trips and recreational trips in particular.

Vonk et al. (2007) investigate data about 1,144 car drivers. Within this group, 28 percent have a navigation system. According to Vonk et al., this percentage is higher than that in other studies (average 20%). Around 35 percent of car drivers having a navigation system use their system in 20 percent of their trips. Around 15 percent use the system in 80 percent of their



trips. The system is mostly used for unknown destinations. Car drivers having a navigation system drive more kilometres a year than drivers without a system do. Sixty percent of the system owners drive more than 20,000 km a year; only forty percent of the non-owners drive that distance.

According to DVS (2008), 86 percent of the car drivers having a navigation system use the setting 'fastest route'. Only a few drivers use 'shortest route'. The main reasons for using a navigation system are: arriving at the destination as fast as possible and a prevention of making detours (each reason was mentioned by 40 percent).

A navigation system informing about the current traffic situation can draw the attention of the driver in time to be prepared for coming events. A driver could change routes because of this advice. One fifth of the respondents in the DVS survey use the option to change routes, given the information about congestion. What would happen if a greater number of drivers would change routes? This effect is still unknown. Over a third of the respondents choose a route without using the (potentially available) information about current or frequent queues.

The road classification used in the navigation system will largely determine the advised route choice. That is because a road class has a characteristic speed limit; this limit is used for calculating travel times, thus determining the fastest route. However, what would road classification look like from a safety point of view? Map producers use more and other road types than Sustainable safety does (VIA, 2007). The road user is led to 'higher' road types as soon as possible. This corresponds with the requirements regarding functionality in Sustainable Safety. Navigation system users claim to drive on motorways (32%) and rural main roads (28%) more often than they would without such a system (DVS, 2008). They also drive on access roads (16% in rural areas, 15% in urban areas) more often; according to the drivers, these roads were advised by the system. The respondents (users of navigation systems) to the survey of Vonk et al. (2007) reported they drove more on highways (18%), secondary roads (17%), and urban roads (6%). Of the road types in these answers, the motorway has the lowest crash risk. For road safety reasons, it is desirable that a greater part of trip lengths is covered by motorways. Vonk et al. also investigated the mental stress of drivers by using system-equipped vehicles in a small-scale experiment (36 drivers). Drivers using a navigation system experienced less stress and mental effort than drivers without a system did. This result was based on both the drivers' opinion and on measurements. The drivers followed routes in an area unknown to them. The system users drove shorter distances (-16%), and spent less travel time (-18%). This result was reached by fewer stops (in time)

and by using more route length on motorways. Given less exposition (time and distance), the crash frequency would be lower.

#### **4.4. Conclusions**

##### **Conclusions regarding route choice**

A significant number of drivers makes a well-founded decision when choosing an alternative route on account of a changer in circumstances. This decision is a weighting of risk (of not adapting) and advantages (of adapting). Personal preferences are less important than was assumed. The context of the trip and the nature of the changing circumstances (disturbance) are also relevant. Drivers have a strong need for up-to-date information. Some drivers deliberately opt for the motorway because information will more often be available on that road type.

Travel time and trip length are without a doubt the most important factors in route choice. For business trips and commuting, these factors are often mentioned. However, travel time and trip length sometimes appear subjective rather than objective values. The number of stops and traffic volumes are related factors for route choice. The road environment (*urban planning aesthetics, scenery*) will also influence route choice. Prior knowledge about a route is of more importance for route choice than perceived route characteristics, which are in their turn, more important than objective characteristics.

Drivers prefer a less congested route as well as (parts of) routes on motorways; they also prefer good road and weather conditions, less stress, and fewer idle stops. Motorways are very much preferred; they are associated with a low stress level.

A driver who frequently travels to the same destination, changes routes most often. They prefer routes with less access, particularly motorways. Road safety is not an issue in route choice matters. The number of selected routes depends on the type of area (rural or urban) as well as on the volumes on the main road network. Most drivers use two or three routes.

##### **Conclusions regarding the steering or influencing of route choice**

Prior to a trip, a significant number of drivers take note of traffic information, mostly by radio, television or the Internet. This information will largely determine route choice or departure time. The traffic information en route is obtained by way of radio, personal observation, variable message systems, and for some drivers, a navigation system. A substantial number of drivers change routes because of this information. Commuters can be divided into

groups differing in flexibility regarding departure time, the likelihood of changing routes on account of prior information, or searches for prior information, and stress on the preferred route.

A series of variable message signs on an urban ring road showed some effect on route choice. The queue length differences between both routes could be related to the changes in route choice. A bigger difference in length will result in more drivers changing routes

At the beginning of a route, more route changes are made than at the end.

In an experimental design, more than 50 percent of the participants follow the advice to exit the motorway, even if the advice is obviously not correct. Almost a third does not follow this advice, even in conditions confirming the correctness of the advice.

A fifth to a quarter of car drivers in the Netherlands own a navigation system. They drive more than average distances a year; they use their navigation systems for unknown destinations.

The expected total effect of navigation systems is: less exposition and less stress for the driver. It is yet unknown what would happen if a greater number of drivers changed their routes. This would certainly affect the traffic circulation in the road network and is a matter deserving further study.

## **5. Road safety aspects of road network structure and road classification**

Road classification, geometrics, legislative rules, and traffic circulation are interrelated. Changes in one of these four factors will affect the other three. For instance, a measure in one street (one-way traffic) may result in a change in traffic circulation in the surrounding area. Sometimes this will cause a difference between the intended function (according to the classification) and the actual function. Another outcome may be a discrepancy between the road design (e.g. a narrow lane) and the actual traffic situation (e.g. a great deal of traffic in both directions).

This interaction needs to be understood to find out why problems arise. This understanding will facilitate more appropriate traffic measures which will affect the interaction most effectively. The present study aims to identify traffic measures that, first and foremost, have positive road safety effects.

In order to find out the consequences of changes in the four areas described above, knowledge is needed about road safety aspects of both road classification and all other kinds of traffic provisions. Road safety aspects are usually expressed in terms of numbers of crashes or numbers of casualties per annum. Subsequently, the absolute numbers have to be related to the exposure to risk, mostly expressed by the number of motor vehicles or the number of motor vehicle kilometres. In many cases, these kinds of data are unknown, either on account of lacking evaluations or because of methodological problems. For instance, from a methodological point of view it is impossible to show an effect of one traffic hump on the number of crashes. Intermediate indicators are available to show an effect after all, in this case driving speeds near the hump. In general, to gain a good insight into road safety more indicators have to be used than the number of crashes only.

Crash analysis has become less important with the introduction of the Sustainable Safety approach. That is because this approach uses general safety knowledge for setting requirements and specifying rules for road classification and road design. The knowledge translated into these requirements and rules is meant to prevent crashes or, if a crash is inevitable, reduce the severity of the crash. In order to achieve these aims large differences in speeds (zone 30), in driving directions (barrier) and in masses

(bicycle path) should be avoided. A systematic check of the existing or planned (parts of the) road network will make clear whether the requirements have been met.

On the level of road networks, a change in structure and/or in road classification will mostly affect traffic circulation, departure times and modal choice. The changes may be of a complex nature. That is why traffic modelling is used to find possible effects.

This *Chapter 5* gives an overview of three types of studies:

1. Studies using a large number of variables in order to describe road structure and travel behaviour. Accordingly, these variables are related to crash figures resulting in statistical models. Such models show the quantitative relationships between the variables and the crash numbers.
2. Studies demonstrating the relationships between, on the one hand, characteristics regarding network structure, accessibility, road classification, and road design and, on the other hand, traffic volumes. Changes in traffic volumes are used as an indicator for the impact on traffic nuisance and unsafety.
3. Studies regarding the direct relationships between the characteristics mentioned at 2., and crash figures.

Studies of the second and third type can be modelling studies and before/after studies. Mostly, the characteristics are changed on the input side (in the model or in reality), while the effects on traffic volumes and on crash numbers (the output) are to be evaluated.

## **5.1. Network structure and travel behaviour related to crash numbers**

This section deals with studies estimating statistical models regarding relationships between various variables and crash numbers. This section seeks to answer the question whether objective characteristics concerning urban areas, road infrastructure, traffic and transport are statistically related to crash frequency. This (statistical) approach usually shows significant and non-significant relationships. It cannot always be understood why the one relationship is significant and the other one is not. In some cases, it has to do with the number of observations, in other cases with the lack of variance within a variable. Sometimes, relationships are hidden because important variables are missing in the model.

Hadayeghi et al. (2003) gathered data from 463 traffic zones in Toronto (Ontario, Canada) regarding socio-economics, traffic, population, and

crashes. The traffic data consisted of the number of intersections, intersection density, length of main roads, length of other roads, speed limits (posted speed), volume to capacity ratio (V/C), inbound and outbound traffic, and the number of motor vehicle kilometres. The authors use models having a negative binomial distribution (of the parameter for 'overdispersion', i.e. extra variation). According to Miaou (1994), this distribution is better than the Poisson distribution (that was used by many other authors). Hadayeghi et al. (2003) built models for the total number of crashes, serious crashes, and crashes during the morning rush hour (total and serious). The models for the rush hour prove to be better than those for the entire day, probably because the traffic data refer to the rush hour only. The best model (total number of crashes during rush hour) comprises the following significant variables: road length, number of employed, volume to capacity ratio, and speed limits. Another type of model was also applied: the geographically weighted regression model. This type of model allows for a spatial distribution of the variables. It comprises the following significant variables: speed limits, volume to capacity ratio, number of households, intersection density, and road length. This model produces a better result than the binomial models.

Hadayeghi et al. (2007) continued the work described above. A follow-up study was set up to estimate a risk model. This was done by using generalized linear modelling, assuming a negative binomial distribution. In total, 23 models were analyzed: twelve for all crashes, eleven for serious crashes. Some models contain variables describing traffic and network structure. Other models (called *comprehensive* models) comprise a few of the preceding variables as well as socio-economical and demographic variables. The comprehensive models have the better statistical results. The best model predicts the number of (serious) crashes by using the following variables: number of motor vehicle kilometres, road length, number of signalized intersections, size of commercial and industrial area, and number of inhabitants.

Ladrón de Guevara et al. (2004) used data from 859 traffic zones in the urban area of Tucson (Arizona, U.S.A.). These data regard socio-economical and demographic variables as well as traffic and crash variables. All models have a negative binomial distribution. Models were estimated for fatal crashes, injury crashes, the sum of these two types of crashes, and crashes with damage only. The model for the sum of fatal and injury crashes produced the best results. In this model, intersection density and road length are significant variables. The additional significant variables are population density and number of employees. The authors do not allow for spatial distribution of the variables, as Hadayeghi et al. (2003) did.

Quddes (2008) set up several models for explaining the number of casualties in 633 London wards (= city districts). His models contain variables regarding traffic, road and socio-demographic characteristics. The traffic variables are volumes and average driving speed; the road variables are number of intersections (and roundabouts), road length per road type, curvature, and number of bus stops. The socio-demographic variables are resident population younger and older than 60 years, number of employees, number of households without a car. The number of motor vehicle kilometres was unknown. Therefore, an estimation of the average number of motor vehicles in a ward was used as an indicator for exposure. The statistical models used can be split up into two groups: non-spatial and spatial models. The non-spatial models having a negative binomial distribution do not allow for spatial dependency of the wards, the spatial models do. The non-spatial models appear to have the following significant variables: resident population older than 60 years, length of main roads and residential streets, and average driving speeds. The number of intersections was not significant, neither was the number of bus stops. The spatial models have about the same results. However, the average driving speed is not significant in the spatial models. In the non-spatial models, driving speed was negatively correlated with the number of casualties meaning that a higher speed would result in fewer crashes. This result (only to be expected on motorways) is absent in the spatial models. For road structure and classification, Quddes' concludes that curvature is not significant, while traffic volumes and length of main roads and residential streets are positively correlated with the number of casualties. The number of intersections and the number of bus stops did not appear to be significant.

## **5.2. Relating characteristics of network structure, degree of access, road classification and road design to *traffic volumes***

Quantitative relationships between various characteristics regarding network structure and traffic on the one hand and traffic volumes on the other hand are the subject of this section. Traffic volumes are regarded to be an important intermediate variable regarding road safety. The assumption is that lowering of traffic volumes will improve road safety and traffic nuisance.

The studies discussed below were conducted by using traffic modelling. *Section 5.3* is meant to check whether the results in this section are supported by empirical evidence.

Van Minnen (1999) studied the effects of the number of accesses to a residential area on the traffic volumes in the residential streets of that area. For this purpose, he used a simulation model. The inputs of the model were size of the areas, dwelling density and number of accesses; the output comprised the volumes in the streets accessing the area, and the length of the trips entering the area (including the part of the trip using the roads surrounding the area). In all cases, he used a grid network structure, in a square type of area. Van Minnen assumed five car trips a day to and from each dwelling unit. This value originated from Walraad & Poppe (1998). *Table 5.1* shows the simulation results. According to CROW (2004) the maximum acceptable volume in residential streets is 3,000 to 5,000 motor vehicles a day, depending on the spatial position of the area (highly urbanized or hardly urbanized). These values are only based on a few observations, and not based on systematic empirical research. In *Table 5.1*, these acceptable daily volumes (between 3,001 and 5,000 vehicles) have been highlighted (bold boxes).

The results are that the size of the area has no detrimental effects on the total number of motor vehicle kilometres (roads inside and outside the area) provided that (Van Minnen, 1999; p. 18):

- there are accesses to the area on all (four) sides,
- the number of accesses per unit length is sufficient (i.e. resulting in acceptable volumes of motor vehicles in residential streets).

A wider area will result in higher volumes on some streets in the area. Van Minnen concluded that a singular (public) access is only acceptable for areas smaller than 30 ha. The number of accesses increases substantially when the size is between a 100 and 200 ha. Van Minnen only used a model for an 'isolated area' with surrounding roads which are not connected to the rest of the network. The connections between the area and the surrounding roads may vary in number and position. Krabbenbos et al. (2002) focused on this topic, using a micro-simulation model (AIMSUN). They modelled a square area (640 x 640 m<sup>2</sup>). The surrounding roads are connected to the rest of the network either at the angular points or in the middle of each side of the square. The area has a grid network structure with three streets in each direction. The speed limit on the surrounding roads is 50 km/h, and on the residential streets 30 km/h. The connections to the rest of the network were



Area (ha)	Dwelling density number per ha	Number of dwellings × 1,000	Traffic volumes vehicles per day × 1,000	Maximum daily volume (× 1,000), given the number of accesses								
				1	2	4	6	8	10	12	16	20
10	30	0.30	1.50	1.50	0.90	0.45	0.30	0.23	0.18	0.15	0.11	0.09
10	45	0.45	2.25	2.25	1.35	0.68	0.45	0.34	0.27	0.23	0.17	0.14
10	60	0.60	3.00	3.00	1.80	0.90	0.60	0.45	0.36	0.30	0.23	0.18
20	30	0.60	3.00	3.00	1.80	0.90	0.60	0.45	0.36	0.30	0.23	0.18
20	45	0.90	4.50	4.50	2.70	1.35	0.90	0.68	0.54	0.45	0.34	0.27
30	30	0.90	4.50	4.50	2.70	1.35	0.90	0.68	0.54	0.45	0.34	0.27
20	60	1.20	6.00	6.00	3.60	1.80	1.20	0.90	0.72	0.60	0.45	0.36
40	30	1.20	6.00	6.00	3.60	1.80	1.20	0.90	0.72	0.60	0.45	0.36
30	45	1.35	6.75	6.75	4.05	2.03	1.35	1.01	0.81	0.68	0.51	0.41
30	60	1.80	9.00	9.00	5.40	2.70	1.80	1.35	1.08	0.90	0.68	0.54
40	45	1.80	9.00	9.00	5.40	2.70	1.80	1.35	1.08	0.90	0.68	0.54
60	30	1.80	9.00	9.00	5.40	2.70	1.80	1.35	1.08	0.90	0.68	0.54
40	60	2.40	12.00	12.00	7.20	3.60	2.40	1.80	1.44	1.20	0.90	0.72
80	30	2.40	12.00	12.00	7.20	3.60	2.40	1.80	1.44	1.20	0.90	0.72
60	45	2.70	13.50	13.50	8.10	4.05	2.70	2.03	1.62	1.35	1.02	0.81
100	30	3.00	15.00	15.00	9.00	4.50	3.00	2.25	1.80	1.50	1.13	0.90
60	60	3.60	18.00	18.00	10.80	5.40	3.60	2.70	2.16	1.80	1.36	1.08
80	45	3.60	18.00	18.00	10.80	5.40	3.60	2.70	2.16	1.80	1.36	1.08
120	30	3.60	18.00	18.00	10.80	5.40	3.60	2.70	2.16	1.80	1.36	1.08
100	45	4.50	22.50	22.50	13.50	6.75	4.50	3.38	2.70	2.25	1.70	1.35
150	30	4.50	22.50	22.50	13.50	6.75	4.50	3.38	2.70	2.25	1.70	1.35
80	60	4.80	24.00	24.00	14.40	7.20	4.80	3.60	2.88	2.40	1.81	1.44
120	45	5.40	27.00	27.00	16.20	8.10	5.40	4.05	3.24	2.70	2.03	1.62
100	60	6.00	30.00	30.00	18.00	9.00	6.00	4.50	3.60	3.00	2.26	1.80
200	30	6.00	30.00	30.00	18.00	9.00	6.00	4.50	3.60	3.00	2.26	1.80
150	45	6.75	33.75	33.75	20.25	10.13	6.75	5.06	4.05	3.38	2.54	2.03
120	60	7.20	36.00	36.00	21.60	10.80	7.20	5.40	4.32	3.60	2.71	2.16
150	60	9.00	45.00	45.00	27.00	13.50	9.00	6.75	5.40	4.50	3.39	2.70
200	45	9.00	45.00	45.00	27.00	13.50	9.00	6.75	5.40	4.50	3.39	2.70
200	60	12.00	60.00	60.00	36.00	18.00	12.00	9.00	7.20	6.00	4.52	3.60

**Table 5.1.** Maximum numbers of motor vehicles in streets connecting a residential area to the distributors, given the size of an area, the number of dwellings, and the number of accesses (Van Minnen, 1999; p. 46)

varied according to the number of sides having a connection and to the number of connections at each side, resulting in 16 variants. The dwelling density of the area amounts to 40 dwellings per ha. The assumption for the number of trips per dwelling unit during rush hour is 0.46 trips. This value looks quite different from that which Van Minnen used (five trips a day). However, Krabbenbos et al. take 10 percent of the daily trips as the rush hour volume. Ten percent out of five trips (= 0.5) is close to the value of 0.46. The next variable in Krabbenbos' study is the degree of through traffic (traffic not having an origin and destination within the area). The degree of this type of traffic was assumed to be either high or low. The amount of local traffic (with origin or destination within the area) amounted to 760 vehicles, the low through traffic value was 534 vehicles, and the high value was 3,740 vehicles. The simulations did not show a specific rule regarding neither the optimal number of connections nor the position of the connections. This appears to depend on the connection of the rest of the network to the area (at the angular points or in the middle of each side), and on the amount of through traffic. The access of the area to the surrounding roads will determine the amount of through traffic; the connections in the middle of each side offer the 'best' short cuts, because through traffic can pass the area without any detour (compared to the route surrounding the area). The connections at the angular points will offer a route which is just as long as the route following surrounding roads. The route surrounding the area will be more attractive because of the higher speed limits. Krabbenbos et al. (2002) gathered empirical data from four residential areas. These areas differed regarding the number of connections and the position of these connections. The degree of through traffic and the amount of local traffic was estimated. However, the number of observations was small and a reference (or control) area was lacking. That is why only a conclusion regarding the local traffic could be drawn. The more sides (of the square) are connected to the surrounding roads, the lower the number of vehicle kilometres of local traffic.

Gadd (1997) analyzed how goals regarding capacity, road safety and environment can be attained simultaneously. For his evaluation, Gadd built a simulation model of a simple (synthetic) network consisting of a main road surrounding a square area. Within the area, two distributors cross each other diagonally. The main road is connected to the rest of the network at the angular points. In a first simulation, all roads belong to the same class; the intersections are non-signalized. The simulation shows a great deal of traffic on the distributors (to a maximum of half the amount on the main road). The main road is upgraded in the next simulation; the intersections at the angular

points have signalization. The intersections within the area have regular priority rules. The results of simulating this new situation are: the volumes on the distributors are not more than a quarter of the volumes on the main road, and the number of motor vehicle kilometres (on both road types) increases by 3 percent. A third simulation keeps the classification as well as the signalization as they were (in the second simulation). However, the intersections within the areas are now stop sign controlled. Now the remaining volumes on the distributors are only 21 percent at the most related to the main road volumes; the motor vehicle kilometres did not change anymore. The final, fourth, simulation concerns a change of the intersections within the area; an additional delay was introduced. Now, the distributors carry only 9 percent of the amount of traffic on the main roads; again, the number of motor vehicle kilometres has not changed. Obviously, the resistance for through traffic was raised to such an extent that only a fraction was left. Road safety and the road environment within the area have improved by these measures. The volumes on the main road have increased by 20 percent. Specific measures are needed to balance the favourable effects within the area against the deteriorating effects (by the increasing number of motor vehicles) on the main road.

Skoupil et al. (1983) evaluated the effects of changing traffic circulation. The street network of five residential areas was modelled in order to find the effect of closing some streets for motorized traffic. The models were calibrated for the existing situation including through traffic. The street closures were only modelled; not applied in practice. The modelled street networks comprise distributor roads (within the residential areas), surrounding main roads, and some connecting external roads. These roads fall into a larger area containing almost all origins and destinations of trips to and from the (five) residential areas; this was found in a street survey. The changes in circulation of traffic were studied for each area. The number of motor vehicle kilometres was calculated for each street type. Traffic circulation changed largely because of the street closures. In four of the five areas, two systems of closures were applied:

- Vehicles could still pass through the entire area; some streets received a new design; on some intersections drivers were not allowed to turn into each direction; some streets changed into a cul-de-sac.
- The area was divided into zones; vehicles could only travel within a zone, and not pass through the entire area anymore.

Both systems reduce the amount of through traffic substantially. The second system (zones) shows the largest reduction in three out of four cases. The

fifth and final area was adapted by mainly using one-way streets, which also reduced through traffic successfully. Skoupil et al. (1983) specifically investigated the effects on local traffic (having origins or destinations within one of the areas). All circulation systems raise the number of motor vehicle kilometres for local traffic. The zone system shows the lowest number of vehicle kilometres on streets within the area compared to both the before situation and to the other closure system. However, the zone system resulted in more kilometres on the surrounding roads and on the other connecting roads than the other system did.

### **5.3. Relating characteristics of network structure, degree of access, road classification and road design to crash figures**

This section deals with the direct effects of network structure and road features on crash frequency or risk. Contrary to *Section 5.1*, differences between situations were studied; particularly comparing existing situations (comparative empirical studies), comparing several future situations (modelling studies), or comparing before and after situations (before-/after studies).

Marks (1957) reports on an accident study carried out in Los Angeles. Two traffic structures were examined: a grid system and a system with limited access. The grid system showed almost eight times as many accidents as the limited access system. At four-arm junctions, the number of accidents per year per junction was three times higher than in the limited access system. According to Marks (1957), a safe design is characterised by:

- a limited access system, preferably with access roads approximately 350 metres apart (a distance that was also mentioned by Le Corbusier in 1924)
- no streets linking two main roads
- (local) distributor roads to be included only if they do not cross through-streets and only when they join arterial roads on one side only
- junctions with four arms are to be avoided wherever possible in favour of simple T-junctions

These recommendations were rediscovered years later and formed part of the major Dutch 'Demonstratieproject herindelung en herinrichting van stedelijke gebieden' (Demonstration project in the reclassification and redesign of urban areas) (Janssen & Kraay, 1984). Two large residential areas

and the surrounding main roads (situated in the cities of Eindhoven and Rijswijk) were changed radically. The project aimed at reducing through traffic in residential areas, improving traffic flow on the main roads, and reducing driving speeds in residential streets. The measures taken appeared to be very effective; in particular because most of the through traffic disappeared. The measures taken can be divided into three types, called options:

1. Introducing mainly one-way traffic
2. Building speed-reducing provisions, partly combined with one-way traffic
3. Introducing the 'woonerf' (home zone) street design type

At the start of the project, the assumption was that these three options would have different effects. This appeared not to be true. Hardly any differences showed up. Differences between areas regarding reductions in through traffic could not be related to the options. Differences between areas concerning road design or traffic circulation could not explain the level of through traffic. In general, through traffic can be reduced by making an area physically unattractive for rat running, and by improving (traffic flow on) the surrounding roads.

Janssen (1991c) evaluated the effects of these three options on both the number of crashes and on crash risk. The crash evaluation is subjected to a before period from 1972 to 1977, and an after period from 1982 to 1986. The years in between are not used for the evaluation because at that time the redesigning was implemented. In the residential areas the number of injury crashes decreased by 80 percent; this decrease was adjusted for the general trend. The injury crash risk was reduced by 75 percent in the residential areas, and by 16 percent on the surrounding main roads. The number of motor vehicle kilometres dropped by 30% in the residential areas, and increased by a few percentages on the main roads. The measures appeared to be successful, not only for reducing through traffic, but also for improving road safety. The small differences between the options were considered an unexpected result. The provisions applied in the experimental residential areas fit into the design practices of the eighties applying all features of area-wide traffic calming schemes (VenW, 1984). In the late nineties, the Start-up Programme of Sustainable Safety (VNG, IPO, VenW & UvW, 1998) was the beginning of a trend towards a more low-cost design of residential areas. The effects of this trend tend to be less beneficial for road safety (Berends & Stipdonk, 2009).

Parallel to the demonstration project, some other European countries did similar large-scale projects and evaluations. In (West) Germany, Pfundt et al.

(1979) showed that in residential areas the number of injury crashes dropped by more than 40 percent. On the surrounding roads of these areas, the numbers of injury crashes decreased too, although to a lower extent. The effects found in the German projects are substantial, although smaller than in Eindhoven-Rijswijk.

Engel & Thomsen (1983) reported about the effects of reclassification and redesigning in the district Østerbro of Copenhagen, the Danish capital. In this district, the number of casualties dropped by 40 percent (adjusted for the general trend). This project shows large effects too.

Obviously, substantial effects can be attained if reclassification and redesigning are applied on a district level.

Dijkstra & Van de Pol (1991) estimated the effect on road safety of the new Amsterdam ring road (motorway A10) in 1989-1990. The authors used general safety indicators for estimating the expected changes. The approach in this type of study is to classify roads according to a system used by Janssen (1988) and Dijkstra (1990). The safety level of the existing situation is checked by retrieving the crash history (three years) of each road class. Subsequently the length and average daily traffic volume of each road class is used in order to find the number of motor vehicle kilometres. Combining these figures with the crash numbers will result in the crash risks for each road class. In these kinds of estimations the assumption usually is that the risk (per road class) will not change in the after period. Adding a new motorway was not the only change; some urban roads were reclassified, a few connections were added, and some roads were upgraded (mainly by adding lanes). The new network was modelled by means of a transport model. The results from the model show a changed traffic circulation, resulting in other volumes for nearly each road class. The figures for the motor vehicle kilometres had to be adapted accordingly to these new volumes. Finally, the numbers of crashes were estimated for each road class. The expected number of crashes would drop by 3.5 percent (minus 64 crashes on a total number of 1,762). The decrease on some urban main roads (-145) would partially be 'compensated' by an increase (+80) on the motorways and some rural main roads. The conclusion is that adding a new motorway does not 'automatically' benefit road safety enormously, since traffic circulation is thoroughly affected which may result in negative effects on some roads.

Poppe (1997) estimated the effects of applying the Sustainable Safety road classification to the road network in the central part of the Netherlands (province of Utrecht supplemented by a few relevant areas). The road

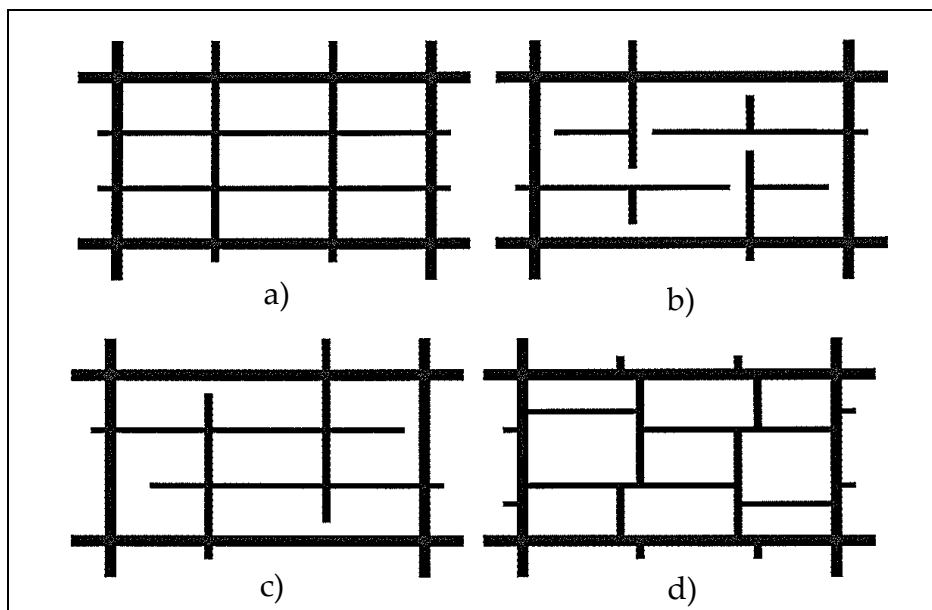
classification in the existing macro model had to be adapted according to the principles of Van Minnen & Slop (1994). One of these principles is the so-called 'trip duration criterion', meaning that that part of a trip which is travelled on access roads (speed limit of 30 km/h in urban areas and 60 km/h in rural areas) should not last longer than 3 minutes. The residential areas, rural and urban, should be kept free from through traffic. The roundabout, a new phenomenon on distributor roads, was applied to a large extent. The network structure did not change very much. The accessibility of residential areas was somewhat limited; hierarchical (tree) structures were avoided as much as possible to prevent detours. Poppe compared the effects of two network structures: the structure proposed by the regional authority for the year 2010 (the so-called MIT option), and the Sustainable Safety structure. The key safety indicators (risks per road class) were taken from SWOV (1997). The results show differences in traffic circulation because of the differences in road classification and speed limits. The number of casualties in the Sustainable Safety option is about 6 percent lower than in the MIT option. The number of motor vehicle kilometres in the Sustainable Safety option and the number of 'moving vehicle hours' (vehicles actually driving) nearly equals the MIT option. The number of lost hours (vehicles waiting at intersections) is considerably lower (15 percent) in the Sustainable Safety option than in the MIT option. This can be explained by the shorter waiting times at roundabouts compared to the waiting times at signalized intersections. The conclusion is that, despite of the lower speed limits, the Sustainable Safety network functions quite well.

Lovegrove & Sayed (2006, 2007) take the approach of Hedayeghi et al. (2003) and Ladrón de Guevara et al. (2004) as a starting point. They derived 47 crash prediction models (CPMs) from 22 variables. They put these models into 16 groups; see *Table 5.2*.

Some of the variables were quantified by way of a traffic model. Lovegrove & Sayed (2006) applied their prediction models to three districts having a specific network structure for traffic calming (reducing through traffic). The results of their models for the three districts together conform quite well to the observed crash reductions. The results for each of the districts separately show larger differences between modelled and observed crash reductions. The authors investigated network structures proposed by Dijkstra (1996). These network structures can also be found in the guidelines for Sustainably Safe urban roads (Infopunt DV, 2000). The network structures are limited access, grid and tree; see *Figure 5.1*, structures a, b and c. The authors added an additional structure containing three-way intersections only; this structure allows for through routes (see *Figure 5.1*, structure d).

Variables per group	Urban or rural	Modelled or observed	Model number
Exposure congestion level kilometres travelled total lane km neighbourhood area	urban	modelled	1
		observed	2
	rural	modelled	3
		observed	4
Sociodemographic population density number of jobs home density average family size unemployment	urban	modelled	5
		observed	6
	rural	modelled	7
		observed	8
Transportation demand neighbourhood core size total commuters short-cut capacity drive to work	urban	modelled	9
		observed	10
	rural	modelled	11
		observed	12
Network signal density intersection density three-way intersections local-arterial intersections	urban	modelled	13
		observed	14
	rural	modelled	15
		observed	16

**Table 5.2.** Grouping of the variables (Lovegrove & Sayed, 2007)



**Figure 5.1.** Four network structures for residential areas



The variables in the crash prediction model for this case were estimated by observations in areas resembling those with the structures shown in *Figure 5.1*. The crash density of structure type 'd' (*Figure 5.1*) appears to be the lowest, followed directly by limited access (structure type 'c'). The limited access structure was somewhat adapted by the authors using three-way intersections instead of four-way intersections. The differences between the calculated crash densities and the average densities of existing residential areas appear to be small. The highest crash densities are found for the grid structure, both higher compared to the calculated values for the other structures and to the empirical average value of all structures. Rifaat & Tay (2009) came to similar conclusions using data from residential areas in Calgary.

#### 5.4. Conclusions

Several statistical models were developed relating variables regarding socio-economical, demographic, traffic, and network structure factors on the one hand to numbers of crashes or casualties on the other hand. Variables showing a strong relationship with road safety are:

- Speed limit, volume to capacity ratio, number of households, intersection density, and road length (Hadayeghi et al., 2003)
- Number of kilometres travelled, road length, number of signalized intersections, size of commercial and industrial area, and number of inhabitants (Hadayeghi, 2007)
- Intersection density and road length per road class, population density, and number of employees (Ladrón de Guevara et al., 2004)
- Resident population older than 60, traffic volume, length of main roads and residential streets (Quddes, 2008); according to this author, the following variables on the level of city districts are *not* related to road safety: average driving speed, number of intersections and roundabouts, and number of bus stops

#### **Results for studies relating characteristics of network structure, degree of access, road classification and road design to traffic volumes or crash figures**

- The lowest crash density can be found in a network structure only having three-way intersections, although allowing for through routes. The limited access structure shows a somewhat higher crash density. The highest crash density belongs to the grid structure.

- The level of through traffic in a square sized residential area (grid network) is determined by the number and the position of the connections of the local network to the external network. Connections in the middle of the sides offer the fastest through routes (no detours). Connections at the angular points will result in through routes which are just as long as routes along the surrounding roads. The latter route will be more attractive because of the higher speed limits on these roads. The more sides of an area are connected, the shorter trip length for local traffic is (origin or destination within the area).
- Several traffic measures in a residential area (one-way traffic, street closures, barring some turning directions on intersections, internal zoning, and speed reducing provisions) will mostly diminish through traffic because of the higher resistance of the through routes. Both the local environment and road safety will benefit from these measures. Traffic volumes on the surrounding road will mostly increase. The worsening conditions on the surrounding mains roads should be outweighed by improvements in the areas.
- A regional network classified according to Sustainable Safety will most probably result in a lower number of casualties than a traditional network. The large numbers of roundabouts in the Sustainable Safety network will decrease the amount of vehicle hours spent on waiting at signals.

Before- and after- studies in several countries confirm the results (from modelling studies) mentioned in the previous four items. Crash or casualty reductions appeared to be ranging from 40 to 80 percent. In most cases, safety on the surrounding roads hardly worsened, because additional measures were taken.

## 6. Detecting the effects of changes in route choice on road safety

It is very difficult to obtain data about route choice, changes in route choice and the resulting changes in road safety. Direct observations, through questionnaires or registration plate surveys, are both time-consuming and labour-intensive. It is almost impossible to undertake such observations on the level of a whole region or even of a smaller area like a city. Moreover, observations only relate to the existing situation. For future situations, observation cannot be used as a method. More insight in this respect can be gained by using traffic and transport models. These models are only reliable, however, when sufficient observations are used for calibration.

Crashes do not happen in traffic models. They are excluded by the programmer. In what other way, then, would it be possible to get to know more about the safety aspects of route choice in models? Somehow an indication should be given of road safety aspects, such as the absolute or relative level and the changes in these levels. To be sure that the indicators really represent road safety they need to be related directly or indirectly to the traditional safety indicator: the number of road crashes or the crash risk.

In this chapter some methodological issues are treated and a number of methods will be described which are potentially useful for showing safety effects (*Section 6.1*). Given the conclusions from *Section 6.1*, the next sections elaborate a few promising methods. *Section 6.2* deals with a method which shows whether the characteristics of the chosen routes fit certain safety requirements. *Section 6.3* is dedicated to methods to be used in micro-simulation modelling.

### 6.1. Methodological issues

Road safety may be assessed in different ways. The most direct way is represented by crash statistics. It is possible to derive all kinds of risk figures from crash statistics by combining the number of crashes with road length or the amount of traffic on a road (type).

Crash statistics are only available for existing roads and existing situations. For new roads and for new types of countermeasures (e.g. Advanced Driver Assistance Systems) the safety level or the safety effects can not be assessed by crash figures. Other safety indicators are needed. One option is to use models which 'predict' the number of crashes given the characteristics of a

road (type) or the amount of traffic to be expected. Other safety indicators are based on more indirect measures such as the number of conflicts calculated by a microscopic simulation model. A third type of safety indicator is generated by expert knowledge, e.g. a road safety auditor who assesses the safety of a new design by using his experience.

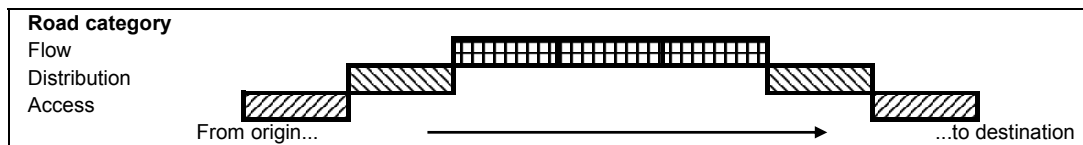
Modelling route choice will have to take the requirements of Sustainable Safety into account. However, the safety effect of these requirements is an issue that will have to be dealt with separately. For an evaluation of the differences regarding the safety level of each route, we need safety indicators. Apart from the traditional safety indicators, another indicator is introduced which expresses the characteristics of a route and the relationship of these characteristics with safety.

In a Sustainable Safety road network, the chosen road type is required to conform to the desired functional distribution of traffic over the road network. Sustainably-Safe also requires residential areas to be 'as large as possible'. This requirement affects the mesh of the distributor roads (Van Minnen, 1999; Krabbenbos et al. 2002).

Apart from the mesh, the natures of the intended connections between various sorts of residential areas, which will depend on the numbers of inhabitants or facilities, are normative for the composition of a Sustainable Safety road network (Dijkstra, 2003).

The consequence of requiring that the safest and quickest route should coincide is that cars would be led right through residential areas, since these areas comprise very safe streets. An additional requirement will prevent this, by stating that a route should only follow access roads at its beginning and end, and that the major part of the route, should be along through-roads. In order to achieve such a route choice, the journey time of a route going right through residential areas must be longer than that of a route which goes along through-roads. In addition, influencing route choice can be achieved by indications along the roadside or in-vehicle and possibly also by the layout of the road and its environment.

In the context of the Sustainable Safety vision, the exposure to safety risks is minimised if, for individual journeys, routes comply with the optimal sequence of road types, expressed in a route diagram (of so-called SuSa Steps), as depicted in *Figure 6.1*. A route starts at an Access Road, switches to a Distributor Road and continues on a Flow Road or Through Road. When approaching the end of the trip, this sequence is followed in reverse.



**Figure 6.1.** Route diagram or Su(stainable) Sa(fety) Steps

### 6.1.1. Crash data, key safety indicators, and crash prediction models

#### Crash data

Crash data are the most direct way of indicating both the nature of the safety problem and the level of safety. A great many tools have been developed for selecting, structuring, analyzing, and visualizing crash data. These tools are useful for existing situations and for existing roads. The nature of crash statistics is that they show the safety in the past. As soon as new roads, new types of technical equipment for vehicles, or new road facilities are being planned, these statistics are of no use anymore. Other indicators are needed for analysing future situations.

#### Key safety indicators

Key safety indicators quantify the safety of certain types of roads and junctions. A key safety indicator is determined by relating the absolute level of unsafety (e.g. the number of crashes) on a certain type of road or junction to the degree of exposure. Janssen (1988, 1991b) gives a general formula for calculating a key safety indicator:

$$\text{Key safety indicator} = \frac{\text{Safety level}}{\text{Degree of Exposure}}$$

The safety level is frequently quantified by using crash records. The number of vehicles or the number of vehicle kilometres is often used to calculate the degree of exposure.

An example of a key safety indicator is the number of accidents involving injury per million vehicle kilometres driven. This key safety indicator is also referred to as the risk of a road or junction type. The risk (indicator) based on vehicle kilometres does not only take the number of accidents into account, but also the road length and the number of motor vehicles that pass along it (Janssen, 2005).

By combining the length of the road section with the volumes, we can calculate the level of exposure, expressed in millions of vehicle kilometres driven in one year. The level of exposure is then calculated as follows:

$$VP_i = L_i * I_i * 3,65.10^{-4}$$

in which  $VP_i$  is the level of exposure of road section  $i$  in millions of vehicle kilometres driven in one year,  $L_i$  is the length of the road section  $i$  in km and  $I_i$  is the daily volume for road section  $i$ .

Then, by multiplying the level of exposure  $VP_i$  by the associated key indicator  $K_i$ , the expected number of injury crashes  $LO_i$  on road section  $i$  can be estimated.

$$LO_i = K_i * VP_i$$

The key indicator for road section  $i$  depends on the type of road. The typical key safety indicators for road classes are presented in *Section 3.1, Table 3.3* (Janssen, 1988 and 2005). These key safety indicators apply to crashes on both the road sections and the intersections belonging to the road class. In this way the intersections are appointed to the highest road class of two intersecting classes; see *Table 6.1*

Intersecting road classes	Higher class	Lower class
Higher class	to higher class	to higher class
Lower class	to higher class	to lower class

**Table 6.1.** Appointing crashes on intersections to one of the intersecting road classes

The sum total of expected injury crashes on a route is derived by totalling the expected injury crashes on the sections of the road classes that form part of the route.

### **Application of key safety indicators**

Traffic flow along the motorways in the Netherlands is gradually diminishing because of increasing use and an almost unchanging capacity. The accessibility of the economic centres is thus under heavy pressure. Immers et al. (2001) presented a solution that, in the meantime, has become known as "Bypasses for accessibility". The main feature of this concept is the introduction of an additional system of "underlying" main roads that can handle a large part of regional traffic thus relieving the existing motorway network. According to Immers et al. (2001), their application will result in a considerable improvement of traffic flow and will contribute to a reduction in the number of traffic casualties. However, Dijkstra & Hummel (2004) state that a 'bypasses network' should also meet the requirements of a Sustainably Safe Road Traffic.

Variant	Road Type Description	Fatalities (per billion motor vehicle kilometres)	In-patients (hospitalized) (per billion motor vehicle kilometres)
Existing Road Types			
MRN	Motorway	2.61	24.14
SRN 80	Limited access, 1 x 2, 80 km/hour, at-grade junctions	10.11	124.25
SRN 100	Trunk Road, 1 x 2, 100 km/hour, at-grade junctions and grade-separated junctions	8.76	81.39
Altered Road Types			
MRN+	Motorway, extra lane	2.74	25.34
SRN+ (Bypasses)	2 x 2, narrowed, 70 km/hour, at-grade junctions and grade-separated junctions	5.36	65.85
RTh (SustainablySafe)	Regional Through Road, 2 x 1, 100 km/hour, grade-separated junctions	4.76	44.20

**Table 6.2.** Crash rates for various types of existing and altered roads

In a first elaboration, Immers et al. (2001) distinguished two alternatives: 1) a motorway network with extra capacity through more lanes and 2) an underlying main road network with greater capacity through more lanes and sometimes split level intersections. Immers et al. used a mesoscopic simulation model to find out the effects on traffic flow.

Dijkstra & Hummel (2004) compared the two bypasses network alternatives with an option in which the underlying road network is designed as a sustainably safe network (*Table 6.2*). This comparison shows that safety is optimized in the sustainably safe option, but that it produces only a relatively slight improvement in accessibility (*Table 6.3*). Although the sustainably safe option has safe split-level intersections, it only has a limited capacity on road sections (one lane per direction). The opposite is true of the bypasses alternatives; they have a greater amount of accessibility but have a lower safety level. This is mainly because of the combination of larger capacity (two lanes per direction) and (less safe) intersections at grade.

In this application of key safety indicators, it becomes obvious that combining crashes on intersections and road sections in one indicator will restrict the insight in the effects of new road classes. If the influence of the intersection design is supposed to be large then the key safety indicator should consider this. A second disadvantage of this application refers to the type of simulation model used. The model only allows for considerations

concerning the capacity of the road sections. Again, the influence of the intersection design is neglected.

	Variant		
	MRN+	SRN+	Sustainably Safe
Vehicle minutes	-19	-20	-12
Vehicle kilometres	5	3	2
Journey speeds	29	29	16
Number of fatalities	5	-4	-10
Number of in-patients (hospitalized)	4	-2	-20
Energy use	5	1	1

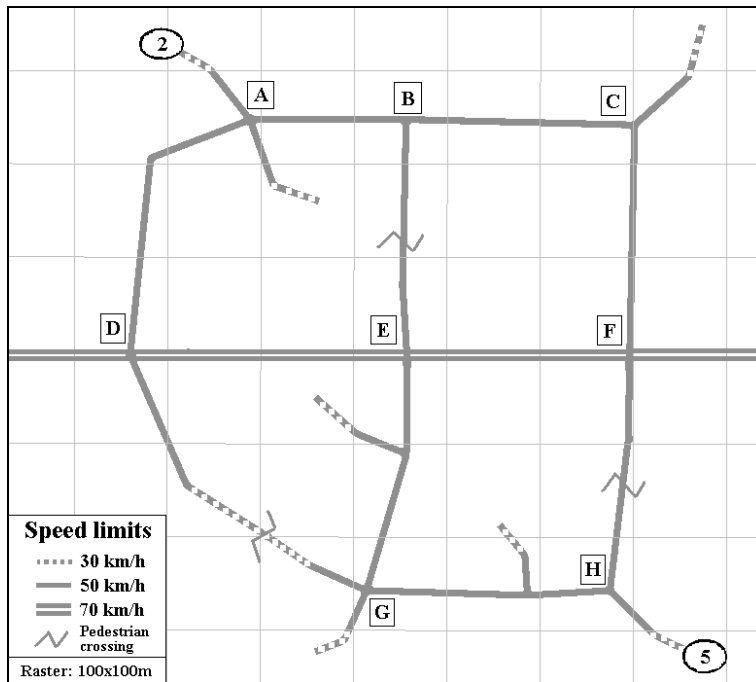
**Table 6.3.** Effects of the different variants in percentages, in comparison to the present situation (Source: Dijkstra & Hummel, 2004)

Measures aimed at influencing route choice should be evaluated by taking into account the effects of intersection design on road safety and on traffic flow.

Van der Sluis & Janssen (2000) evaluated three alternative networks for an existing through-road (a motorway) in the inner city of Maastricht (the Netherlands). These alternative networks aimed at diverting the through-traffic from the inner city to routes which did not interact with the traffic. Both the existing situation and the three alternative situations were modelled in a macro simulation model (TRIPS). The model calculates the traffic volumes for each road section. This output is used for the safety calculations. The key safety indicators method is used for estimating the total number of crashes in each alternative network. The differences between the alternative networks, regarding the number of crashes, are very small. One of the reasons for this result could be that the differences between the three networks are also very small as far as road length and the actually adapted road types are concerned. This type of evaluation needs differences between alternatives large enough to result in relevant output. Differences between crash figures will only be relevant and statistically significant for relatively long stretches of road (a few kilometres).

Different route choices in various networks may be studied in various ways. Simulation models are widely accepted as an evaluation instrument. Wismans (2003) compared a great many existing models, gave criteria for choosing models for evaluating route choice, and concluded that S-Paramics is a good tool for the purpose of route choice evaluation.





**Figure 6.2.** Test network in the micro-simulation model S-Paramics

In S-Paramics an urban test network was set up (*Figure 6.2*), consisting of nodes, links, and zones. Vehicles travel between zones. The test network comprises three road types, Access, Distributor, and Through Roads, which (in this test) only differ in speed limit: 30, 50, or 70 km/h respectively. The Through Road, with an external zone on both sides, runs right through the network. All traffic approaching this Through Road should give priority to traffic on this through road. Vehicles that do not enter or leave the network via these external zones always use the 30 km/h areas: these vehicles always begin or end a route through the network on a 30 km/h road. Both the 4-arm intersections D, E, and F, and the 3-arm intersections B, C, and H are priority intersections.

The safety assessment, using route diagrams and simulated conflicts, can be applied to every Origin-Destination pair in the network. To illustrate this, only the OD-pair 2-5 is considered (*Figure 6.2*). In this OD-pair six possible routes can be chosen:

1. Node A – B – C – F – H;
2. Node A – B – E – F – H;
3. Node A – B – E – G – H;
4. Node A – D – E – F – H;
5. Node A – D – E – G – H;
6. Node A – D – G – H.

In simulation I, the stochastic all-or-nothing assignment with a 'perturbation' factor 15 (percentage of link cost) is applied. In simulation II, the vehicles are equipped with a route information system that advises on the up-to-date situation on the network every minute. On the basis of this up-to-date information, the model estimates the journey time for each vehicle and, at the same time, determines the choice for a particular route. Simulation III focused on the effects of a growing amount of external traffic on the route choice of the internal traffic. For this reason the volume on the Through Road was doubled. None of the roads in either of the three simulations reached full capacity.

In the first simulation all vehicles chose route 2. In the second and third simulations the vehicles are distributed along more routes. In simulation II, 39% chose route 2, 36% route 1, and 25% route 4. In simulation III, four routes were followed: 60% chose route 2, 20% route 1, 13% route 6, and 7% route 4.

The total number of crashes (during one hour) was calculated for each route, using the key safety indicator method. When converting these hourly numbers to the number of accidents per year, we find a crash level varying between 0.2 to 0.6 crashes. The crash level of route 3 is highest in every simulation. Given the key safety indicator method, higher volumes on a route (in this case route 3) will result into more crashes. The key safety indicator approach functioned quite well in this application because the intersections did not change but only the volumes did.

### Crash Prediction Models

Crash Prediction Models are another way of indicating road safety. Using Average Annual Daily Traffic and road characteristics as an input, the number of crashes or casualties can be calculated (FHWA, 2000, 2005; Reurings et al., 2006).

The general formula for a crash prediction model is:

$$\mu_i = \alpha \cdot AADT_i^\beta \cdot e^{\gamma_j x_{ij}},$$

where  $\mu$  is the expected number of crashes in a certain period,  $AADT$  is the Annual Average Daily Traffic in the same period,  $x_j$  are other explanatory variables,  $\alpha$ ,  $\beta$ ,  $\gamma_j$  are the parameters to be estimated and the subscript  $i$  denotes the value of a variable for the  $i$ -th road section.

Reurings et al. (2006) conclude that for main rural roads the other explanatory variables should at least include section length, number of exits, carriageway width, and shoulder width. This type of model can be used for

either intersections or road sections; a combined model for the route level has not been developed yet.

### **6.1.2. Traffic conflicts and surrogate safety measures**

Road safety on the level of road sections and junctions is mostly expressed as the number of crashes or casualties. However, these numbers are usually too small to allow for an in-depth analysis of separate road sections or junctions. Therefore, safety indicators have been developed that have a direct or indirect relationship with crashes. This section will describe the most important safety indicators.

#### **Traffic conflicts**

The number of traffic conflicts and near-crashes is much higher than the number of crashes or casualties. They are, therefore, more suitable for analysis. Studying conflicts and near-crashes presumes a relationship between a conflict and a 'real' crash. This relationship was studied extensively by Hydén (1987) and Svensson (1998). In Germany, Erke et al. (1978) and Zimolong (1982) gave a first overview. Subsequently, Perkins & Harris (1968) started using conflict analysing techniques. Erke et al. (1985) compiled a handbook.

The assumption underlying this method is that situations with a large number of conflicts have a higher probability for accidents. Trained observers interpret traffic situations, count the number of (serious) conflicts, and analyse these conflicts. Conflicts are actions by road users, which may lead to problems (e.g. late braking, cutting of bends) and which have a high frequency. Several measurements have been proposed to characterize traffic conflicts in detail. For example time to collision (TTC), deceleration rate (DR), encroachment time (ET), post encroachment time (PET), etc. are used to determine the severity of a traffic conflict objectively. (PIARC, 2004). This technique enlarges the amount of data but the used parameters resulting from the manoeuvres are not necessarily direct indicators of accident risk and accident severity.

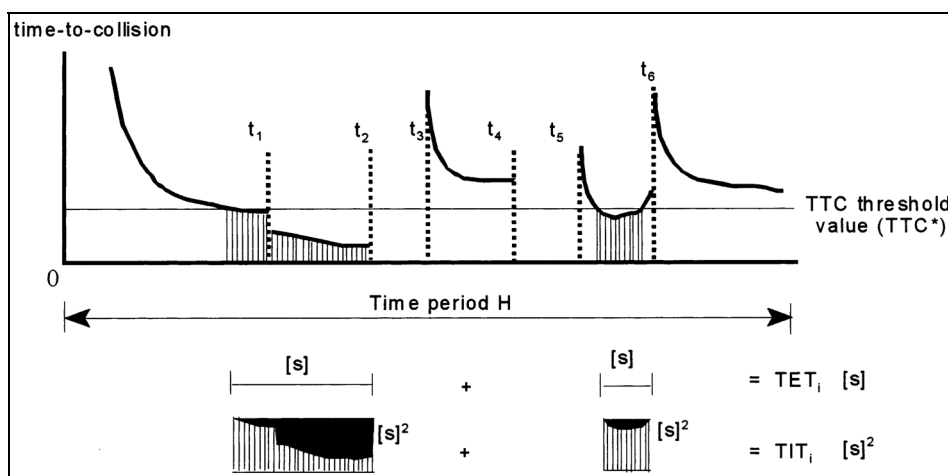
#### **Surrogate safety measures**

Surrogate safety measures in general are measures indicating aspects of road user behaviour that are related to road safety. Well-known examples of these measures are driving speed, red-light running, headway, overtaking, and giving right of way. In addition to these real-life indicators, safety measures have been developed for microscopic simulation models. When using a microscopic model conflicts between vehicles will be an integral part of the

simulation. A microscopic model uses a set of internal models for simulating driver behaviour. These behavioural models are usually calibrated by using observations of car drivers in several conditions. This thesis will not go into these internal models, and will treat these as black boxes.

The Time To Collision (TTC) is an indicator for the seriousness of a traffic conflict. A traffic conflict is defined by FHWA (2003) as "an observable situation in which two or more road users approach each other in time and space to such an extent that there is a risk of collision if their movements remain unchanged." The TTC value differs for junctions and road sections. A TTC on road sections will only be relevant when one vehicle is following another one. A vehicle on a road section can only have one TTC value. A TTC value on junctions relates to vehicles approaching each other on two different links. A vehicle approaching a junction can have more than one TTC value, depending on the number of vehicles on the other links.

Minderhoud and Bovy (2001) have developed two indicators that can be applied in micro-simulation models and are based on the TTC: the Time Exposed TTC (TExT) and the Time Integrated TTC (TInT). The TExT expresses the duration that the TTC of a vehicle has been below a critical value -  $TTC^*$  - during a particular period of time. The TExT is thus the sum of the moments that a vehicle has a TTC below the  $TTC^*$  (Figure 6.3). That means that the smaller the TExT, the shorter time a vehicle is involved in a conflict situation, and therefore, the safer the traffic situation is. The TExT indicator does not express the extent to which TTC values occur that are lower than the critical value. In order to include the impact of the TTC value, the TInT indicator has been developed. This is the area between  $TTC^*$  and the TTC that occurs (Figure 6.3).



**Figure 6.3.** Safety indicators in a micro-simulation model according to Minderhoud & Bovy (2001)

The impact of a conflict may also be expressed by calculating the potential collision energy (PCE) that is released when the vehicles are in conflict and collide with each other. Masses and speeds of the vehicles, as well as the way in which the vehicles collide with each other, i.e. the conflict type, influence the potential collision energy.

The outcome of these conflict analyses will be used to compare the types of conflicts in a given simulation with the types of conflicts being 'acceptable' in a Sustainably Safe road environment, (e.g. conflicts with opposing vehicles should be minimised at high speed differentials).

Dijkstra et al. (2007) have applied these types of indicators in a test network (*Figure 6.2*). Three simulations (I, II, and III in *Section 6.1.1*) were used to compare the outcome for the indicators. They divided the value of each indicator by the number of vehicles on a route, in order to get indicator ratios. The four ratios (for the number of conflicts, TExT, TInT and PCE) do appear to differ from each other. The ratio for the number of conflicts depends on the amount of traffic in the network: the more traffic, the more conflicts. The TExT ratio values are also subject to the volumes in the network: the more traffic, the more exposure to conflicts. The changes in the three consecutive simulations apparently do not influence the scores of TExT ratio very much. This is not true for the TInT ratio values, which show many changes between the simulations. Furthermore, the levels of the TInT ratio values do not change when the volumes go up. The TInT ratio is very much influenced by the nature (seriousness) of the interactions between vehicles, not by the amount. The differences between the simulations are not specifically focused on changing this nature.

Finally, the PCE ratio values are much higher in the third simulation (with more traffic on the central main road) than in the other two simulations. That is because of both more traffic on this road and higher driving speeds, resulting in potentially more collision energy in each conflict.

Each of the conflict indicators appears to have its own surplus value for assessing the safety of routes in a network. More research is needed to find out the pros and cons of using these kinds of indicators in networks that are more complex.

### **6.1.3. Qualitative safety assessment**

In a qualitative safety assessment, existing or planned road infrastructure is examined to find out the safety conditions. This can be done either by comparing the infrastructure to a sort of ideal situation or by giving an expert opinion.

## **Comparing design features to design requirements: road sections and intersections**

In the Netherlands, the concept 'Sustainably-Safe traffic' (Koornstra et al., 1992; Wegman & Aarts, 2006) is the leading concept for road safety policy and research. The main goal of a Sustainably-Safe road transport system is that, in thirty years time, only a fraction of the annual number of road accident casualties would remain.

It is of great importance for a Sustainably-Safe traffic system that, for each of the different road categories, road users know what behaviour is required of them and what behaviour they may expect from other road users. Their expectations should be supported by optimising the recognition of the road categories.

The three main principles in a Sustainably-Safe traffic system are:

- functionality,
- homogeneity,
- recognition/predictability.

The functionality of the traffic system is important to ensure that the actual use of the roads is in accordance with the intended use. This principle led to a road network with only three categories: through roads, distributor roads, and access roads. Each road or street may only have one function; for example, a distributor road cannot have any direct dwelling access. The speed limit is an important characteristic of each road category: access roads have low speed limits (30 km/h in urban areas and 60 km/h in rural areas) while through roads have speed limits of 100 or 120 km/h.

The homogeneity is intended to avoid large speed, direction, and mass differences by separating traffic types and, if that is not possible or desirable, by making motorised traffic drive slowly.

The third principle is that of the predictability of traffic situations. The design of the road and its environment should promote recognition, and therefore the predictability, of any possible occurring traffic situation.

The three principles have been translated into safety design requirements, for instance:

*For road sections*

- Avoiding conflicts with oncoming traffic
- Avoiding conflicts with crossing traffic
- Separating different vehicle types
- Avoiding obstacles along the carriageway

*For junctions*

- Avoiding conflicts with crossing traffic
- Reducing speed
- Limiting the number of different traffic facilities

Design requirements in general, which are part of design manuals, are not only based on safety arguments but also on other arguments, like capacity and liveability. In addition a designer will apply the requirements given the constraints in a real-life situation. Therefore, Van der Kooi & Dijkstra (2000) suggested a test to find out the differences between the original safety requirements and the characteristics of the actual design features. This Sustainable Safety Test systematically compares each design element or feature with the relevant safety requirements. The correspondence of a design element to a requirement is expressed by a percentage (of the road length). The total score of a design on Sustainable Safety is the average of these percentages.

### **Comparing design features to design requirements: routes**

Very little attention has been paid to the consequences of the functional requirements, i.e. the route choice issues (Hummel, 2001). The present study is directed towards the analysis of the mechanisms behind route choice and route management measures, such as route information systems (roadside and in-vehicle) and speed limits of different road categories.

Sustainably-Safe aims to incorporate road safety in transportation planning. In the planning phase one needs to determine whether the network will function according to the preceding network requirements, especially regarding safety. It is difficult to review the consequences of a traffic plan because of the large amount of data that plays a role in such plans. That is why planners often use traffic models and simulation models. The classic traffic models assign the total traffic volume to the road sections of the different networks. An example of the application of such a model to the mesh of the main road network is given in Immers et al. (2001). In micro-simulation models, however, it is possible to allow separate vehicles to follow a route through a network. The route choice of every simulated vehicle depends on a number of previously established conditions and on several variables that are functions of: in-vehicle equipment, facilities along the road, the driver's motive, time of day, and interaction with the rest of the traffic. In this way, it is possible to determine in advance how route choice changes if facilities are planned along the road, or in-vehicle. AVV (2002) and Wismans (2003) give a general overview of the features and use of simulation

models. Hidas (2005) compares three frequently used models: AIMSUN, VISSIM and Paramics.

Morsink et al. (2004) used a micro-simulation model for an urban network to study which consequences occur by adapting the current speed limits per road type. The main ingredients for the analysis of route choice by dynamic microscopic modelling are: an efficient model of a representative road network, features for modelling route choice behaviour, and indicators for traffic safety and network performance.

The route choice analysis reference case is the 1997 Utrecht traffic situation focusing on the morning rush-hour between 07.00h and 10.00h. In this period, 230,000 vehicles were involved, with the 7.45h to 8.45h time interval as the busiest hour.

For modification of the reference case, measures were applied at road network level to increase route resistance defined by travel time. For this purpose, the maximum speed on distributor and access roads was lowered in three cases according to *Table 6.4*. No other modifications were made to the model or simulation procedure for these cases. This means that the dynamic OD-matrices were unaltered and the effects of the modification of maximum speeds concerning modal split and departure time were not taken into account.

Cases	Access roads		Distributors	
	Urban	Rural	Urban	Rural
Reference case	50	50	50	80
Case 1	30	50	50	80
Case 2	30	30	30	80
Case 3	20	50	40	80

**Table 6.4.** Modification of speed limits (km/h) on access roads and distributors for three cases; speed limits on through roads (100 or 120 km/h) remained unchanged

These cases were selected on the basis of the following hypothesis per case:

Case 1: driving on urban access roads will be minimized and driving on distributors and flow roads will be stimulated.

Case 2: driving on through (flow) roads will be stimulated, without making a distinction between access and (urban) distributors.

Case 3: driving on through roads will be stimulated and driving on distributors will be stimulated in favour of access roads.



The total number of vehicle kilometres did not show significant changes for the modified cases (*Table 6.5*). The urban access roads show fewer vehicle kilometres in all cases because of their lower attractiveness (higher resistance). The urban distributors in case 2 have fewer vehicle kilometres because these roads were as attractive (or unattractive) as access roads.

	Absolute values	Reference	Case 1	Case 2	Case 3
Vehicle hours	52,540	100	106	131	122
Vehicle kilometres	1,761,938	100	100	101	101
<i>Vehicle kilometres per road category</i>					
	Absolute values	Reference	Case 1	Case 2	Case 3
Through (flow) road	990,869	100	100	103	102
Distributors, rural	324,234	100	101	105	104
Distributors, urban	314,102	100	107	92	105
Access road, rural	950	100	100	100	100
Access road, urban	131,782	100	80	98	75
Total	1,761,938	100	100	101	101

**Table 6.5.** Quantitative overview of network performance of the modified cases with respect to the reference case

This study by Morsink et al. shows that comparing an existing situation to an ideal situation can be done on a network level by using a simulation model. In doing so, the comparison even gains a quantitative nature, given the assumption that the ideal situation (the system of speed limits) is the safest situation.

### **Expert judgement**

The main objective of safety audits is to ensure that highway schemes operate as safely as possible, i.e. to minimise the number and severity of occurring accidents. This can be achieved by avoiding accident prone elements and by providing suitable accident reducing elements. The purpose of safety audits is to ensure that ‘mistakes’ are not built into new schemes.

The UK definition is as follows: A formal procedure for assessing accident potential and safety performance in the provision of new road schemes, and schemes for the improvement and maintenance of existing roads (IHT, 1996). Safety audits can be applied in schemes of various types. Such schemes generally fall into the following categories:

- major highway schemes;
- minor improvements;
- traffic management schemes;
- development schemes;
- maintenance works.

The auditor should be a road safety expert, preferably working as part of an audit team. During an audit, checklists can be used. A set of checklists is usually available, consisting of specific checklists for each road type.

Whether this type of expert judgement will have an impact on the reduction of the number of crashes is still subject to research. Estimations of the effect of a safety audit are in the order of a few percent points (SWOV, 2009b).

#### **6.1.4. Selection of methodologies with respect to the route level**

*Crash data* can be used for existing roads and streets, given the past history of road users and vehicles. Planned or newly built road sections have no accident history, and neither do traffic situations with vehicles equipped with experimental ADAS systems. Therefore, accident data will be used only as a reference for the safety level of existing situations.

*Key safety indicators* can be used for evaluating new roads and streets. This method shows the total number of crashes on a road type, or on a road section. It does not show the number of crashes for a specific route choice. This type of indicator only takes into account one kind of change caused by ADAS: the sum of route choice behaviour for all users (resulting from changes in traffic flows, which are input for the indicator).

*Crash prediction models* are of the same nature as key safety indicators. The additional value of crash prediction models is that these can be more detailed regarding road and traffic characteristics than crash safety indicators. Nevertheless, crash prediction models do not incorporate characteristics about vehicles with and without ADAS.

*Comparing design features to design requirements* is above all useful for designers to check their designs in a preliminary stage. This method may also be used when modelling road networks. Both features and requirements may be varied. The method may be applied to road sections and intersections separately and to strings of road sections like routes.

*Traffic conflicts* may be used in a method for studying specific safety problems at a few locations, mostly intersections. The method requires a high

level of expertise for the observers, and takes quite a lot of time (a few days) for each location. The method is particularly useful for individual locations.

*Surrogate (safety) measures* have been developed to be used in micro-simulation models. These measures are calculated for each vehicle separately. In this way the safety of each vehicle route can be computed.

*Expert judgement* is mostly used for safety assessment of either new road schemes or new ADAS. Applying this method to routes would be a new way of safety auditing.

## **Conclusions**

From the list of methods, it can be concluded that a few methods are suited for studying road safety effects of changes in the use of the road network, caused by adaptations of the network structure and/or road classification. The effects of these changes on route choice, in particular, determine the choice of method. The methods are key safety indicators, crash prediction models, comparing features to requirements, and surrogate safety measures. Only surrogate safety measures will show output for the safety of individual routes.

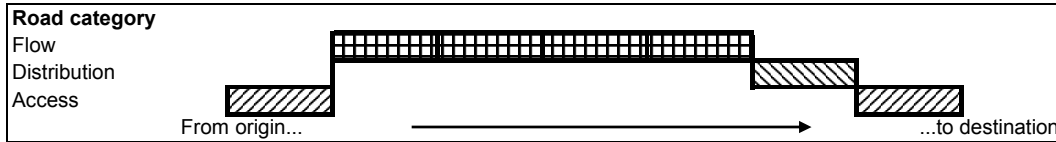
## **6.2. Route criteria, route scores and route stars**

On the route level one can compare design features to design requirements according to the concept of the Sustainable Safety concept. This concept comprises functional requirements which can be focused on the route level. The most important requirement for trips is: the shortest and safest route should coincide. In order to test this requirement more detailed safety criteria were developed. These criteria are determined for all routes belonging to one OD-pair. Next a safety score for each route and for each OD-pair will be introduced. Finally, the safety score for a set of OD-pairs is formulated.

Route criteria, route diagrams and route stars are indicators of the safety of routes in a road network. They can be applied when assessing effects of changes in a road network, e.g. when adding new trip generating areas to an existing urban area or when inserting a new road section to the network. These major changes to a network will in their turn change a great many routes, and will therefore also affect road safety. The methods described show, which routes will be safest, and which of these routes will attract most of the traffic.



A category transition fulfils the second requirement if  $AO = 1$ . The category transition does not meet the requirement if  $AO > 1$ . The number of faulty category transitions in a route is calculated in this way.



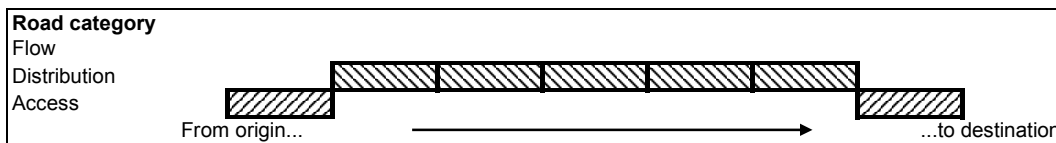
**Figure 6.4b.** Route diagram showing two steps at the same location

3. *As few missing road categories as possible (Figure 6.4c)*

The number of road categories encountered in a route, in relationship to the number of road categories present in the network, forms the third requirement. This may be expressed in the formula:

$$OWC = WCN - WCR$$

in which  $OWC$  is the number of missing road categories,  $WCN$  is the number of road categories present in the network and  $WCR$  is the number of road categories encountered in the route under consideration.

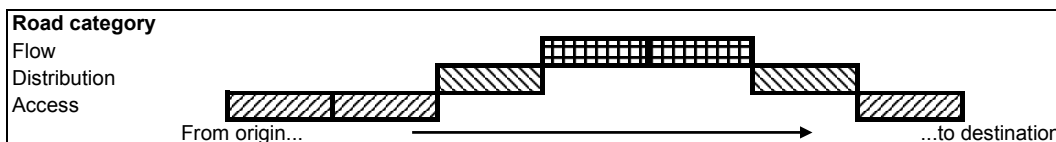


**Figure 6.4c.** Route diagram showing a missing road category

4. *Proportion (in length) of access roads as low as possible (Figure 6.4d)*

From a road safety viewpoint, through traffic in 30 kph (20 mph) zones should be avoided. The proportion, in length, of access roads  $AL_{ETW}$  in relation to the total length  $L_{TOT}$  is calculated as follows:

$$AL_{ETW} = \frac{L_{ETW}}{L_{TOT}} \times 100\%$$



**Figure 6.4d.** Route diagram showing a relatively long access road

5. Proportion (in length) of distributor roads as low as possible (Figure 6.4e)

Distributor roads are the least safe when it comes to the accident risk. For that reason, the ratio in length of these roads should be kept as low as possible. The proportion, in length, of distributor roads  $AL_{GOW}$  in relation to the total length  $L_{TOT}$  is calculated as follows:

$$AL_{GOW} = \frac{L_{GOW}}{L_{TOT}} \times 100\%$$

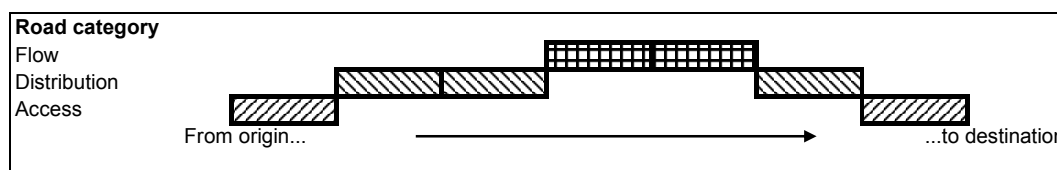


Figure 6.4e. Route diagram showing a relatively long distributor road

6. Travel distance

The smaller the total distance  $L_{TOT}$  travelled on a route, the less risk to which a vehicle is exposed. The total distance  $L_{TOT}$  is equal to the sum of the distance over access roads  $L_{ETW}$ , the distance over distributor roads  $L_{GOW}$  and the distance over through roads  $L_{SW}$ . This is expressed as the formula:

$$L_{TOT} = L_{ETW} + L_{GOW} + L_{SW}$$

7. Travel time

The total travel time  $R$  is calculated for each route on the basis of an empty network. This is done by totalling the length of the categories divided by their respective speed limits, expressed by the formula:

$$R = \frac{L_{ETW}}{V_{ETW}} + \frac{L_{GOW}}{V_{GOW}} + \frac{L_{SW}}{V_{SW}}$$

Travel time can also be derived from a simulation model. However, this will make this criterion very dynamic, and hard to interpret. This argument also holds for a criterion called 'loss time', based on subtracting the minimal travel time (empty network) from the real travel time (from the model).

8. As few turnings as possible across oncoming traffic

The number of left turns ( $LAB$ ) at junctions can be recorded for each route. Because turning left is seen as the most dangerous manoeuvre (Drolenga, 2005), the score declines as the number of these movements increases.

### 9. Low junction density on distributor road

The purpose of this requirement is to assess the route's potential for disruption on the distributor roads within it. The junction density *KPD* is defined as the number of junctions on distributor roads *K* per km of distributor road. This is expressed as the formula:

$$KPD = \frac{K}{L_{GOW}}$$

### Nine criteria summarised

The nine criteria including their dimensions are shown in *Table 6.6*.

Most of these criteria are related to each other. Criteria 1 to 5 are closely related to each other because they are the quantitative description of the route diagram. These five criteria should preferably be applied together, in order to be sure that the route fulfils the aims of Sustainable Safety. Travel distance is related to travel time in an 'empty' network. As soon as the network is saturated, this relationship will disappear. The proportion of a certain road category and travel distance seem to be mutually dependent, however, two routes having the same length of access roads will have different proportions of access roads when the total travel distances of both routes differ.

Criterion	Description	Unit
1	Number of transitions	Number of additional transitions
2	Nature of transitions	Number of wrong transitions
3	Missing road categories	Number of missing categories
4	Proportion of access roads	Percentage of total distance
5	Proportion of distributors	Percentage of total distance
6	Travel distance	Meters
7	Travel time	Seconds
8	Left turns	Number of left turns
9	Junction density	Number of junctions per kilometre

**Table 6.6.** Nine criteria for route diagrams

## 6.2.2. Route scores and stars

### Sustainable Safety Score

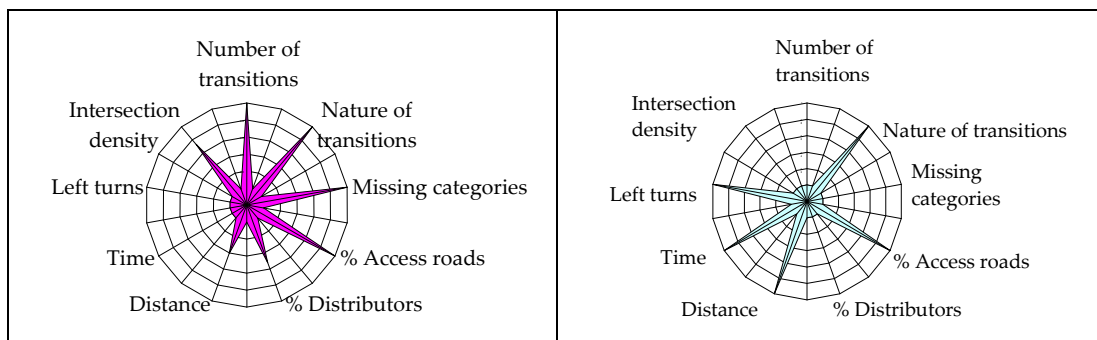
For each route we calculate the scores for the nine aforementioned criteria by collecting the data and applying the formulae. Using a multi-criteria analysis, we then try to arrange alternative routes in order of preference. Standardisation of the criterion scores is necessary if the different scores of the various routes are to be compared. The scores are standardised on the basis of interval standardisation. This means that the best alternative is awarded a score of 0, the worst a score of 1, and the other options are scaled between 0 and 1. This is done by reducing the score by the lowest score for the criterion in question and dividing this difference by the difference between the maximum score and the minimum score for the criterion in question. This is expressed as the formula:

$$G_{ji} = \frac{C_{ji} - \min_j\{C_{ji}\}}{\max_j\{C_{ji}\} - \min_j\{C_{ji}\}}$$

in which  $G_{ji}$  is the standardised score of alternative  $i$  for criterion  $j$  and  $C_{ji}$  is the criterion score of alternative  $i$  for criterion  $j$ .

In determining the minimum and maximum scores for a criterion, not only the routes that are actually followed should be taken into account, but also the routes that are not followed but are nevertheless available in the infrastructure.

Routes can easily be compared by using stars to visually represent the standardised scores for the nine criteria. The nine points of the star represent the nine criteria. Each point shows '1 -  $G_{ji}$ ': the longer a point, the better the score for this route is in relationship to alternative routes. This means that the more complete the star is, the more sustainably safe the route is. The scores for the nine criteria on two routes are shown as an example in *Figure 6.5*.



**Figure 6.5.** Examples of route stars for two routes



If a star is nearly complete for criteria 1 to 5 (starting at the '12 o'clock' arrow), this implicates that the route diagram will also be according to the Sustainable Safety criteria.

The left-hand route (purple star) has the worst score for the first requirement (the number of additional transitions) because no point, or only part of a point, is visible. By contrast, the right-hand route (green star) has the best score for this requirement because the entire point is visible. Because the green star is more complete than the purple star, it may be concluded that the right-hand route fulfils the requirements of the Sustainable Safety policy more than the left-hand route.

### Criteria weights

After the scores have been standardised, the weighting of the criteria can be determined. If each criterion is determined to be of equal importance, then each of them has the same weight. If one or more criteria are considered more important, these may be allocated a greater weight than less important criteria. The sum of the weights of the criteria must always come to 1, so if all nine criteria are considered of equal importance, each criterion is given a weight of 1/9.

### Total score for a route

To arrive at a total score for each route, the standardised score is multiplied by the weight and added up over the nine criteria to give total scores (*weighted totalling method*). The outcome of this total score indicates the degree of unsafety. To arrive at a safety score, the unsafety score is deducted from 1 and multiplied by 100% so that the safety score will fall between 0 and 100%. This is expressed as the formula:

$$VV_r = 100 - 100 \times \sum_{c=1}^C ss_c \times g_c \quad (6.1)$$

in which  $VV_r$  is the safety score of route  $r$ ,  $C$  is the number of criteria,  $ss_c$  is the standardised score for criterion  $c$  and  $g_c$  is the weight of criterion  $c$ .

### Sustainable Safety Level OD-relationship

Using the calculated safety scores of the various routes that are associated with an OD relationship and distribution of the vehicles over these routes, we calculate the safety level of a OD relationship. In doing so, it is important to also include the safety level of routes that are not selected (in this simulation). After all, traffic may well follow these routes in a subsequent simulation.

### **Distribution of vehicles over routes**

The distribution of vehicles over the routes per OD relationship is indicated by calculating the percentage of the total number of vehicles per OD relationship that travel via route  $r$ . This is expressed by the formula:

$$V_{OD,r} = \frac{I_r}{I_{OD}} \times 100\% \quad (6.2)$$

in which  $V_{OD,r}$  is the percentage of vehicles that travel via route  $r$  from origin  $H$  to destination  $B$ ,  $I_r$  is the absolute number of vehicles that travel via route  $r$  and  $I_{OD}$  is the total number of vehicles that travel from origin  $H$  to destination  $B$ .

### **Safety level OD**

The unsafety score for each route is multiplied by the percentage distribution of the vehicles following this route, and then added up over the various routes to give a total score for an OD relationship. The outcome of this total score indicates the degree of unsafety of the OD relationship. To arrive at a safety score, the unsafety score is deducted from 1 and multiplied by 100%, so that the safety score will fall between 0 and 100%. This is expressed by the formula:

$$VV_{OD} = 100 - \sum_{r=1}^R \frac{(100 - VV_r) \times V_{OD,r}}{100}$$

or, in a more simple formula:

$$VV_{OD} = \sum_{r=1}^R \frac{VV_r \times V_{OD,r}}{100} \quad (6.3)$$

in which  $VV_{OD}$  is the safety score of OD relationship  $OD$ ,  $R$  is the number of routes associated with OD relationship  $OD$ ,  $VV_r$  is the safety score of route  $r$ , calculated using formula Y.2.10, and  $V_{OD,r}$  is the percentage of vehicles that travel via route  $r$  from origin  $H$  to destination  $B$ , (Formula 6.2).

### **Sustainable Safety Level of OD-relationship given the infrastructure**

In the Sustainable Safety Level of an OD relationship, discussed above, both route choice and infrastructural characteristics of the routes are given factors. Improvements in the infrastructural characteristics may increase the Sustainable Safety level, as may another choice of route. In order to separate these two effects, which are probably interdependent, we introduce the Sustainable Safety Level of an OD relationship *given the (existing) infrastructure*. In doing so, we ignore the infrastructural inadequacies of the

routes. This gives us more insight into the safety benefits that may be achieved by influencing the route choice of vehicles.

The safest route in an OD relationship, which does not have to have a safety level of 100 by definition, is standardised to the value of 100 and the least safe route is standardised to the value of 0. If all vehicles make use of the safest route, the safety level of the OD relationship under consideration is 100 *given the infrastructure* and no more progress can be achieved by influencing route choice. If all vehicles make use of the least safe route, the safety level of the OD relation under consideration is equal to 0 *given the infrastructure*.

The standardised road safety score of a route  $r$  may be defined as follows:

$$VV_{rs} = \frac{VV_r - \min_r\{VV_r\}}{\max_r\{VV_r\} - \min_r\{VV_r\}} \times 100\%$$

By entering the standardised safety score of a route  $VV_{rs}$  instead of the non-standardised safety score  $VV_r$ , it is possible to define the safety score of an OD *given the infrastructure* as follows:

$$VV_{OD} = \sum_{r=1}^R \frac{VV_{rs} \times V_{OD,r}}{100} \quad (6.4)$$

### 6.3. Retrieving conflicts from micro-simulation models

The definition of TTC is "the time to a collision with a vehicle that is in front (on road sections) or conflicting (on junctions) if neither vehicle changes its course or speed". The TTC is an indicator for a traffic conflict and is therefore related to the crash risk. Low TTCs mean a higher crash risk and high TTCs mean a lower crash risk.

On a junction, the TTC is calculated on the basis of one or more vehicles coming from another arm of the junction. In addition, a vehicle on a road section can only have one TTC at any given time but on a junction a vehicle can have multiple TTCs simultaneously.

The border line between the end of a road section and the beginning of a junction is determined by the safe stopping distance, referred to henceforth and in the formulae as SSD. The SSD for a vehicle  $i$  on road section  $j$  is defined as:

$$SSD_{ij} = \left( \frac{V_j}{3.6} \times rt_i \right) + \left( \frac{V_j^2}{2 \times 3.6^2 \times A_i} \right) \quad (6.5)$$

in which  $V_j$  is the speed limit in kph for road section  $j$ ,  $rt_i$  is the reaction time of vehicle (driver)  $i$  in seconds and  $A_i$  is the deceleration rate in  $m/s^2$  of vehicle  $i$ .

This means the safe stopping distance is made up of a reaction distance and a braking distance (PIARC, 2004). As an example we assume a reaction time of 1 second and a deceleration rate of  $4 m/s^2$ . At a speed of 50 kph the SSD will be 38 m (13.9 m during reaction time and 24.1 m during braking).

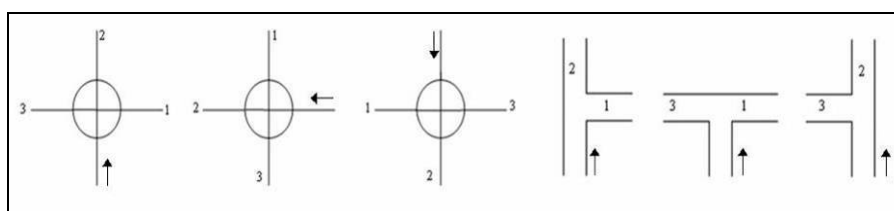
The TTC for a vehicle approaching a junction is either a TTC that is calculated for the interaction with a vehicle in the same direction or one or more TTCs for the interactions with a vehicle in one or more conflicting directions.

### 6.3.1. Passive vehicles and active vehicles

Vogel (2003) makes a distinction between 'passive' and 'active' vehicles. A vehicle is designated as passive if there is a leading vehicle (a vehicle whose distance to the junction is less than that of the subject vehicle) on the same arm of the junction. The TTC for a passive vehicle is calculated for the interaction with the vehicle ahead and therefore in the same way as for vehicles whose distance to a junction is greater than the safe stopping distance SSD. An active vehicle is one that comes into conflict with a vehicle in a conflicting direction or with multiple vehicles in various conflicting directions simultaneously.

### 6.3.2. Conflicting flows

The conflicting directions in relation to a vehicle are determined by the type of junction (3-arms or 4-arms) and the manoeuvres (turning right, left or going straight ahead) of both the subject vehicle and of the potentially conflicting vehicle. The potential conflicting directions (arms of the junction) are numbered anti-clockwise. *Figure 6.6* shows a number of examples for a vehicle  $i$  (arrowed in *Figure 6.6*) driving at a crossroads (on the left-hand side in *Figure 6.6*) and a T junction (on the right-hand side).



**Figure 6.6.** Numbering of arms from the viewpoint of the vehicle entering the intersection

### 6.3.3. Time required to conflict zone

Per time step  $t$ , the time required by both active vehicles to reach the conflict zone is estimated by dividing the distance to the conflict zone by the speed (the dimensions of the conflict zone are determined by the width of both vehicles). This is expressed as the formula below (Van der Horst, 1990):

$$AT_i(t) = \frac{d_i(t)}{V_i(t)}$$

in which  $AT_i$  is the time required by vehicle  $i$  to reach the conflict zone at point in time  $t$ ,  $d_i$  is the distance to the conflict zone at point in time  $t$  and  $V_i$  is the speed at point in time  $t$ .

### 6.3.4. First vehicle

Using the estimated arrival times per step in time, it is possible to calculate which vehicle will arrive at the conflict zone first; this is the vehicle with the lowest AT as calculated with the formula given above. The vehicle that will arrive first is designated vehicle  $i$  and the second vehicle is designated vehicle  $k$ .

### 6.3.5. Clearance time

For the vehicle that will arrive first (vehicle  $i$ ), the time required to leave the conflict zone is calculated. This required time is the difference between the moment when the vehicle is estimated to enter the conflict zone ( $AT_i$ ) and the moment when the vehicle is estimated to leave the conflict zone. The required clearance time  $TO$  for vehicle  $i$  at point in time  $t$  is equal to:

$$TO_i(t) = \frac{l_i + b_k}{V_i(t)}$$

in which  $l_i$  is the length of vehicle  $i$ ,  $b_k$  is the width of vehicle  $k$  and  $V_i(t)$  is the speed of vehicle  $i$  at point in time  $t$ .

This formula may be used for all converging conflicts. In some types of conflict this formula is also valid, for example, in a frontal conflict both vehicles could hit each other at a very small angle.

### 6.3.6. Collision course

Active vehicles are on a collision course if the difference between the arrival times of the two vehicles  $i$  and  $k$  is less than the required clearance time of vehicle  $i$ :

$$AT_k(t) - AT_i(t) < TO_i(t)$$

If this is the case, the TTC is equal to the arrival time of the second vehicle:

$$TTC_{i,k}(t) = AT_k(t) \quad (6.6)$$

If the difference between the arrival times of the two vehicles is greater than the required clearance time of the first vehicle, then the vehicles are not on a collision course and the TTC is not calculated.

FHWA (2003) defines a conflict as an observable situation in which two or more vehicles approach each other in time and space and there is a risk of collision if their movements remain unchanged. If a vehicle's TTC gets below a certain critical value, this can be considered an unsafe situation and it is designated a 'conflict situation'. Minderhoud and Bovy (2001) conclude that different values are used for critical TTCs in different studies. A TTC of less than 1.5 seconds is the critical value for road safety in urban areas (Archer, 2005). In his analysis, Van der Horst (1990) takes into account TTC values that are lower than 2.5 seconds. Various critical values of TTC can therefore be argued for. Lu et al. (2001), in their study of TTC at junctions, distinguish three accident risk classes based on three critical TTC values. If these are translated into the minimum TTC value of conflicts, we arrive at three different conflict levels (*Table 6.7*).

Risk level	Description
Low	1.5 sec $\geq$ TTC < 2.0 sec
Moderate	1.0 sec $\geq$ TTC < 1.5 sec
High	TTC < 1,0 sec

**Table 6.7.** Conflicts according to risk level, depending on the TTC value (Lu et al., 2001)

The number of conflicts  $NOC_i$  in which vehicle  $i$  becomes involved is expressed as follows:

$$NOC_i = \sum_{n=0}^T \delta_i(\zeta_n) \quad (6.7)$$

in which  $\delta_i(\zeta_n) = 1$  if  $0 \leq TTC_i(\zeta_n) \leq TTC^*$  and  $TTC_i(\zeta_{n+1}) > TTC^* = 0$  otherwise.

In this formula,  $TTC_i$  is the TTC for vehicle  $i$  at point in time  $t$  as calculated in *Formula 6.6*.  $TTC^*$  is the critical TTC value,  $\zeta_0$  is the point in time when

vehicle  $i$  enters the network and  $\zeta_T$  the point in time when the vehicle leaves the network. This method prevents double counting of conflicts.

## 6.4. Other conflict based indicators

### 6.4.1. Conflict measures on the vehicle level

#### Time Exposed Time To Collision (TE<sub>x</sub>T)

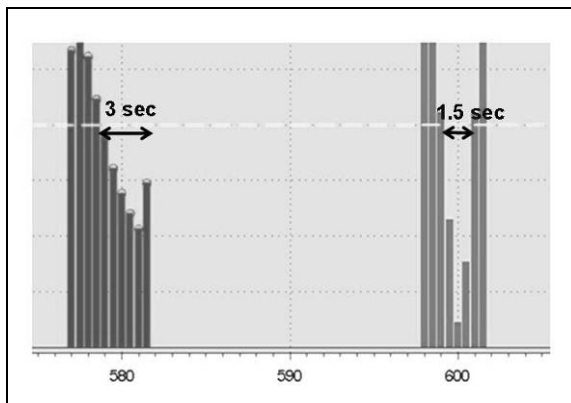
The TE<sub>x</sub>T (Time Exposed Time-to-collision) indicates the length of time that a vehicle's TTC is below a critical value (TTC\*) during a certain time period (Minderhoud & Bovy, 2001). The TE<sub>x</sub>T is therefore the sum of the moments that a vehicle has a TTC that is below the TTC\*. This means that the lower the TET is, the less time the vehicle is in a conflict situation and thus, the safer the situation is.

The example in *Figure 6.7a* shows the TTC progress of a vehicle during the time period  $H$ . The time that the TTC of this vehicle drops below the TTC\* (horizontal line) is shown by the shading in vertical lines. The sum of these moments gives the value of the TET indicator. This is expressed as the formula:

$$TE_{xT_i}^* = \sum_{t=0}^T \delta_i(t) \cdot \tau_{sc}$$

in which  $TE_{xT_i}^* = TE_{xT}$  value for vehicle  $i$

$$\begin{aligned} \delta_i(t) &= 0 & \text{and} \\ &= 1 & \text{if } 0 \leq TTC_i(t) \leq TTC^* \\ \tau_{sc} &= \text{time interval (sec.)} \end{aligned}$$



**Figure 6.7a.** Time Exposed Time To Collision (TE<sub>x</sub>T)

### Time Integrated Time To Collision (TInT)

A disadvantage of the TExT indicator is that any TTC value that is lower than the critical value is not included in the calculation. As an example, let us take a situation (*Figure 6.7b*) in which a critical TTC\* of 3 seconds has been set: a TTC that has a value of 1 second for a period of 3 seconds has the same weighting in the calculation of the TExT indicator as a TTC that has a value of 2 seconds for a period of 3 seconds. The first situation is more dangerous than the second situation. In order to properly reflect the impact of the TTC value, the Time Integrated Time-to-collision (TInT) indicator was developed. The TInT calculates the surface area between the TTC\* and the TTC that occurs. This is expressed as the formula

$$TInT_i^* = \sum_{t=0}^T [TTC^* - TTC_i(t)] \cdot \tau_{sc} \quad \text{for } 0 \leq TTC_i(t) \leq TTC^*$$

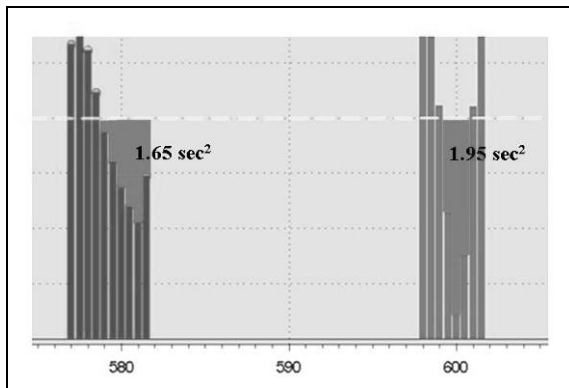
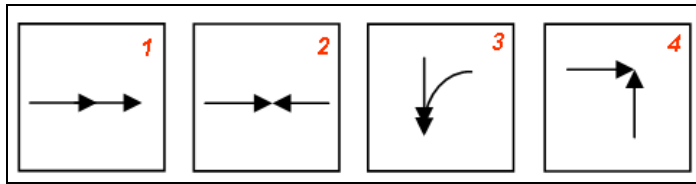


Figure 6.7b. Time Integrated Time To Collision (TInT)

### Potential Collision Energy (PCE)

Another way of reflecting the impact of a conflict is via the potential collision energy. This indicates how much energy is released in the event of a collision between the vehicles that are in conflict with each other. The potential collision energy is built up from the weights and speeds of the vehicles involved and the way in which they collide: this identifies the type of conflict. On road sections, only longitudinal conflicts ('1' in *Figure 6.8*) are identified. At junctions, a distinction is made between frontal (2), converging (3) and transverse conflicts (4).





**Figure 6.8.** Conflict types

### *Longitudinal conflict*

In order to calculate the potential impact energy  $PCE_T$  at point in time  $t$  in the event of a longitudinal conflict between vehicle  $i$  and vehicle  $k$ , the kinetic energy of one vehicle is deducted from that of the other. This is expressed as the formula:

$$PCE_T(t) = \frac{1}{2} (m_i \cdot v_i^2(t) - m_k \cdot v_k^2(t))$$

in which  $m$  is the mass and  $v$  is the velocity.

### *Frontal conflict and transverse conflict*

In order to calculate the potential impact energy  $PCE_T$  at point in time  $t$  in the event of a frontal or transverse conflict between vehicle  $i$  and vehicle  $k$ , the kinetic energy of one vehicle is added to that of the other. This is expressed as the formula:

$$PCE_T(t) = \frac{1}{2} (m_i \cdot v_i^2(t) + m_k \cdot v_k^2(t))$$

### *Converging conflict*

In order to calculate the potential impact energy  $PCE_T$  at point in time  $t$  in the event of a converging conflict between vehicle  $i$  and vehicle  $k$ , the kinetic energy of one vehicle is added to that of the other and the result is corrected by a factor  $1/4$ , to take into account the angle ( $45^\circ$ ) between the vehicles. This is expressed as the formula

$$PCE_T(t) = \frac{1}{4} (m_i \cdot v_i^2(t) + m_k \cdot v_k^2(t))$$

### *Distribution of PCE between vehicles*

The total potential collision energy  $PCE_T$  that is released if vehicles  $i$  and  $k$  with a mass  $m$  collide at point in time  $t$  (calculated using the three formulae for  $PCE_T$ ), is distributed between the vehicles according to their masses. The lighter vehicle has to absorb the greater part of the potential collision energy and the heavier vehicle has to absorb the lesser part. The potential collision energy  $PCE$  to be absorbed by vehicle  $i$  is calculated as follows:

$$PCE_i(t) = \frac{m_k}{m_i + m_k} * PCE_T(t).$$

Subsequently for vehicle  $k$  as:

$$PCE_k(t) = \frac{m_i}{m_i + m_k} * PCE_T(t).$$

#### 6.4.2. Conflict measures on higher levels

The scores of the various road safety indicators at vehicle level can be totalled for each road section or junction to produce an indication of the safety of a road section or junction. For example, the number of conflicts that occur on a road section during a certain period of time is a measure of the safety of that road section. If the absolute score is divided by an exposure index such as the number of vehicles passing per time unit, a relative measure is obtained. This makes it possible to compare a variety of road sections and various simulations.

In the following sections, the safety of road sections and junctions is defined in general terms. This implies that road safety can be assessed using a variety of indicators at vehicle level: the number of conflicts, the TET, the TIT and the potential collision energy. The method of arriving at road section/junction level is the same for all four road safety indicators.

##### **Absolute measure on road sections**

The unsafety  $VOV$  on road section  $m$  during time period  $T$  is equal to the sum of unsafety on the road, on which the number of vehicles  $l$  that pass through road section  $m$  during time period  $T$  are involved. This is expressed as the formula

$$VOV_{m,T} = \sum_{i=0}^l VOV_{i,m,T}$$

In this the unsafety  $VOV$  is determined by the number of conflicts ( $NOC$ ),  $TExT$ ,  $TInT$ , and  $PCE$ .

##### **Relative measure on road sections**

The relative unsafety  $RVOV$  for road section  $m$  (length  $L_m$ ) during time period  $T$  is equal to the absolute unsafety (as calculated using the previous formula) divided by the product of length  $L_m$  and the number of vehicles  $l$  that pass through road section  $m$  during time period  $T$ . This is expressed as the formula:

$$RVOV_{m,T} = \frac{VOV_{m,T}}{(I_{m,T} \times L_m)}$$

### **Absolute measure on intersections**

#### *Longitudinal conflicts*

The unsafety  $VOV$  for longitudinal conflicts at junction  $n$  for manoeuvre  $m$  during time period  $T$  is equal to the total of the unsafety in which the  $I$  number of vehicles executing manoeuvre  $m$  at junction  $n$  during time period  $T$  are involved. This is expressed as the formula

$$VOV_{n,m,T} = \sum_{i=0}^I VOV_{i,n,m,T}$$

in which manoeuvre  $m$  can be a right turn, a left turn, going straight ahead or a manoeuvre specified in more detail at direction level. At a 4-arm junction, 12 directions (4 arms times 3 directions) are involved; at a 3-arm junction, 6 directions (3 arms times 2 directions) are involved.

#### *Converging, transverse and frontal conflicts*

The relative unsafety  $RVOV$  for converging, transverse and frontal conflicts at junction  $n$  and manoeuvre  $m$  during the period  $T$  is equal to the total number of conflicts in which the  $I$  number of vehicles executing manoeuvre  $m$  at junction  $n$  during time period  $T$  are involved. Because a conflict between two vehicles takes place at the same junction and therefore counts as a conflict for both vehicles, the conflicts for the junction must be divided by 2. This is expressed as the formula

$$VOV_{n,m,T} = \sum_{i=0}^I VOV_{i,n,m,T} \times 0.5$$

in which manoeuvre  $m$  can be a right turn, a left turn or going straight ahead.

### **Relative measure on intersections**

The relative unsafety  $RVOV$  for junction  $n$  during time period  $T$  is equal to the unsafety  $VOV$ , as calculated using one of the two previous formulae (for longitudinal or other conflicts), divided by the number of passing vehicles  $I$  executing manoeuvre  $m$  at junction  $n$  during time period  $T$ . This is expressed as the formula

$$RVOV_{n,m,T} = \frac{VOV_{n,m,T}}{I_{n,m,T}}$$

### 6.4.3. Conflict measures on route level

A route  $r$  is defined as a chain of a number  $M$  of road sections and a number  $N$  of junctions that can be followed to reach destination  $j$  from origin  $i$ . To indicate the safety of a route, we use the relative unsafety of road sections and junctions. The general formula is given below.

The safety of a route  $r$  between origin  $i$  and destination  $j$  (length  $L_r$ ) is equal to the sum of the unsafety  $VOV$  during time period  $T$  on the number  $M$  of road sections and the number  $N$  of junctions, specified according to the type of manoeuvre, that form part of the route. This is expressed as the formula:

$$VOV_{ij,r,T} = \sum_{m=0}^M VOV_{m,T} + \sum_{n=0}^N VOV_{n.m.T}$$

The relative measure is formulated as:

$$RVOV_{ij,r,T} = \frac{VOV_{ij,r,T}}{(I_{ij,T} \times L_r)}$$

If a route is not taken by any vehicle, the  $RVOV$  can nevertheless be calculated. That is because other vehicles, following different routes, will be using the road sections of the route in question. Those vehicles will be part of the calculation of  $RVOV$ .

#### **From route level to OD level**

Using the road safety indicators as described at the route level, it is possible to calculate the road safety of an OD pair for all the routes that are associated with that OD pair. Then, by making clear how vehicles are spread over these routes, we can see to what extent vehicles select the safest route and how many do so. Here, it is also important to include the safety level of routes that are not selected (in this step). After all, traffic may well follow these routes in a subsequent step. This produces a picture of the road safety of an OD pair. We then explain, step by step, how these calculations were arrived at.

#### *Distribution of vehicles over all routes*

The distribution of vehicles over the routes per OD pair is indicated by calculating the percentage of the total number of vehicles per OD pair that travel via route  $r$ . This is expressed in the formula

$$V_{OD,r} = \frac{I_r}{I_{OD}} \times 100\%$$

in which  $V_{OD,r}$  is the percentage of vehicles that travel via route  $r$  from origin  $H$  to destination  $B$ ,  $I_r$  is the absolute number of vehicles that travel via route  $r$  and  $I_{OD}$  is the total number of vehicles that travel from origin  $H$  to destination  $B$ .

*Safety at the OD level*

In order to define the safety level of an OD pair, the scores for the number of conflicts, TExT, TInT and potential collision energy are standardised. The standardised road safety score of a route  $r$  can be defined as follows:

$$VV_{rs} = \frac{VV_r - \min_r\{VV_r\}}{\max_r\{VV_r\} - \min_r\{VV_r\}} \times 100\% \quad (6.8)$$

in which the road safety score of a route  $VV_r$  is given by the number of conflicts (NOC), TExT, TInT and PCE.

The safety score of an OD pair is then defined as follows:

$$VV_{OD} = \sum_{r=1}^R \frac{VV_{rs} \times V_{OD,r}}{100} \quad (6.9)$$

in which the standardised road safety score of a route  $VV_{rs}$  is given by NOC, TExT, TInT and PCE.

## **7. Quantitative relationships between calculated conflicts and recorded crashes**

The best-known safety indicator in micro-simulation models is the 'conflict' situation - a situation in which two vehicles approach each other and where, if no action were taken, a crash would occur. These conflict situations in the simulation model can be detected. This method does not necessarily relate directly to any actual observed conflicts, let alone recorded crashes. This chapter examines the quantitative relationship between the detected conflicts at intersections in the model and the recorded crashes at the same locations in reality. The methods chosen for detecting conflicts and for selecting crashes are explained. A micro-simulation model was constructed for a regional road network. A description of this regional network is given as well as the choices that were made in order to model this network. Subsequently, the conflicts in the simulated network were detected, and the recorded crashes were selected. Finally, both safety indicators were related to each other.

### **7.1. Descriptions of the study area and the micro-simulation model**

#### **7.1.1. Study area**

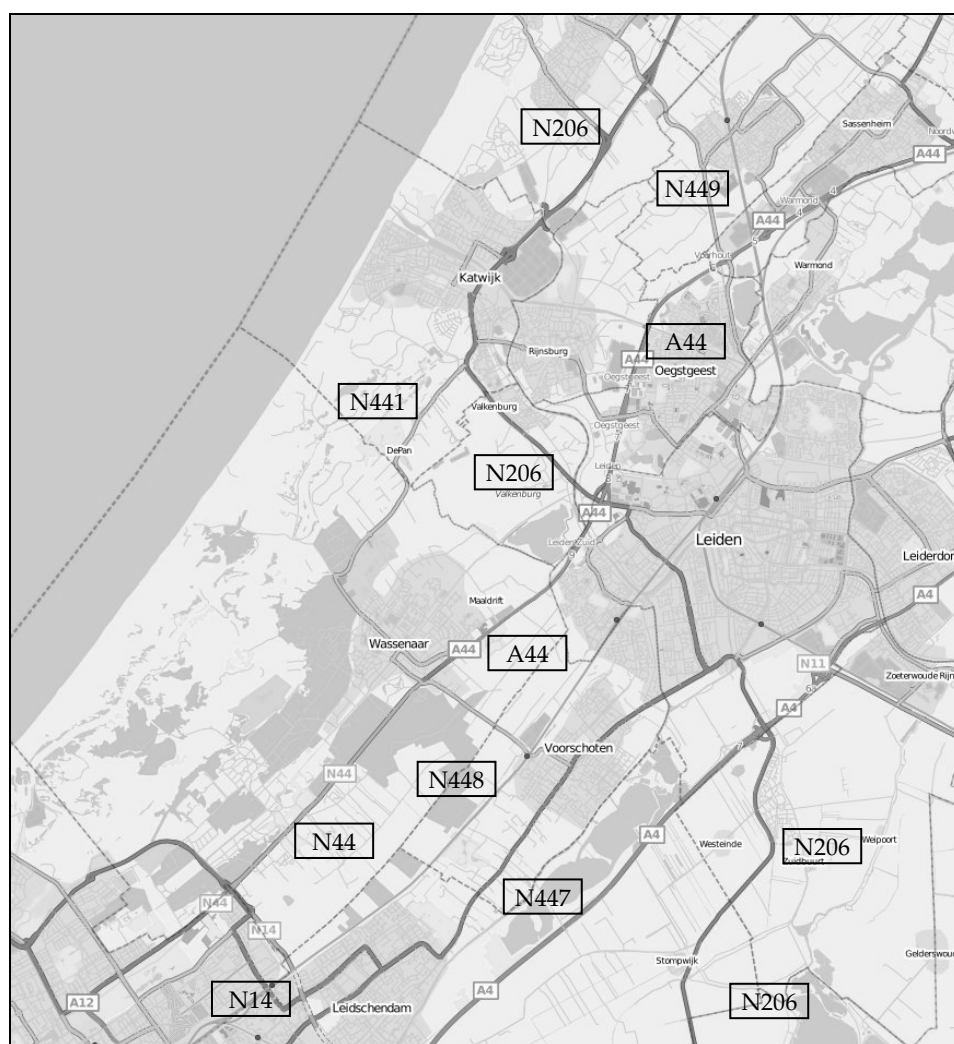
The study area is situated in the west of the Netherlands and it covers an area of about 300 km<sup>2</sup>. The total number of inhabitants amounts to 900,000 (CBS Statline, 2008); the population density is 3,000 residents per square kilometre. Most of the population is concentrated on the outskirts of the area. The area contains (calculated according to Dutch proportions) one large town (475,000 inhabitants), two medium-sized towns (64,000 and 118,000 inhabitants), and thirteen smaller communities (4,000 to 32,000 inhabitants). The area is traversed by two main roads (A4 and A44/N44) which are part of the national main road network (see *Figure 7.1*). There are a few regional roads that run parallel to these two main roads.

The area has many interactions with the other parts of The Netherlands and is situated at the North Sea coast. That is why many external relationships are oriented southwest to northeast and vice versa. The A4 motorway connects Amsterdam with The Hague while the A44/N44 road is the connection between Leiden, Wassenaar and The Hague. The three main

regional routes are the N447 road from Voorschoten to Leidschendam, the (first part of the) N206/local roads from Katwijk to Wassenaar, and (the final part of the) N206/local roads from Leiden, through Stompwijk to Leidschendam (see *Figure 7.1*).

Car drivers do not prefer the route through Stompwijk (Goldenbeld et al., 2006). Most of the drivers choose (one of) the other four routes. However, Goldenbeld et al. reported that some drivers prefer the secondary road situated next to the A44.

Three routes are situated perpendicular to the five parallel routes: a part of the N206 road near Leiden, the N441/N448 road through Wassenaar and Voorschoten, and the N14 road through Voorburg. Compared to the five parallel routes, these three routes do not have many similarities, because they connect quite different origins and destinations.



**Figure 7.1.** Study area

### **7.1.2. Modelling the study area**

The roads and the traffic in the study area have been modelled with the micro-simulation model *S-Paramics* (SIAS, 2005). The modelled network comprises the most important roads and streets of the area; residential roads have been omitted (*Figure 7.2*). The model consists of approximately 9,000 links and 4,500 nodes. A node connects at least two links, and may sometimes be an actual intersection. The model contains more than 1,000 intersections (signalized, non-signalized, or roundabout); see *Figure 7.3*. The model has been calibrated for the morning rush-hour traffic on weekdays (6.00 a.m. to 10.00 a.m.). The traffic assignment during this period is in accordance with the observed flows. The calibration particularly focused on the spread of traffic over the five parallel connections between the two most important urban centres in the area (Leiden/Katwijk and The Hague), using traffic counts and the observed lengths of queues.

The model was tailored to the situation in 2005 and only represents the movements of motor vehicles. This is typical in micro-simulation models. However, to investigate safety extensively, a model that incorporates other road users is needed – see the recommendations in *Section 7.3*

## **7.2. Conflicts and crashes**

The road design elements in a Paramics network are quite detailed. Using this network to calculate the conflicts (*Section 6.3*) would require a large number of additional steps. This would certainly be necessary for analysing effects of changes in design features at the intersection level. However, the analyses in this section are intended for a more overall study of total numbers of conflicts and numbers of crashes. Therefore the conflicts were calculated using a more abstract network.

### **7.2.1. Abstract network and S-Paramics network**

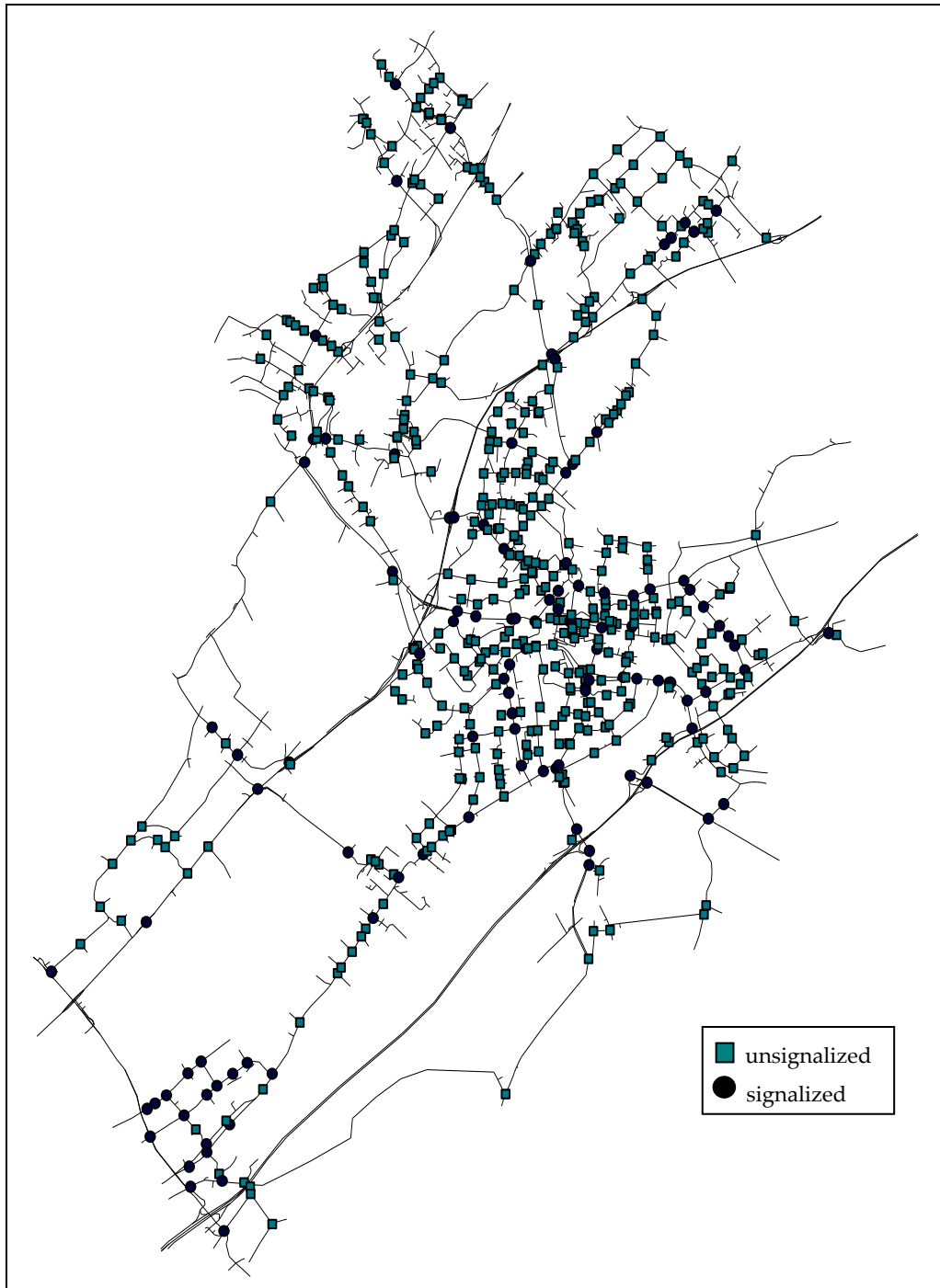
The calculations formulated in *Section 6.3* were carried out on vehicles that are meant to move in an abstract network, i.e. a network that has been simplified to links and nodes which consist of lines and points respectively (*Figure 7.4*). The S-Paramics network consists of links and nodes which respectively have a cross sectional profile and an intersection area (*Figure 7.4*). This means that the calculations of the Time To Collision (TTC) values in the abstract network could produce different results to those of the S-Paramics network. In the abstract network, the calculation of the TTC is based on the measurements of the vehicles for clearance time (TO), but not



for the exact position of the vehicles in the cross sectional profile or on the intersection area. Moreover, results of the S-Paramics model indicate that, for calculating TTC values, the position on the intersection area is less accurate than desired.

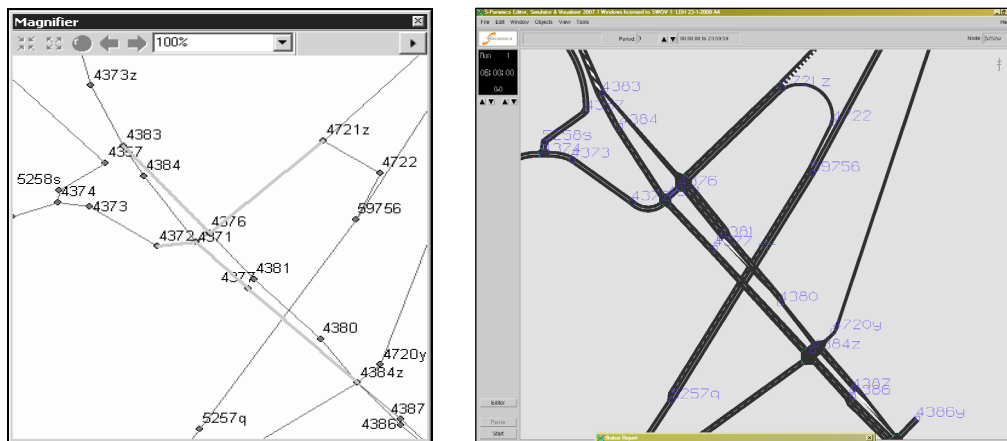


**Figure 7.2.** Micro-simulation model of the study area



**Figure 7.3.** Signalized and unsignalized (priority) intersections in the simulation model

Every second, the number of conflicts is calculated for all vehicles that conflict with each other. This is determined by the way S-Paramics works. The program determines and stores the position of all vehicles every second.



**Figure 7.4.** Example of the abstract network (left-hand side) and the S-Paramics network (right-hand side).

### 7.2.2. Crash data

The details of crashes in the Netherlands are linked to the National Roads Database (NRD) (AVV, 2003). This is a digital geographic data set containing almost all Dutch roads. It includes all roads which have a street name or number and which are controlled by one of all the road authorities. In cases where the carriageways of a road are separated, they are treated as separate road sections in the NRD. The NRD is very detailed, more detailed than a classification of the road network by sections of roads and intersections alone. In order to select the crashes on a particular road section or intersection from the NRD, it is necessary to link the location of the road section or intersection to the relevant parts of the NRD accurately. This is usually done by a computer program, but it is advisable to check the selection visually via a GIS. The NRD is constantly changing due to changes in the road network. The crashes are linked to the version of the NRD for the year in which they were recorded. With a selection of crashes from different years, one must check whether all the crashes recorded in those years were traced in the various versions of the NRD for the road section or intersection in question.

The crashes selected for this study occurred during the period 2002 – 2007. They are crashes resulting in injury or property damage only. It is well known that crashes, in particular those without injury, are only recorded to a limited degree. However, there is no reason to assume that in the chosen area the degree of registration would be different for the various locations.

The analyses will concentrate on intersections. In the first instance, 777 intersections and 63 roundabouts were selected. During the analysis, a number of intersections were dropped because the deviations between the

modelled intersection and the actual design were too large; 569 intersections remained. The roundabouts are not discussed in this study, as the modelling of this type of intersection requires more research, and can therefore only be dealt with at a later stage. The crash data are limited to crashes which involve only motor vehicles, and the point in time of a crash lies between 6 and 10 a.m. on weekdays. This matches the characteristics and pre-requisites of the simulation model used. Therefore only about 8% of all recorded crashes in the area have been selected for these analyses.

### 7.2.3. Analysis and results

The micro-simulation model describes the period from 6 – 10 a.m. on weekdays. The model produces the passing vehicles per intersection and the vehicles that may come into conflict with each other for this period. A sub-program then calculates the conflicts according to the method described earlier. It is possible that these values for passing vehicles and conflicts are excessively subject to coincidence. During a consecutive 'run' these values could be totally different. In order to check this, 36 runs were carried out. This number of runs is much higher than is usually done. The 36 runs were carried out to ensure constancy (a small variance) in the numbers of conflicts and the numbers of passing vehicles. These numbers were found to be sufficiently stable. The average values of the number of passing vehicles and conflict situations were calculated from these runs for each intersection. The description and analysis of the variables is treated in the following four sections:

- Type of intersection (number of arms, with/without signals) (roundabouts were not analysed, as stated in the previous section).
- Type of conflict (lateral, frontal, rear-end).
- Classification according to the number of passing vehicles.
- Statistical model (passing motor vehicles, conflicts, crashes).

#### **Type of intersection**

A classification of intersections according to type (three-arm or four-arm and with or without signals) shows that the majority of intersections (375 of the 569) are three-arm and have no signals (*Table 7.1*).

Three-arm priority intersections have the lowest number of crashes per intersection, as well as the lowest number of calculated conflicts per intersection. The highest number of crashes per intersection can be found at four-arm intersections with signals. The highest number of conflicts per intersection can be found at three-arm intersections with signals. In total, there are 372 relevant crashes (only between motor vehicles and on

weekdays between 6 and 10 a.m.) at 569 intersections. This means there are many intersections on which no crashes occurred.

Type of control	Numbers					Risks	
	Arms	Intersections	Passing vehicles per intersection	Crashes	Conflicts	Crashes per 100 intersections	Conflicts per intersection
Priority	3	375	2,186	112	97,254	29.9	259
	4	83	2,878	46	33,849	55.4	408
Signalized	3	40	6,260	54	38,870	135.0	972
	4	71	6,196	160	49,498	225.4	697
All types		569	3,074	372	219,470	65	386

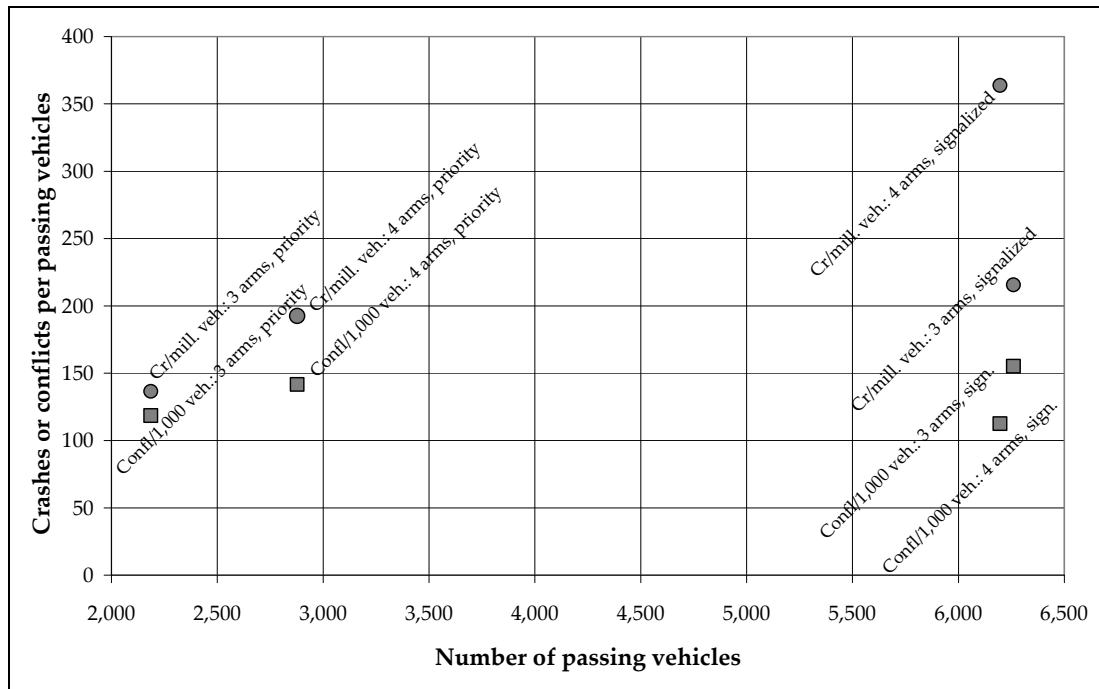
**Table 7.1.** Several variables for four different types of intersections

The conflicts were calculated according to the formulas mentioned in *Section 6.3*. The critical TTC value here is set at 2.5 s. Where risk is concerned, the number of crashes per million passing motor vehicles and the number of conflicts per 1,000 motor vehicles is measured against the number of passing motor vehicles (*Figure 7.5*). Analogous to the number of crashes and conflicts, the risk of crashes at four-arm intersections with signals is higher than for other types of intersection, and the conflict risk is highest for three-arm intersections with signals.

### **Type of conflict**

The conflicts and crashes are divided into three types: frontal, lateral and rear-end. These types are relevant to intersections. Rear-end conflicts on the arms of an intersection can be calculated at varying distances. In this case a distance was chosen of up to 50 m before the intersection.

*Table 7.2* shows that the distribution of crashes according to crash type at priority intersections corresponds better to the distribution of conflicts than at intersections with signals. At the intersections with signals, it is also clear that both 'rear-end' type crashes and conflicts dominate the crash type to a large degree. However, at these intersections, a 'lateral' crash occurs relatively much more frequently than a 'lateral' conflict.



**Figure 7.5.** Crash and conflict risk related to the number of passing vehicles

Type of control	Arms	Frontal		Rear-end		Lateral	
		Conflicts [%]	Crashes [%]	Conflicts [%]	Crashes [%]	Conflicts [%]	Crashes [%]
Priority	3	0.34	0.36	0.28	0.25	0.37	0.39
	4	0.23	0.26	0.31	0.22	0.47	0.52
Signalized	3	0.21	0.15	0.61	0.44	0.18	0.41
	4	0.05	0.18	0.74	0.46	0.20	0.36

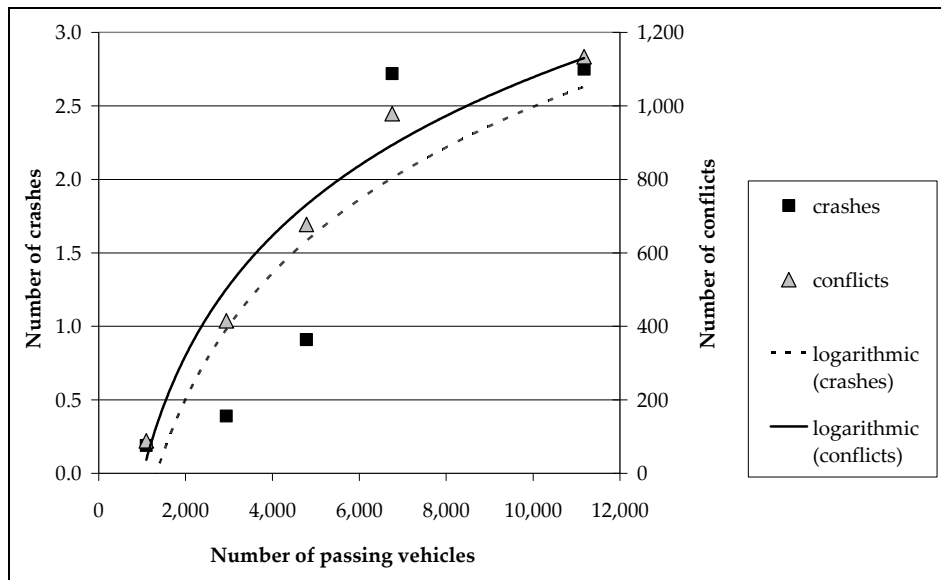
**Table 7.2.** Collision types for crashes and conflicts (in %) on different intersection types

*Number of passing motor vehicles*

The intersections were then divided into five traffic volume classes (Table 7.3). Both the average number of crashes and the average number of conflicts increase with the level of the average volume. Figure 7.6 illustrates that – the greater the volume, the higher the number of crashes and conflicts.

Passing vehicles per intersection	Number of intersections	Per intersection		
		Passing vehicles	Crashes x 100	Conflicts
0 - 2,000	243	1,096	19	88
2,001 - 4,000	180	2,937	39	415
4,001 - 6,000	79	4,784	91	677
6,001 - 8,000	39	6,755	272	979
> 8,000	28	11,175	275	1,134
Total	569	3,074	65	386

**Table 7.3.** Intersections divided into five classes according to the mean number of passing vehicles, mean number of crashes and mean number of conflicts for each class



**Figure 7.6.** Number of crashes and number of conflicts plotted against the number of passing vehicles (mean numbers)

### Statistical modelling

Due to the discrete nature of the data, the relationship between observed crashes and simulated conflicts was assessed using generalized linear models, in the GENMOD procedure of the SAS software (SAS, 2005). Assuming either a Negative binomial or a Poisson distribution of the crashes, different log-linear models were developed. The observed number of crashes per intersection was the dependent variable and the various combinations of independent variables tested were derived from 36 runs: average number of

passing vehicles, average number of conflicts, and maximum number of conflicts.

Various threshold values for the TTC were used in the calculation of conflicts which resulted in different data sets. Regression analyses were performed with the different data sets.

The assumption of two different crash distributions (Poisson and Negative binomial) led to similar results with regards to the goodness of fit of the models and the significance of the variables. The goodness of fit was assessed, with e.g. Pearson's chi-square test and the results indicate a good fit to the data.

Table 7.4 displays the goodness of fit and the parameters estimates of a log-linear model assuming a Negative Binomial distribution of the crashes. The log-linear model referred to in Table 7.4 is:

$$\mu = e^{-6.31} \cdot flow^{0.48} \cdot noc^{0.28}$$

In which  $\mu$  is the expected number of crashes,  $noc$  the number of conflicts (for TTC\*=2.5s), and  $flow$  the number of passing vehicles.

Parameter	Estimate	SE	$\chi^2$	p-value
Intercept	-6.3165	1.4151	19.92	<.0001
log $flow$	0.4838	0.2296	4.44	0.0351
log $noc$	0.2869	0.1134	6.39	0.0115

Degrees of freedom (DF) = 455; Pearson  $\chi^2 = 470.60$ ; Pearson  $\chi^2/DF = 1.03$

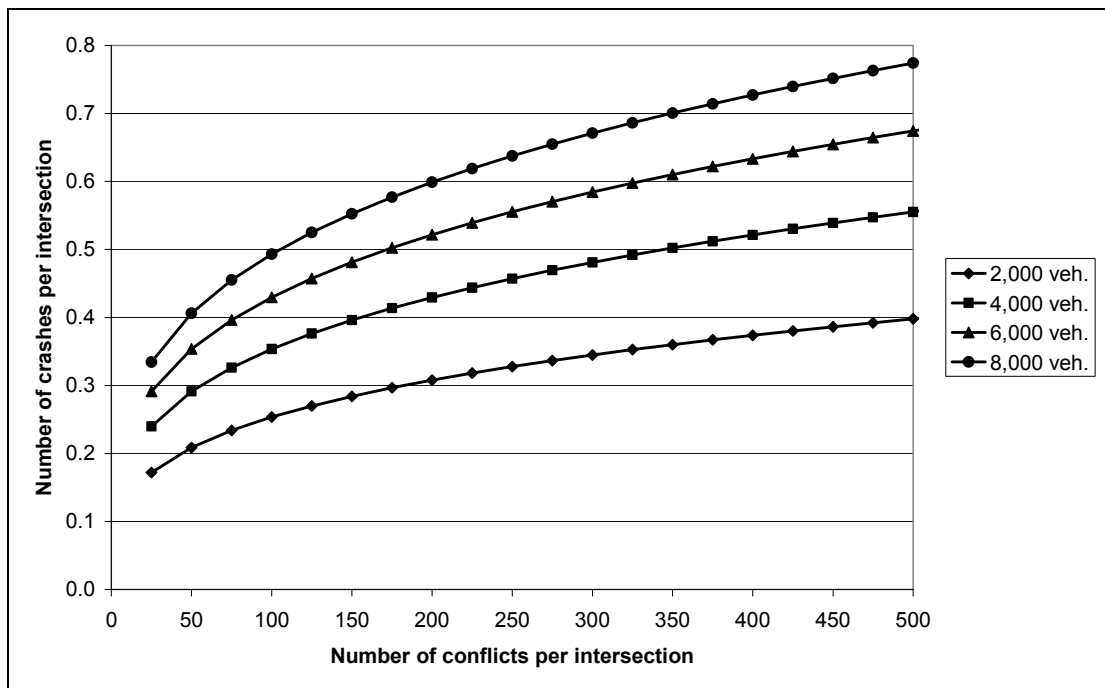
**Table 7.4.** Goodness of fit and parameter estimates of a log-linear model (assuming Negative Binomial distribution of crashes)

The number of conflicts and the number of passing vehicles were found to be significant at confidence levels higher than 95 percent (p-values smaller than 0.05).

Other models were created by adding a categorical variable 'number of arms of the intersection'. The distinction between three-arm and four-arm intersections was significant only for confidence levels in the range of 90 percent.

Even though the level of significance of the variables is not the same in the different models, the analyses lead to the same conclusions. The results show that there is a statistical relationship between observed crashes and calculated conflicts. The results do not show which combination of variables explains the observed crash frequency best. Figure 7.7 shows the relation according to the formula in Table 7.4.





**Figure 7.7.** Number of crashes related to number of conflicts (according to the model described in *Table 7.4*)

### 7.3. Conclusions and recommendations

The estimated numbers of conflicts between vehicles in a micro-simulation model have been calculated here according to a specified method. The number of conflicts at junctions and the number of passing motor vehicles appear to be quantitatively related to the number of observed crashes for all junctions. The goodness of fit of this relationship could be statistically confirmed.

A classification of crashes and conflicts makes it clear that junctions with signals show considerable differences between lateral conflicts and crashes. This difference probably occurs because the method used also counts and calculates conflicts between two vehicles of which one is standing still (at a red light). At junctions with signals, the proportion of rear-end conflicts is also higher than the number of crashes of this type. This phenomenon occurs because the method consistently indicates conflicts between all vehicles that approach the junction in succession. The small differences in speed between the vehicles ensure that the conflicts are less serious. If the critical TTC value is lowered, the number of rear-end conflicts will decrease.

The model does not allow for detecting conflicts regarding red-light running. So crashes of this type will not be 'predicted' by the model.

The four-arm junctions with signals show a considerable deviation between the number of conflicts and crashes, both per junction and per passing vehicle (risk). It is possible that these differences and deviations are linked to the chosen method (via the road link) for determining conflicts. A detailed definition of the driving course through the intersection area could well provide a different result. It is possible that there are junctions showing deviations due to modelling errors or excessive simplification (deviations between the model and reality).

Models like S-Paramics are, to a great extent, black boxes. For research purposes, the internal modelling of vehicle movements and interactions should be clearer.

The model does not yet take traffic other than motor vehicles into account. Addition of cyclist and pedestrian movements is, however, desired.

## 8. Quantitative relationships between route criteria, calculated conflicts, and travel time

This chapter focuses on the design of a method enabling the planner to find out the safety effects of existing route choice, and the effects resulting from changes in route choice. A description of the road safety of a route can be made by constructing a so-called 'route diagram'. This diagram can be checked according to a series of criteria, each representing requirements for a route choice according to the principles of Sustainable Safety. Each criterion of the route diagram contributes to the entire safety level of a route by the number of 'demerit points' scored by the criterion. Some additional safety criteria are added in order to find the total safety level of a route, referred to as the 'DV score'<sup>2)</sup>. The relative importance of a criterion can be changed by introducing coefficients of weight. Such coefficients should express the contribution of a criterion to the safety level of the DV score.

The DV scores are applied to a regional network and are demonstrated in a micro-simulation model of this network.

The quantitative relationships between the different types of DV scores and the number of simulated conflicts are analysed. This analysis focuses on the alternative routes within each OD-pair. The analysis is extended to a check on the requirement in Sustainable Safety regarding the routes within an OD: 'the shortest route should also be the safest route' (*Chapter 1*).

### 8.1. Examples of applying DV scores to the study area

In *Section 6.2*, several safety scores were defined. Henceforth, the safety score for a route  $VV_{rs}$  (as defined in *Formula 6.8*) will be called DV score. The safety score for an OD pair  $VV_{OD}$  (using *Formula 6.9*) will be called OD score hereafter. Route stars were introduced to visualize the contribution of each safety criterion to the safety level of a route. The route stars of all routes within an OD can be used to compare the routes regarding their safety criteria.

The study area was described in *Section 7.1*. Within this area, some of the safety indicators will be applied to show the characteristics of the method. The regular DV score was calculated for routes within two OD pairs. These

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<sup>2)</sup> DV: abbreviation of *Duurzaam Veilig*, which is Dutch for Sustainable Safety

OD pairs were selected because of the importance of the routes involved. The questionnaire by Goldenbeld et al. (2006) also focused on these routes.

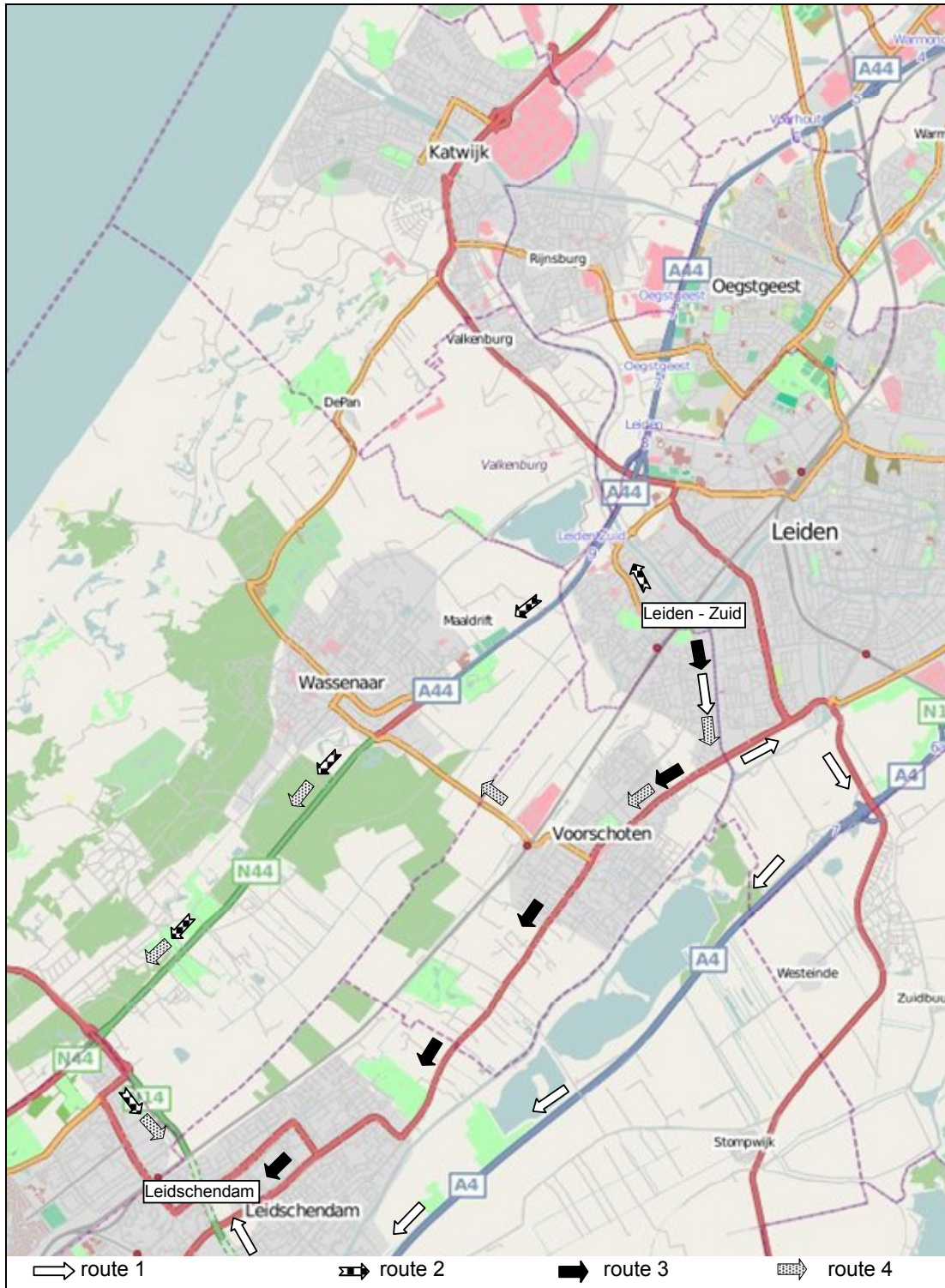
Given the DV scores, the OD score was calculated. The OD score takes into account the actual use of each route. A route with a high DV score, carrying most of the traffic of the OD-pair, will contribute (positively) to the OD score to a large extent. The OD score will be low if most of the traffic uses a route with a low DV score. The DV score can be calculated for a route carrying no traffic within the OD-pair but this route will not contribute to the OD score.

### **8.1.1. From Origin Leiden (Southern side) to Destination Leidschendam**

Most of the journeys between Leiden (Southern side) and Leidschendam follow the four routes shown in *Figure 8.1*. According to Goldenbeld et al. (2006) the routes are used as stated below (in percentages of the total OD traffic volume):

- A4: 32%;
- A44 - N44: 54%;
- Voorschoten - N447: 10%;
- Voorschoten - N448 - N44: 3%.

In order to simplify the calculations the beginnings and endings of all routes are cut off. So the routes only consist of main roads (through roads and distributor roads), while access roads are left out. The routes along the A4 and along the combination A44 - N44 only consist of motorways and quasi motorways. These routes attract most of the traffic in spite of the many queues on these roads. The other two routes, through Voorschoten, are characterized by a lower capacity, lower speed limits and more disruptions by crossing traffic. *Table 8.1* shows the scores  $C_{ji}$  on the criteria. From these scores the DV scores are calculated, see *Table 8.2, row No. 1*. The route stars for these routes are shown in *Figure 8.2*.



**Figure 8.1.** Four routes between Leiden (Southern side) and Leidschendam

Cr.	Description	Weight $g_c$	A4	A44-N44	Voorschoten-N447	Voorschoten-N448-N44
1	Number of transitions	0.111	0	0	2	0
2	Nature of transitions	0.111	0	0	0	0
3	Missing road categories	0.111	0	0	1	0
4	Proportion of access roads	0.111	0.00	0.00	0	0
5	Proportion of distributors	0.111	43.2	31.5	100	64.0
6	Travel distance [km]	0.111	16.0	12.7	10.8	13.9
7	Travel time [min.]	0.111	18	17	15	20
8	Left turns	0.111	1	2	0	2
9	Intersection density (per km)	0.111	0.81	1.18	3.15	1.44
	Sum	1.000				

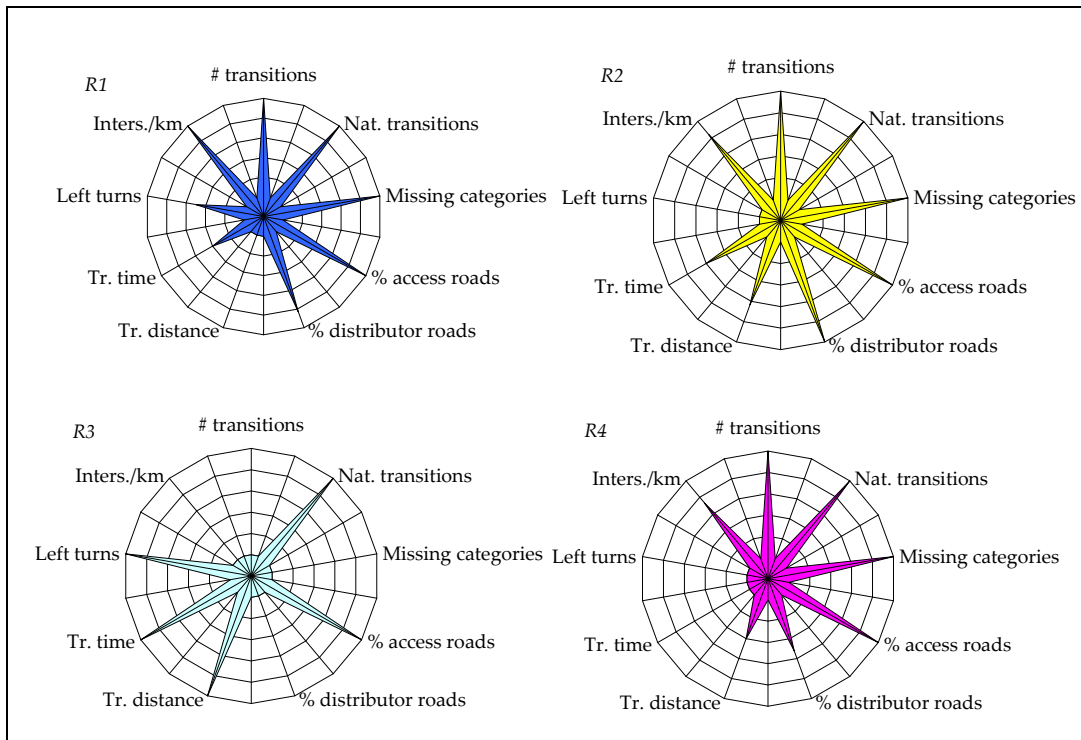
**Table 8.1.** Scores  $C_{ji}$  for four routes between Leiden (Southern side) and Leidschendam

No.	Description of alternative	A4	A44-N44	Voorschoten-N447	Voorschoten-N448-N44	OD score
1	See <i>Table 8.1</i>	75	79	56	63	75
2	Weights according to <i>Table 8.3</i>	82	73	46	59	73
3	No. 1 and alt. distribution of traffic	75	79	56	63	70
4	No. 2 and alt. travel time	78	67	46	64	69

**Table 8.2.** DV scores and OD scores for each alternative

As expected, the first two routes have the highest scores because of the high share of (quasi) motorways. The other routes have a much lower score because of a high share of low-standard roads. The route using the N447 is characterized by missing transitions, a missing category (missing through road), and a high intersection density. However, shorter distance and travel time as well as the absence of left turns are positive criteria for this route. The route using the N448 is partly using a motorway, which is an advantage. On the other hand, a longer travel time and a higher number of left turns are disadvantages. Another finding is that the fastest route (Voorschoten - N447) is not the route with the highest DV score.

The OD score amounts to 75%. This score is in the same order as the DV scores for both A4 and A44 - N44. That is because most of the traffic chooses either of these two routes, which significantly contributes to a relatively high OD score.



**Figure 8.2.** Route stars for the routes between Leiden (Southern side) and Leidschendam; top left: A4, top right: A44 - N44, bottom left: Voorschoten - N447, bottom right: Voorschoten - N448 - N44

### Adapting coefficients of weight

In the previous calculations, the coefficients  $g_c$  are of equal weight (*Table 8.1*). The effect of adapting the weights is shown in the following example. The criteria regarding the number of left turns and the intersection density get a higher weight because of their relationship with the number of crashes. The travel distance has been set to 0.00 in order to exclude any interference between travel distance and travel time (see *Table 8.3*).

The effects of these changes are shown in *Table 8.2*, row No. 2. The A4 route benefits most from these changes; the scores of the other routes have decreased. The advantage of a shorter length of the A44 - N44 route related to the A4 route is removed by assigning no weight to travel distance. The higher intersection density on the A44 - N44 in relation to the A4 route is less favourable on account of the higher weight for this criterion. The DV scores of the other two routes are also lower because of both the higher weight for intersection density and the lower weight for travel distance. The OD score drops only slightly from 75 to 73, because in both cases the safest routes are also the busiest routes.

Criterion	Description	Coefficient of weight $g_c$
1	Number of transitions	0.11
2	Nature of transitions	0.11
3	Missing road categories	0.11
4	Proportion of access roads	0.05
5	Proportion of distributors	0.12
6	Travel distance [kilometres]	0.00
7	Travel time [minutes]	0.10
8	Left turns	0.20
9	Intersection density (per km)	0.20
	Sum	1.00

**Table 8.3.** Alternative coefficients of weight

#### *More examples*

In a third example it is the traffic distribution which is changed (see *Table 8.4*). The results are shown in *Table 8.2*, row No. 3. These kinds of changes do not affect the DV scores; only the OD score is affected (from 75 down to 70). The OD score is lower because the routes with a lower DV score have to carry more traffic. It should be mentioned that the traffic distribution in this example is not very realistic because the capacity of the routes through Voorschoten is too low to carry the traffic involved.

A final example for this OD pair relates to travel time. In the previous examples, the travel time is calculated according to the speed limits of the roads within each route, assuming that traffic is not queuing up. In this example travel times on the A4 route and the A44 - N44 route are increased by a few minutes (*Table 8.5*). The results are shown in *Table 8.2*, row No. 4. The results should be compared to the results in row No. 2. The DV scores for the routes with higher travel times have dropped. The DV score of the route with the highest travel time (Voorschoten- N448 - N44) increases slightly because the relative position of this route has improved (it is not the longest route anymore).



Route	According to Goldenbeld et al. (2006)	Imaginary values
A4	32	10
A44 - N44	54	45
Voorschoten-N447	10	15
Voorschoten-N448-N44	3	30

**Table 8.4.** Alternative traffic distribution (percentages of the total OD volume)

Route	Travel times in a network without queues (empty network)	Imaginary values
A4	18	25
A44 - N44	17	25
Voorschoten-N447	15	15
Voorschoten-N448-N44	20	20

**Table 8.5.** Alternative travel times (minutes)

### 8.1.2. *From Origin Katwijk to Leidschendam (through Wassenaar)*

Most of the journeys between Katwijk and Leidschendam (through Wassenaar) follow the three routes shown in *Figure 8.3*. According to Goldenbeld et al. (2006) the routes are used as stated below (in percentages of the total OD traffic volume):

- Wassenaar short cut: 38%;
- N206 - A44 - N44: 39%;
- N449 - A44 - N44: 23%.

Again, in order to simplify the calculations the beginnings and endings of all routes are cut off. So the routes only consist of main roads (through roads and distributor roads), while access roads are left out. *Table 8.6* shows the scores  $C_{ji}$  on the criteria.

The Wassenaar short cut route has a high share of distributor roads, a long travel time, many left turns, and a high intersection density. The differences between the other two routes are much smaller than the differences between the first route and the latter ones, also because the routes along the A44 - N44 overlap each other. *Table 8.7 (row No. 1)* shows the corresponding DV scores and OD score. The DV score for the N449 route is rather good; however, this does not affect the OD score very much, caused by the low share of traffic

(23%). Compared to the N206 route, the N449 route scores better on the nature of transitions and travel distance. Compared to the Wassenaar short cut route, it also scores better on the proportion of distributors, travel time, number of left turns and intersection density.

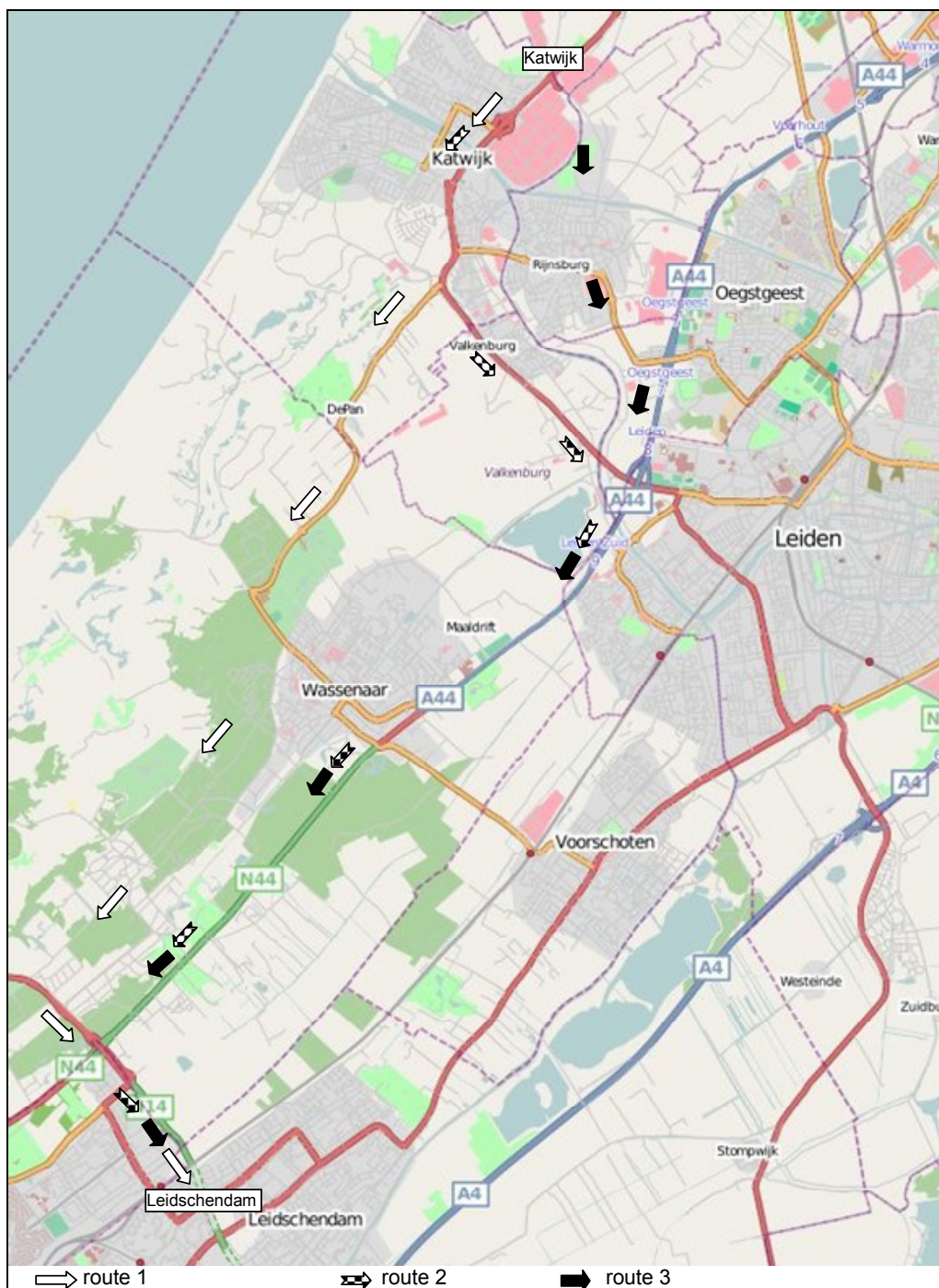


Figure 8.3. Four routes between Katwijk and Leidschendam

Cr.	Description	Weight $g_c$	Wassenaar short cut	N206 - A44 - N44	N449 - A44 - N44
1	Number of transitions	0.111	1	1	1
2	Nature of transitions	0.111	1	1	0
3	Missing road categories	0.111	1	1	1
4	Proportion of access roads	0.111	0.0	0.0	0.0
5	Proportion of distributors	0.111	92.4	64.7	69.8
6	Travel distance [kilometres]	0.111	17.0	18.4	17.2
7	Travel time [minutes]	0.111	23.0	19.0	19.0
8	Left turns	0.111	2.0	1.0	1.0
9	Junction density (per km)	0.111	1.9	0.4	1.2
	Sum	1.000			

**Table 8.6.** Scores  $C_{ji}$  for four routes between Katwijk and Leidschendam

For this OD pair, the fastest routes are also the routes with the highest DV scores. *Figure 8.4* depicts the route stars of these three routes. Obviously, the bottom left figure represents the best route.

No.	Description of alternative	Wassenaar short cut	N206 - A44 - N44	N449 - A44 - N44	OD score
1	See <i>Table 8.6</i>	44	78	91	68
2	Weights according to <i>Table 8.3</i>	27	89	88	65
3	No. 1 and alt. distribution of traffic	44	78	91	73
4	No. 1 and alt. travel time	56	78	80	70

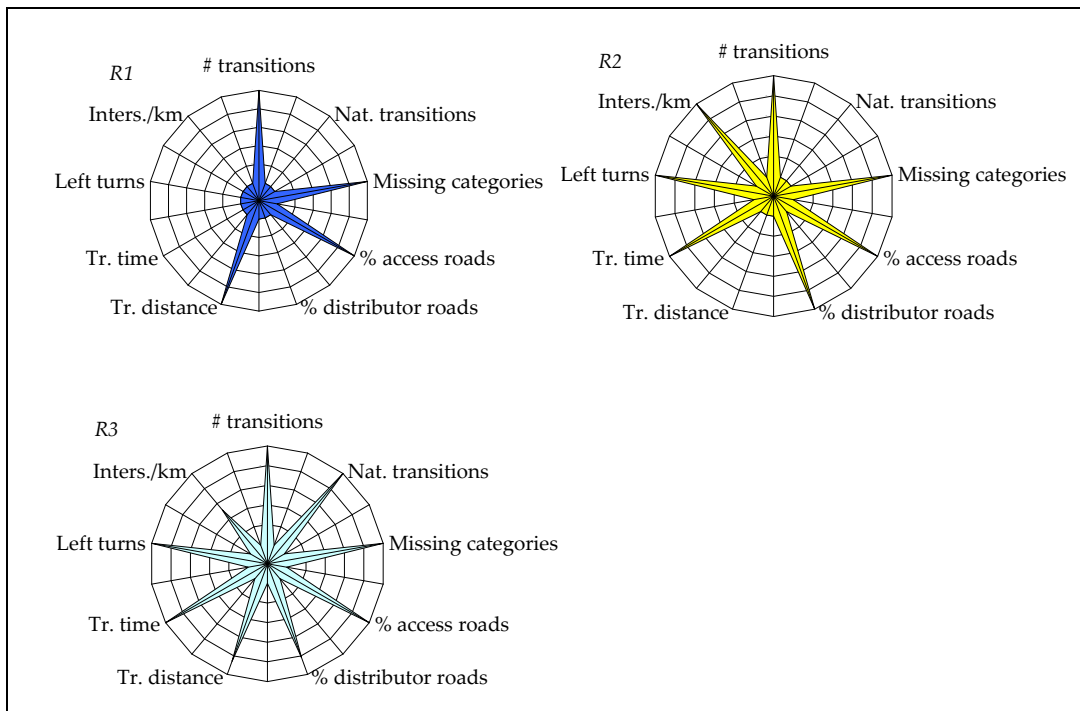
**Table 8.7.** DV scores and OD scores for each alternative

*Table 8.7* contains the results of calculations regarding three sets of assumptions. First, the weights are chosen according to *Table 8.3*. Applying these weights, changes the DV scores substantially (*Table 8.7, row No. 2*). The score of the Wassenaar short cut route decreases (from 44 to 27) while the scores of the other two routes hardly differ anymore (from a difference of 13 to only 1). The OD score does not change very much: the improvement of one route (N206) and the 'decline' (Wassenaar) of another route cancel each other out.

For the second and third calculations, we assume travel times and traffic distribution respectively as values for the actual resistance of each route. The actual travel times are 23, 19 and 19 minutes respectively. This implies a resistance  $R_{OD}$  of the OD pair equal to:

$$R_{OD} = \frac{1}{\sum_{i=1}^3 \frac{1}{R_i}}$$

In which  $R_i$  is the resistance of an individual route, in this case travel time.



**Figure 8.4.** Route stars for the routes between Katwijk, through Wassenaar to Leidschendam; top left: Wassenaar short cut, top right: N206 - A44 - N44, bottom left: N449 - A44 - N44

For this OD pair  $R_{OD} = 6.72$ . This value was used for calculating the traffic distribution. The calculated distribution (29%, 35%, 35%) differs from the actual distribution (38%, 39%, 23%) regarding the first and third route: the Wassenaar route is more popular than it should be according to the theoretical resistance. In reality the second and third route are characterized by many queues during rush hours. The next assumption is that travel times are supposed to be 23, 24 and 26 minutes respectively. The resistance of the OD increases to  $R_{OD} = 8.09$ . The resulting traffic distribution is 36%, 34%, 30% respectively. This approximates the observed values more closely. The DV scores and OD score are calculated for the assumption regarding a travel

distribution of 29%, 35%, 35% respectively (*Table 8.7, row No. 3*), using the original set of weights. The DV scores do not change (the criteria are not altered); the OD score increases to 73 because the safest route is used more intensively. If the distribution is adjusted for a higher resistance because of queues (36%, 34%, 30%), then the OD score drops to 70 because the safest route again loses traffic.

In the final third example, travel time is adapted by, again, using a calculation regarding the resistance. The actual traffic distribution is taken as a starting point. If this is the indicator for the resistance, then the travel times should be in line with this resistance. The calculated travel times are 23, 19, 19 minutes respectively; the travel times in line with the traffic distribution are 18, 18, 29 minutes respectively. These values were input for the calculation of the OD score. This OD score appears to be 70 (*Table 8.7, row No. 4*), which is the same value as in the previous calculation using the traffic distribution assuming queues.

### **8.1.3. Concluding remarks**

The examples in *Section 8.1* demonstrate the way safety indicators such as DV scores and OD scores can be applied. These examples are meant to clarify the procedures for calculating and interpreting these kinds of indicators. Of course, it still has to be verified whether these scores are related to conflict indicators and/or crash indicators (see *Sections 8.2/8.3*).

The examples show that adapting the set of weights affects the DV and OD scores. Adapting the traffic distribution has a noticeable effect on the OD score. Another result is that the fastest route is not always the route with the best DV score. The route attracting most traffic (within the OD) is not always the route with the best DV score either.

The observed route choice cannot directly be explained by the calculated travel times (assuming an empty network). It is quite certain that the queues on some routes 'force' drivers to choose another route. This alternative route is not necessarily the route with a high DV score.

## **8.2. Approach, methodological issues and description of data**

The route criteria and the scores derived from these criteria are presented in *Chapter 4*, and have been demonstrated in *Section 8.1*. It has to be shown whether these types of safety indicators (hereafter called *DV indicators*) are related to other safety indicators, in particular crash numbers. The ins and

outs of the quantitative relationships between crash numbers and conflict numbers were shown in *Section 7.2*. Showing a direct relationship between crash numbers and DV indicators in a similar way is hardly possible. That is because the crash numbers for individual routes are very insignificant: solid quantitative relationships can therefore not be established. To bypass this problem, the relationships between conflict numbers and DV indicators will be examined. If these types of relationships appear to be strong, then the existence of a relationship between DV indicators and crash numbers is plausible.

The data about DV indicators and other route characteristics will also be used to analyse general assumptions regarding the safety of routes and route choice.

This section will deal with describing the data (sets), formulating hypotheses, and discussing some methodological issues.

### 8.2.1. Description of the data

Some of the data are the output of the micro-simulation model: these (dynamic) data are the averages of ten runs. They are data about the number of vehicles per route and per road section, the vehicle movements (in particular near intersections), the actual travel times, the departure and arrival times, and the driving speeds. The other data have been calculated using the previous data as input; *Table 8.8a and 8.8b* show these 'other' data. The conflicts on the intersections can be divided into frontal, longitudinal (rear-end), transversal (lateral), and converging conflicts (*Section 6.4, Figure 6.8*). For the analysis, it is relevant to focus on conflicts that involve vehicles following the route. For a transversal (lateral) conflict, it is always certain that one of the vehicles is following the route to be analysed. For this reason, the following analyses will be limited to these lateral conflicts.

Variable name	Description
Origin	Identification number of Origin zone
Destination	Identification number of Destination zone
Volledig	Are Origin and Destination both within the study area?
NRoutes	Number of routes (being used) within the OD
DVtotaal	DV score ( <i>Formula 6.3</i> )
DVtotaalSTD	Standardized DV score ( <i>Formula 6.9</i> )

**Table 8.8a.** Variables regarding OD pairs

Variable name	Description	Std
Origin	Identification number of Origin zone	
Destination	Identification number of Destination zone	
DVTrap	All road classes from Origin to Destination	
RouteNR	Route identification number	
Voertuigen	Number of vehicles using the route (during the simulation)	
AantalOvergangen	Number of transitions within a route	
AantalOvergangenMax	Maximum number of transitions within the OD pair	
Vtgkm	Number of vehicle kilometres	
ExtraOvergangen	Number of additional transitions	+
FouteOvergangen	Number of wrong transitions	+
OntbrekendeCategorien	Number of missing transitions	+
Lengte	Length of a route [meters]	+
ETW_Lengte	Length of the road class ETW (access roads)	+
GOW_Lengte	Length of the road class GOW (distributor roads)	+
Reistijd_model	Travel time during simulation	
Reistijd_Ideaal	Travel time in an empty network (given speed limits and road lengths)	+
KpGowTot	Number of intersections on the GOWs along a route	
KpGowVRI	Number of signalized intersections KpGowTot	
Kruispunt dichtheid	Number of KpGowTot per route length	+
Linksaf	Number of left turns	+
Conflicts	Number of conflicts on the intersections along a route	
Crashes	Number of crashes on the intersections along a route	
DV score	DV score ( <i>Formula 6.1</i> )	+
Voertuigaandeel	Number of vehicles using a route related to the total number of vehicles using the OD [%]	

**Table 8.8b.** Variables regarding routes; a '+' in the column 'Std' means that this variable is also available as a standardized variable, e.g. to put together a route star

Three types of routes can be distinguished:

1. Routes with both origin and destination within the study area.
2. Routes with only origin or destination within the study area.
3. Routes with neither origin nor destination within the study area.

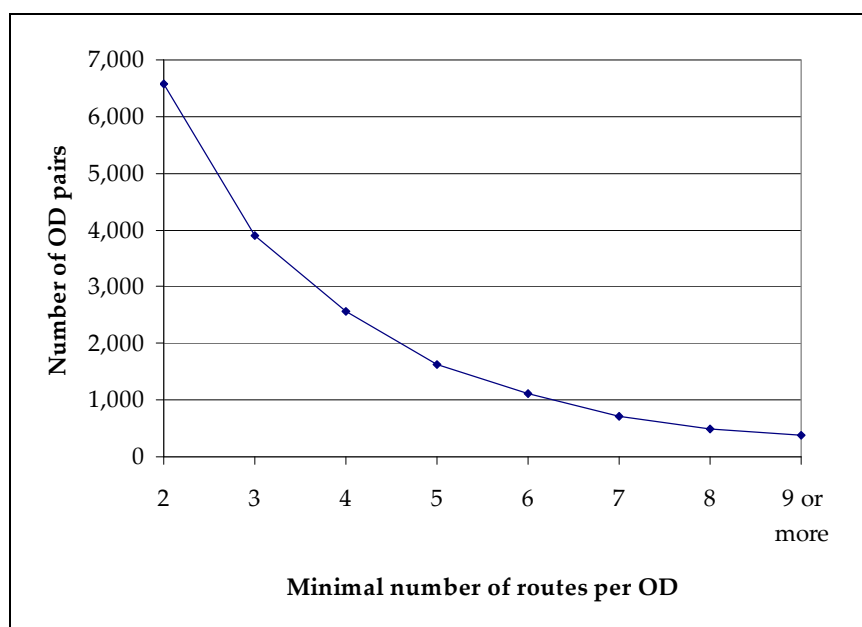
For the analyses, the route characteristics of the whole route are needed, from origin to destination. These data are only available for the first type of routes. That is why the analyses in this report only deal with 'type 1' routes (belonging to 11,659 OD pairs).

Another restriction is made for OD pairs only having one route. Within such a type of OD pair, it is obviously not possible to make a route choice. Therefore, these 5,078 OD pairs are also left out of the analyses.

The number of OD pairs with at least two routes and with both origin and destination within the study area amounts to 6,581. The total number of routes belonging to these OD pairs is 25,181; the resulting average number of routes per OD pair is 3.83.

In *Figure 8.5* the number of OD pairs is a function of the minimal numbers of routes per OD pair. The number of OD pairs given their number of routes is shown in *Table 8.9*.

For this network, the maximum number of routes observed within an OD pair is 34 routes.



**Figure 8.5.** Minimal numbers of routes per OD pair



Number of routes per OD pair	Number of OD pairs
2	2,685
3	1,328
4	933
5	523
6	395
7	218
8	129
9 or more	370
Total number	6,581

**Table 8.9.** Number of OD pairs given the number of routes within the OD pair

### 8.2.2. Formulation of hypotheses

The hypotheses for analysing the routes and OD pairs focus on numbers of conflicts and on DV scores.

The most important hypotheses relate to the Sustainable Safety requirement: the shortest route should also be the safest route. The hypothesis is that within an OD pair the route with the shortest travel time will have the lowest safety indicator. In this analysis the safety indicator can be:

1. Number of conflicts.
2. Number of conflicts per kilometre (conflict density).
3. Number of conflicts per vehicle kilometre (conflict risk).

The following hypotheses relate to the DV scores. A hypothesis is formulated for the routes within an OD pair. Mind that a higher DV score is equivalent to a higher safety level.

4. The higher the DV score, the higher the vehicle flow on the route: the more vehicles on a route, the better facilities on that route.
5. The higher the DV score, the shorter the route length: that is because the shorter a route, the fewer irregularities may occur.
6. The higher the DV score, the lower the number of intersections: the safety of a route is largely determined by the number of intersections.
7. The higher the DV score, the shorter travel time: this is similar to the one regarding travel time and number of conflicts.
8. The higher the DV score, the lower the number of left turns.

9. The higher the DV score, the lower the number of intersections per kilometre:
10. The higher the DV score, the lower the number of conflicts.
11. The higher the DV score, the lower the number of conflicts per kilometre.
12. The higher the DV score, the lower the number of conflicts per vehicle kilometre.

The routes differ in length: the shortest route amounts to 62 metres (!), the longest one to 23.9 kilometres. The shorter routes may differ from the longer ones, since they might miss essential route characteristics. Therefore, the next hypothesis is:

13. Hypothesis 10 can best be tested for longer routes instead of all 25,181 routes.

These thirteen hypotheses will be tested according to a procedure explained in *Section 8.2.4*.

### **8.2.3. Varying the DV scores**

The DV scores for the hypotheses in *Section 8.2.2* are calculated according to *Formula 6.8*, using equal weights for all criteria. However, it is very likely that the criteria are not equally important regarding their relationship with the safety indicators. That is why a series of DV scores will be tested. These DV scores are listed in *Table 8.10*. The scores DV1 to DV7 are meant to test whether the systematic addition of a criterion gradually produces a better result. DV8 and DV9 are intended to test the assumption that the number of left turns and the intersection density are strongly related to the conflict indicators. The wghDV score was introduced in *Section 8.1*.

	DV	wgh DV	DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DV9
Number of transitions	0,11	0.11	1.00	0.50	0.33	0.25	0.20	0.17	0.14	0.00	0.00
Nature of transitions	0,11	0.11	0.00	0.50	0.33	0.25	0.20	0.17	0.14	0.00	0.00
Missing road categories	0,11	0.11	0.00	0.00	0.33	0.25	0.20	0.17	0.14	0.00	0.00
Proportion of access roads	0,11	0.05	0.00	0.00	0.00	0.25	0.20	0.17	0.14	0.00	0.00
Proportion of distributors	0,11	0.12	0.00	0.00	0.00	0.00	0.20	0.17	0.14	0.00	0.00
Travel distance [kilometres]	0,11	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.14	0.00	0.00
Travel time [minutes]	0,11	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00
Left turns	0,11	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00
Intersection density (per km)	0,11	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.00
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

**Table 8.10.** Criteria with different weights, resulting in a series of DV scores (The wghDV score is also listed in *Table 8.3*)

#### 8.2.4. How the hypotheses are tested

Most of the hypotheses are tested in two ways. The first is to compare different combinations of two routes within an OD pair. For instance, if an OD pair has three routes numbered 1 to 3, then routes 1 and 2 are compared, routes 2 and 3, and routes 1 and 3. For each comparison, the result will be a 'yes' or 'no' as the answer to the question whether the hypothesis is true. The number of tests is added up as well as the number of affirmative and negative answers. The total number for 'yes', related to the total number of tests is the input for a binomial test. A hypothesis which is tested for more than 10,000 cases is taken to be 'true' when at least 50.1 % of the answers are 'yes'.

The second way of testing the hypotheses is to perform a regression analysis for all routes within an OD pair. The most important element in this regression analysis is the *slope* of the tangent line. A hypothesis such as 'if A is bigger, then B is also bigger' will have a positive slope, while a hypothesis such as 'if A is bigger, then B is smaller' will have a negative slope.

These regression analyses are applied to the OD pairs having a maximum of eight routes. The remaining 370 OD pairs (with nine or more routes) are put aside because their contribution to the total result will be small while the calculation procedure will become more and more complicated.

Again, the hypothesis is true when the number of negative or positive slopes (depending on the type of hypothesis) related to the total number of tested OD pairs is more than 50.1%.

The first way of testing is applied to all hypotheses; the second way is applied to a selected number of hypotheses.

### **8.3. Analysing scores, numbers of conflicts, and travel times**

The hypotheses formulated in *Section 8.2* will be tested below, by pair-wise comparisons first, followed by the regression analyses.

#### **8.3.1. Pair-wise comparisons**

The pair-wise comparisons are meant to gain a clear insight into the mutual relationships between the routes within an OD pair. Not all routes within an OD pair are compared to each other. The comparisons are structured according to the system in *Table 8.11*: consecutive routes ( $i+1$  and  $i$ ) are compared to each other as well as routes  $i+2$  and  $i$  ( $i \leq 9$ ). This limitation has a merely practical motivation: to reduce the number of operations. However, this approach still results in many comparisons, more than enough for executing the binomial tests satisfactorily.

A methodological drawback to this procedure regards routes that are included in two or more tests. This can be observed in *Table 8.11*: e.g., route 1 (in OD pair A -B) is involved in two tests. Therefore, these tests are not considered completely independent. To check the effect of this dependency, the sequence of the routes within an OD pair was randomly changed in some tests (at the end of *Section 8.3.1*).

A second drawback regards routes that have some road sections in common: the overlapping of routes. This will also harm the assumption of independency in a statistical test. On the other hand, from a traffic and transport point of view the entire route has to be considered instead of only part of it. Although consideration of a shorter part may result in the desired independency (of another part of another route), the essence of the route

concept is that the route should be treated with all its characteristics. That is why the routes are analysed in their entirety, not as parts.

The regression analyses in *Section 8.3.2* are meant to partially overcome these drawbacks. The results of the pair-wise comparisons are expressed as percentages; the hypothesis is true if the percentage is at least 50.1 (*Section 8.2.4*).

Row number	OD pair	Route, serial number	Comparing routes
1	A - B	1	-
2	A - B	2	2 to 1
3	A - B	3	3 to 2 and 3 to 1
4	A - B	4	4 to 3 and 4 to 2
5	A - B	5	5 to 4 and 5 to 3
6	A - B	6	6 to 5 and 6 to 4
7	A - B	7	7 to 6 and 7 to 5
8	A - B	8	8 to 7 and 8 to 6
9	A - B	9	9 to 8 and 9 to 7
10	A - B	10	10 to 9
11	A - B	11	11 to 10
12	A - B	i+1	i+1 to i
13	A - C	1	-
14	A - C	2	2 to 1
15	A - C	3	3 to 2 and 3 to 1

**Table 8.11.** Procedure for testing routes

### Hypothesis 1, 2, and 3

These hypotheses are relevant to the Sustainable Safety requirement 'the shortest route should be the safest route'. The procedure for testing routes was different from the procedure depicted in *Table 8.11*. For the following procedure, only OD pairs were analysed having no more than five routes. *Table 8.12a* shows the results for travel time in an empty network. Only hypothesis 1 (number of conflicts) can be confirmed. The hypotheses for conflict density and the conflict risk cannot be confirmed.

An additional test was performed for travel time in the model related to the conflict risk; this test did not confirm the hypothesis either (*Table 8.12b*).

Travel time in empty network	Number of route pairs tested	Hyp. 1 (conflicts)	Hyp. 2 (conflict density)	Hyp. 3 (conflict risk)
OD pairs with 2 or 3 routes	4,013	59	41	49
OD pairs with 2, 3 or 4 routes	4,946	56	38	46
OD pairs with 2, 3, 4 or 5 routes	5,469	55	40	46

**Table 8.12a.** Results for hypotheses 1, 2, and 3 (percentages 'true' of the total number of tests)

Travel time in model	Number of route pairs tested	Hyp. 3 (conflict risk)
OD pairs with 2 or 3 routes	4,013	39
OD pairs with 2, 3 or 4 routes	4,946	35
OD pairs with 2, 3, 4 or 5 routes	5,469	37

**Table 8.12b.** Results for hypothesis 3, (percentages 'true' of the total number of tests)

### Hypotheses 4 to 13

Hypotheses 4 to 13 have been tested for both DV score and wghDV score. The tests in *Table 8.13a* follow the procedure according to *Table 8.11*. The test for hypothesis 7 (*Table 8.13b*) follows a procedure analogously to the tests for hypotheses 1 to 3.

All hypotheses are accepted. The tests with the highest 'true' values can be found for hypotheses 6 (both scores), and 5 (DV score). The difference between the DV score and the wghDV score for hypothesis 5 can be explained by the weight for the criterion 'route length'. The DV score has a weight of 0.11 for this criterion while the wghDV score has a weight of 0.0. So, the influence of length is much smaller for the wghDV score, resulting in fewer 'true' outcomes for hypothesis 5.

The hypotheses regarding the safety indicators (10 to 13) show the best results for the number of conflicts (DV score) and the conflict risk (wghDV score). The results are satisfactory for both score types (DV and wghDV). This will be elaborated in *Section 8.3.2*.

Hypothesis 13 is accepted, although resulting in the same percentage as the corresponding test with all routes. So the longer routes do not differ from the whole set of routes.

Hypothesis	Test results	
	DV score	wghDV score
4 (vehicle flow)	63	61
5 (route length)	72	56
6 (number of intersections)	79	79
8 (number of left turns)	53	57
9 (intersection density)	54	60
10 (number of conflicts)	67	65
11 (conflict density)	57	63
12 (conflict risk)	62	67
13 (longer routes)	67	-
Number of route pairs tested (for hypothesis 13: 13,397 routes)	28,077	28,528

**Table 8.13a.** Results for hypotheses 4 to 13, except for hypothesis 7: see *Table 8.13b* (percentages that verify the hypothesis)

	Number of route pairs tested	DV score	wghDV score
OD pairs with 2 or 3 routes	4,013	75	62
OD pairs with 2, 3 or 4 routes	4,946	73	58
OD pairs with 2, 3, 4 or 5 routes	5,469	69	56

**Table 8.13b.** Results for hypothesis 7 (percentages that verify the hypothesis)

In a second test procedure, the original sequence of routes within an OD pair was changed in order to find any effect on the test results. The effect on the test results appeared to be very small, however. There may be an effect of routes taking part in two or more tests, however, this effect could not be found in repeating the tests after changing the sequence of routes within the OD pair.

### Alternative DV scores

The original DV score is split up systematically into scores with different weights. The results of the DV score and wghDV score for the hypotheses 10 - 12 are compared with the results of the DV1 - DV9 scores; see *Table 8.14*. Only the DV8 score and DV9 score show a somewhat better result than the

(wgh)DV scores. The good results for the DV9 score are remarkable, considering that this score only consists of one criterion (intersection density). The DV9 score will, therefore, be looked at more thoroughly in the next section.

Type of score	Criteria or criterion	Number of route pairs tested	Hyp. 10 (conflicts)	Hyp. 11 (conflicts density)	Hyp. 12 (conflict risk)
DV	all	28,077	67	57	62
wghDV	all but crtn. 6	28,528	65	63	67
DV1	crtn. 1	700	58	52	45
DV2	crta. 1 - 2	3,441	45	38	25
DV3	crta. 1 - 3	5,359	48	54	53
DV4	crta. 1 - 4	27,356	46	52	58
DV5	crta. 1 - 5	14,148	53	59	62
DV6	crta. 1 - 6	28,193	60	50	53
DV7	crta. 1 - 7	28,161	61	49	53
DV8	crta. 8 - 9	26,928	64	67	67
DV9	crtn. 9	27,486	65	69	70

**Table 8.14.** Results for hypotheses 10, 11, and 12 (percentages that verify the hypothesis)

Compared to other score types, the numbers of route pairs tested for DV1 to DV3 are rather low (*Table 8.14*). This is caused by the high number of OD pairs showing exactly the same score for all routes. These OD pairs are left out of the testing procedure resulting in rather low numbers for the test.

### **Additional DV scores**

Within each DV score in *Table 8.10* and *Table 8.14*, except for wghDV, the weights are equal. Choosing different weights within a score could improve the results, as the wghDV score shows. The DV5 score represents the five criteria for the entire route diagram. Three scores (DV51 - DV53) were derived from DV5 by varying the weights; see *Table 8.15*. The DV8 score is based on two crash indicators. Two additional scores, DV81 and DV82, give more weight to one of these indicators; see *Table 8.15*.



	DV51	DV52	DV53	DV81	DV82
Number of transitions	0.26	0.12	0.12	0.00	0.00
Nature of transitions	0.26	0.12	0.12	0.00	0.00
Missing road categories	0.26	0.12	0.12	0.00	0.00
Proportion of access roads	0.11	0.32	0.12	0.00	0.00
Proportion of distributors	0.11	0.32	0.52	0.00	0.00
Travel distance [kilometres]	0.00	0.00	0.00	0.00	0.00
Travel time [minutes]	0.00	0.00	0.00	0.00	0.00
Left turns	0.00	0.00	0.00	0.25	0.75
Intersection density (per km)	0.00	0.00	0.00	0.75	0.25
Sum	1.00	1.00	1.00	1.00	1.00

**Table 8.15.** Additional criteria with different weights, resulting in a series of DV scores

Consequently, these DV scores were tested according to the same procedure as the other DV scores; the results are shown in *Table 8.16*. Related to the percentages for DV5 (*Table 8.14*), the tests for DV51 to DV 53 do not result in any improvements.

The DV81 score proves to be somewhat better than the DV8 score.

Type of score	Criteria or criterion	Number of route pairs tested	Hyp. 10 (conflicts)	Hyp. 11 (conflicts density)	Hyp. 12 (conflict risk)
DV51	crt. 1 - 5	13,111	52	57	58
DV52	crt. 1 - 5	15,410	53	58	63
DV53	crt. 1 - 5	28,071	52	54	50
DV81	crt. 8 - 9	27,971	65	68	69
DV82	crt. 8 - 9	27,828	62	63	64

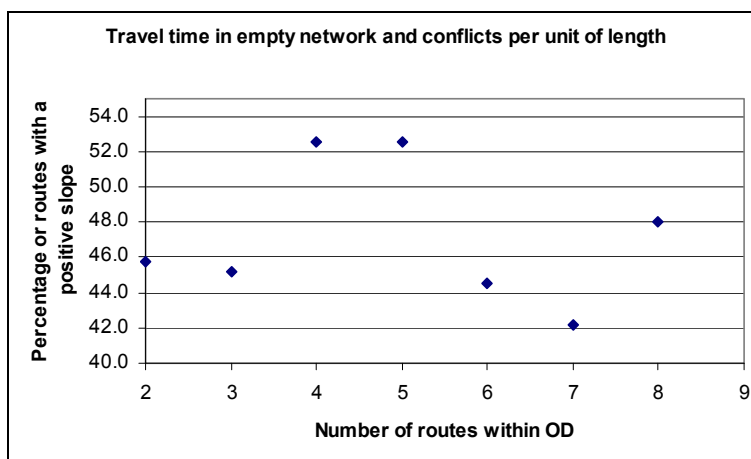
**Table 8.16.** Results for hypotheses 10, 11, and 12 (percentages that verify the hypothesis)

### 8.3.2. Regression analysis

The regression analyses, as described in *Section 8.2.4*, will be applied to the most important hypotheses, in particular hypothesis 1 (travel time, conflicts), 7 (DV score, travel time), 10 (DV score, conflicts), 11 (DV score, conflict density), and 12 (DV score, conflict risk).

Number of routes within OD pair	Is the slope according to hypothesis 1?
2	45.8
3	45.2
4	52.5
5	52.6
6	44.6
7	42.2
8	48.1
2 - 8	47.1

**Table 8.17a.** Variable Travel time in empty network, results for hypothesis 1



**Figure 8.6.** Percentage of OD pairs with a positive slope, for different numbers of routes per OD pair

Starting with hypothesis 1, both travel time indicators will be analysed: 'travel time in empty network' and 'travel time in model'. *Table 8.17a* contains the percentages of OD pairs with a *positive* slope, for each number of routes per OD pair. All of these percentages are below 50.0 percent, except for the OD pairs with four and five routes; see also *Figure 8.6*.

The analyses for 'travel time in model' result in percentages of the same size, showing only one (six routes) above 50.0 percent (*Table 8.17b*).

Given these results, the conclusion must be that hypothesis 1 has to be rejected for both variables. Of course, these are the results for the current network. Changing the network in the right direction may improve the results.

Number of routes within OD pair	Is the slope according to hypothesis 1?
2	47.2
3	47.3
4	49.5
5	43.6
6	51.1
7	43.1
8	38.0
2 - 8	47.2

**Table 8.17b.** Variable travel time in model, results for hypothesis 1

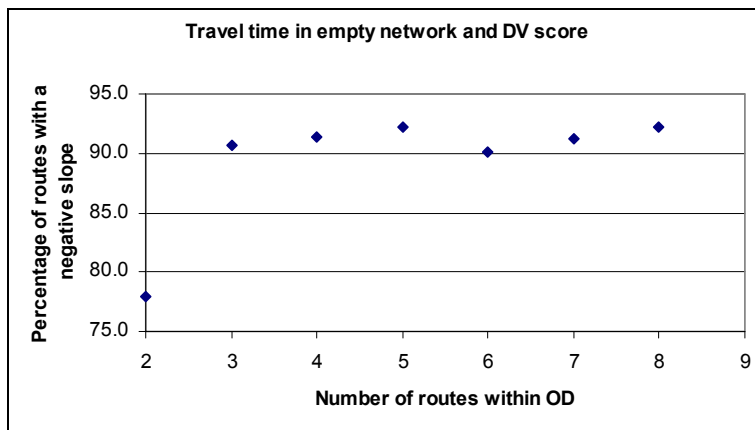
The analyses for hypothesis 7 appear to give much better results, both for DV score and wghDV score. In *Table 8.18a* the percentages for the negative slopes are all more than 50.0 percent; see also *Figure 8.7*.

The results for the wghDV score are also satisfying (*Table 8.18b*) although the percentages are somewhat lower than for the DV score.

Hypothesis 7 is accepted for both variables – DV score and wghDV score. The outcome is that the network is functioning according to the Sustainable Safety requirement 'shortest route must coincide with the safest route'.

Number of routes within OD pair	Is the slope according to hypothesis 7?
2	77.9
3	90.7
4	91.4
5	92.2
6	90.1
7	91.3
8	92.2
2 - 8	85.4

**Table 8.18a.** Variable DV score, results for hypothesis 7



**Figure 8.7.** Percentage of OD pairs with a negative slope, for different numbers of routes per OD pair

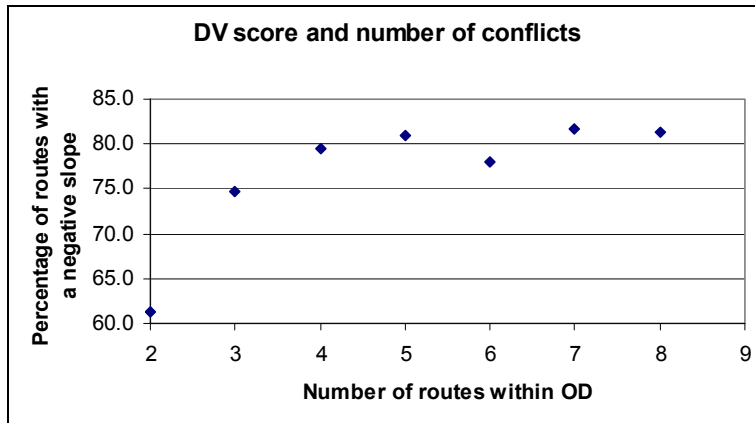
Number of routes within OD pair	Is the slope according to hypothesis 7?
2	67.7
3	68.2
4	68.7
5	69.8
6	65.1
7	67.4
8	69.0
2 - 8	68.0

**Table 8.18b.** Variable wghDV score, results for hypothesis 7

The next hypotheses 10, 11 and 12 are dealing with the relationships between the DV score types and the conflict safety indicators. Hypothesis 10 was tested for DV score and wghDV score. The resulting percentages of OD pairs with negative slopes are summed up in *Table 8.19* as well as in *Figure 8.8* (regarding the DV score). Both score types show percentages far above 50%. This hypothesis is therefore accepted.

Number of routes within OD pair	DV score	wghDV score
2	61.3	64.3
3	74.8	74.5
4	79.5	77.7
5	80.9	77.1
6	78.0	76.7
7	81.7	79.4
8	81.4	82.9
2 - 8	70.8	71.3

**Table 8.19.** Results for hypothesis 10 (number of conflicts)

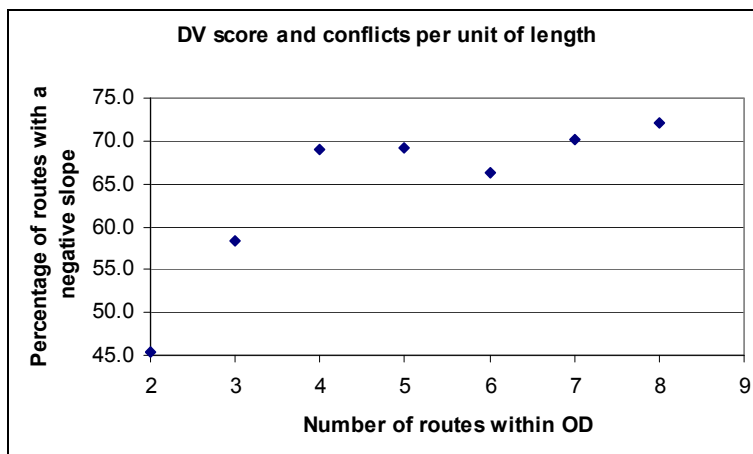


**Figure 8.8.** Percentage of OD pairs with a negative slope, for different numbers of routes per OD pair

The results for hypothesis 11 are put into *Table 8.20* (DV score and wghDV score) and *Figure 8.9* (DV score). The percentages are above 50 percent, except for the DV score of an OD pair with two routes. This hypothesis is accepted as well.

Number of routes within OD pair	DV score	wghDV score
2	45.5	62.6
3	58.3	67.0
4	68.9	74.2
5	69.2	75.0
6	66.3	77.2
7	70.2	77.5
8	72.1	84.5
2 - 8	56.5	68.2

**Table 8.20.** Results for hypothesis 11 (number of conflicts per unit of length)

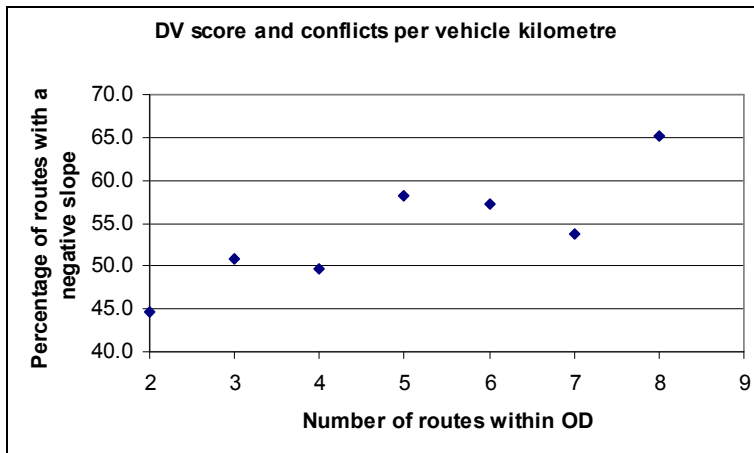


**Figure 8.9.** Percentage of OD pairs with a negative slope, for different numbers of routes per OD pair

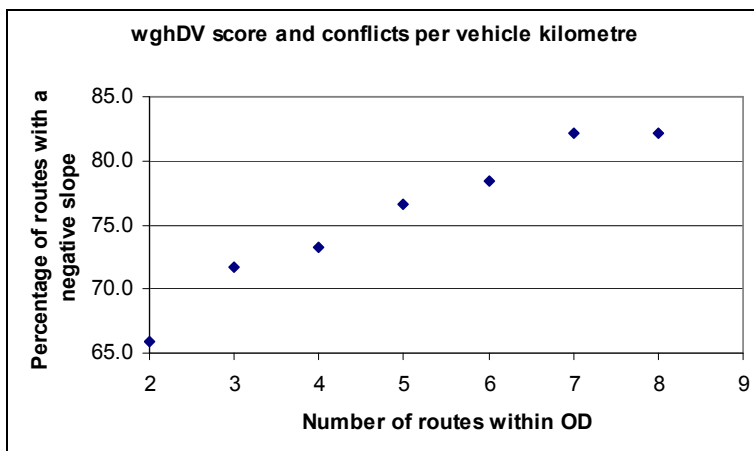
Finally, hypothesis 12 is tested for three score types: DV score, wghDV score and DV9 score. *Section 8.3.1* learned that the DV9 score had a good result for pair-wise comparisons. Possibly this good result will show up in the regression analysis as well. *Table 8.21a* contains the percentages of OD pairs with a negative slope. *Figures 8.10, 8.11 and 8.12* also depict the results. The DV scores do not perform very well. The wghDV score and DV9 score perform much better. The results for the DV9 score, however, are not better than for the wghDV score. The hypothesis is accepted for both the wghDV score and the DV9 score.

Number of routes within OD pair	DV score, 6,211 OD pairs	wghDV score, 6,211 OD pairs	DV9 score, 6,211 OD pairs
2	44.7	65.9	63.8
3	50.8	71.8	70.9
4	49.7	73.3	72.6
5	58.1	76.7	74.4
6	57.2	78.5	78.2
7	53.7	82.1	83.0
8	65.1	82.2	77.5
2 - 8	49.4	70.9	69.4

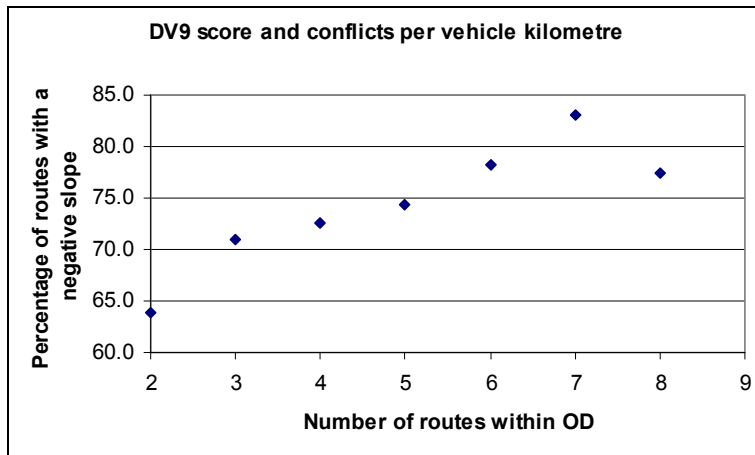
**Table 8.21a.** Results for hypothesis 12 (number of conflicts per vehicle kilometre)



**Figure 8.10.** Percentage of OD pairs with a negative slope, for different numbers of routes per OD pair



**Figure 8.11.** Percentage of OD pairs with a negative slope, for different numbers of routes per OD pair



**Figure 8.12.** Percentage of OD pairs with a negative slope, for different numbers of routes per OD pair

Looking at the results for the DV score more closely, the OD pairs with two routes appear to have a high share of OD pairs with a horizontal slope (15% of 2,685 routes). This percentage is much higher than in the other analyses (mostly around 1 percent). If these OD pairs with a horizontal slope are left out of the analyses, then the percentage of routes with negative slopes rises from 44.7 to 52.6 (*Table 8.21b*). The percentage for all OD pairs (2 to 8 routes) rises from 49.4 to 53.1 percent. In this way, the hypothesis can also be accepted for the DV score. Leaving out the OD pairs with horizontal slopes hardly affects the percentages for wghDV score (*Table 8.19b*).

Number of routes within OD pair	DV score, 5,776 OD pairs	wghDV score, 6,188 OD pairs
2	52.6	66.2
3	51.5	72.0
4	50.0	73.5
5	58.2	76.8
6	57.7	79.1
7	53.7	82.1
8	65.1	82.2
2 - 8	53.1	71.2

**Table 8.21b.** Results for hypothesis 12 (number of conflicts per vehicle kilometre): excluding slopes of which the coefficient equals 0



## R<sup>2</sup> values

The R<sup>2</sup> values of the previous regression analyses have been summarized in *Table 8.22*. The value for OD pairs with two routes is always 1.00: these values have not been added to *Table 8.22*. The R<sup>2</sup> values include OD pairs with negative, positive and horizontal slopes. The information regarding the R<sup>2</sup> values is taken from the previous tables mentioned in *Table 8.22*.

The focus is on the eight hypotheses that were accepted (*Table 8.22, third row*). If the regression analyses show a low share of R<sup>2</sup> values smaller than 0.4, then the acceptance of the hypothesis is given a firmer foundation. This share ranges from 27.0 percent (hypothesis 7, DV score) to 61.4 percent (hypothesis 10, wghDV score); see *Table 8.22, bottom row*.

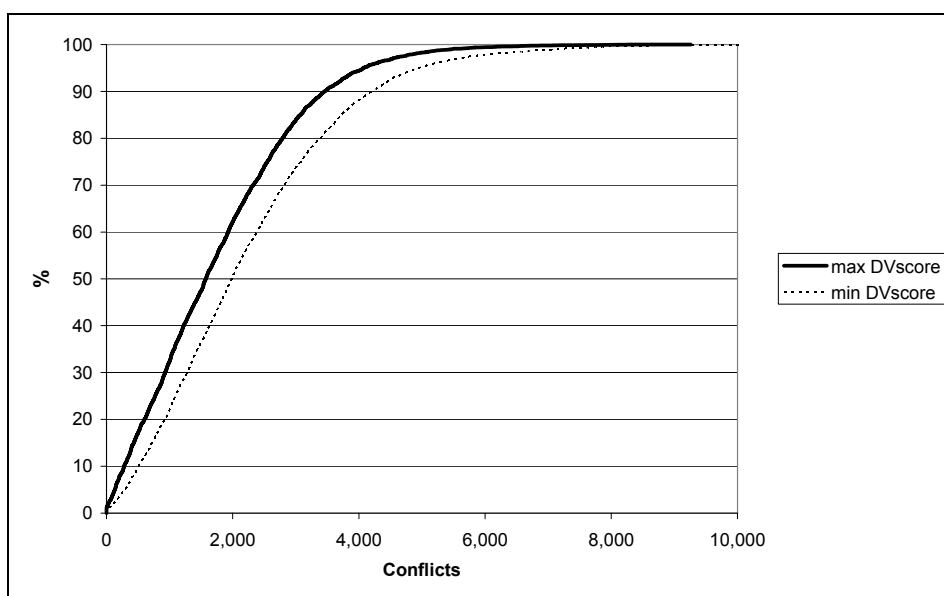
The highest shares are in hypothesis 10 (wghDV score), hypothesis 11 (DV score), and hypothesis 7 (wghDV score). The lowest shares regard hypothesis 7 (DV score) as well as hypothesis 12 (both DV9 score and wghDV score). The hypotheses with the lowest shares represent three different score types: DV, wghDV and DV9. Apparently these different types are, in their own way, relevant for indicating safety aspects of routes in an OD pair.

3,526 OD pairs, 3 ≤ routes ≤ 8	Table 8.17a	Table 8.17b	Table 8.18a	Table 8.18b	Table 8.19		Table 8.20		Table 8.21a		
Hypothesis	Hyp. 1	Hyp. 1	Hyp. 7	Hyp. 7	Hyp. 10		Hyp. 11		Hyp. 12		
Accepted?	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Variable 1	Travel time	Travel time	DV score	wghDV score	DV score	wghDV score	DV score	wghDV score	DV score	wghDV score	DV9 score
Variable 2	Conflict density		Travel time		Conflicts		Conflict density		Conflict risk		
R <sup>2</sup> > 0.95	13.4	7.0	18.9	10.9	12.4	7.6	7.3	16.1	7.9	16.0	26.8
0.75 < R <sup>2</sup> ≤ 0.95	20.5	12.0	28.6	16.8	21.3	12.5	12.6	22.3	12.5	23.2	21.5
0.4 < R <sup>2</sup> ≤ 0.75	22.4	23.2	25.4	25.6	26.3	18.5	21.7	23.7	20.5	24.5	20.1
R <sup>2</sup> ≤ 0.4	43.6	57.8	27.0	46.7	40.0	61.4	58.3	38.0	59.1	36.3	31.7
Sequence R <sup>2</sup> ≤ 0.4	-	-	1	6	5	8	7	4	-	3	2

**Table 8.22.** R<sup>2</sup> values for the OD pairs involved in the previous analyses (presented in *Tables 8.17a to 8.21a*)

### 8.3.3. Comparing minimum and maximum scores within an OD pair

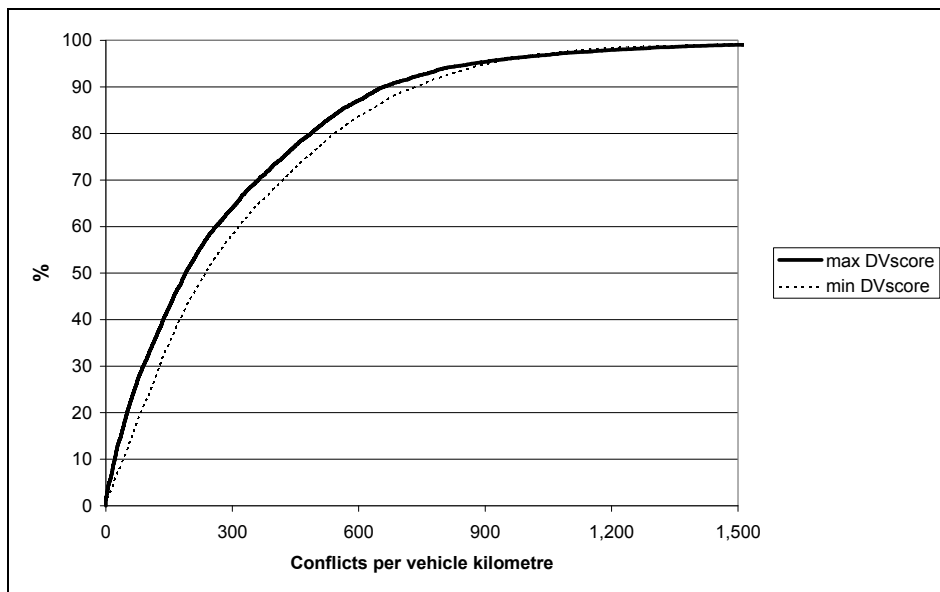
A final analysis focuses on the differences within each O-D pair between the route with the lowest DV score (minimum score) and the route with the highest DV score (maximum score). The hypothesis is that the number of conflicts for all minimum scores should be lower than the number of conflicts for all maximum scores. For that purpose the distribution of the numbers of conflicts is calculated for both the minimum scores and the maximum scores; see *Figure 8.13a*. The difference between both distributions is tested using the Kolmogorov-Smirnov test. The difference between the maximum and minimum scores is significant at confidence levels higher than 99%.



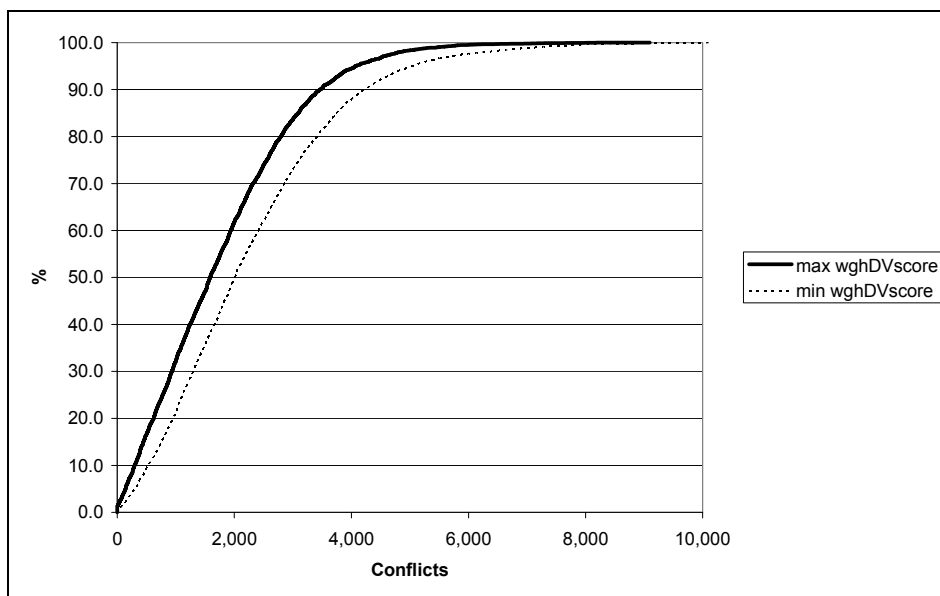
**Figure 8.13a.** Distribution of the number of conflicts regarding minimum and maximum DV scores within an OD pair

The same test procedure is used for the numbers of conflicts per vehicle kilometre (*Figure 8.13b*). This results in significance at confidence levels higher than 99%.

The difference between the two distributions of numbers of conflicts is also tested for the routes with a minimum or maximum wghDV score (*Figure 8.14*). The outcome shows significance at confidence levels higher than 99%.



**Figure 8.13b.** Distribution of the number of conflicts per vehicle kilometre (conflict risk), regarding minimum and maximum DV scores within an OD pair



**Figure 8.14.** Distribution of the number of conflicts regarding minimum and maximum wghDV scores within an OD pair

*Appendix B* presents more information about these comparisons. *Figure B.1* regards the number of conflicts per unit of length (conflict density); *Figure B.2a* and *Figure B.2b* regard the maximum and minimum wghDV scores for conflict density and for conflict risk respectively. The differences between the two distributions show the same outcome levels as the aforementioned tests. The conclusion of the tests is that a higher DV score (or a higher wghDV

score) is related to a lower number of conflicts, to a lower conflict density, and to a lower conflict risk.

## 8.4. Conclusions

The examples in *Section 8.1* demonstrate the way safety indicators such as DV scores and OD scores can be applied. These examples are meant to clarify the procedures for calculating and interpreting these kinds of indicators. The examples show that adapting the set of weights affects the DV and OD scores. Adapting the traffic distribution has a noticeable effect on the OD score. Another result is that the fastest route is not always the route with the best DV score. The route attracting most traffic (within the OD) is not always the route with the best DV score either.

The observed route choice cannot directly be explained by the calculated travel times (assuming an empty network). It is quite certain that the queues on some routes 'force' drivers to choose another route. This alternative route is not necessarily the route with a high DV score. Whether the current network complies with the Sustainable Safety requirement 'the shortest route coincides with the safest route' depends on the safety criterion that is chosen. The requirement cannot be confirmed when conflict risk or conflict density are chosen as safety criteria. The opposite is true when the number of conflicts is taken as the safety criterion. *Chapter 10* will show whether changes in the network will affect traffic volumes and route choice, resulting in different test results.

An important finding regards the confirmation that both the DV score and wghDV score relate to the number of conflicts as well as to conflict density (higher score, fewer conflicts or lower conflict density). The wghDV score and the DV9 score are both related to conflict risk (higher score, lower risk). This implies an indirect relationship between the score types and the number of crashes because the number of conflicts is directly related to the number of crashes.

## 9. Integrated network design

The ultimate goal of this study is to show that, three factors interact and how they do so: road structure and road classification at the starting point, route choice as an intermediate factor and finally, the resulting road safety factor. Road structure and road classification can be influenced by spatial and infrastructural measures. Route choice can be influenced by spatial and infrastructural measures as well as by traffic management measures. The resulting *unsafety* should be as low as possible. Safety at the street level can also be improved by applying more detailed (mitigating) traffic measures.

*Chapter 9* will show a general approach to designing a road network structure that will serve transport demand and that, at the same time, can be assumed to be inherently safe. Whether this statement can be supported by empirical evidence will be shown in *Chapter 10*.

*Section 9.1 and 9.2* propose a procedure for designing the road network structure. A so-called network analysis - an important step in this procedure - was applied to the study area: the area between Noordwijk, Katwijk, Leiden and The Hague (*Section 9.3*). The network analysis gave some clues for adapting the road network. *Section 9.3* also selects the design variables (defined in *Section 9.2*) to be used for improving the network.

### 9.1. Integrated network design for improving road safety

A method for an integrated network design was described in *Section 3.1*; this method was introduced in Germany during the eighties (FGSV, 1988) and was recently improved (FGSV, 2008). Integrated network design is based on connecting housing clusters systematically, given a classification of these clusters and a classification of the connections (*Figure 3.4*).

#### 9.1.1. Connecting clusters

Dijkstra (2003) introduced a simplified classification of the clusters, using a classification according to the number of inhabitants (classes K1 to K5, K1 comprising clusters with the highest numbers of inhabitants, K5 with the lowest numbers). The clusters in a region are classified in such a way that each class is filled with at least one cluster. The next step is making the connections between the clusters. One option would be to connect all clusters with each other, not recognizing their importance or size. This would result in a situation in which a lot of road infrastructure is provided while the

volumes on most of these connections would be very low. To overcome this abundant use of connections the following clustering of the connections is used:

1. Between territories<sup>3)</sup> (national level)
2. Between neighbouring regions
3. Within a region
4. Between small clusters

According to the German guidelines (FGSV, 2008) each level of connection is supposed to have a specific road network. As Section 9.3 will show, this is currently not true for the Western part of the Netherlands.

The target of the proposed procedure is to connect clusters that are really related to each other. Two neighbouring clusters will mostly be closely related; connecting these clusters is justified. On the other hand, more distant clusters - not being large cities - will mostly not be closely related. Therefore a direct connection would be redundant. Following this general idea, the procedure is sketched in *Table 9.1*.

Level of connection	Connection between two clusters	
	Highest level on which two clusters will be usually connected. K(n+1) will be connected to the nearest K(n)	Level on which a connection will sometimes be important, especially if the <i>route factor</i> is greater than 1.5
Between territories, on national level	K1 - K1	
Between neighbouring regions	K1 - K2	All combinations except for K4 - K5 and K5 - K5
Within a region	K1 - K2, K1 - K3, K1 - K4 K2 - K2, K2 - K3, K2 - K4	K2 - K5, K3 - K3, K3 - K4, K3 - K5, K4 - K4
Between small clusters	K4 - K5	K5 - K5

K1 comprises clusters with the highest number of inhabitants; consequently K5 comprises clusters with the lowest number of inhabitants.

**Table 9.1.** Procedure for connecting clusters one by one (Dijkstra, 2010)

The procedure is meant to result in connections that have to be planned as a rule (second column in *Table 9.1*) – the so-called *desired connections*. In general, only the largest clusters are connected directly. If an existing route,

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<sup>3)</sup> Territory: a number of neighbouring regions, covering a substantial part of the country.

indirectly connecting two smaller clusters, is too long then an additional connection will be allowed. The criterion for 'too long' is the route factor (distance by road divided by the direct distance); the route factor should be 1.5 at most (Hummel, 2001; p. 10).

### **Example**

This procedure is illustrated by the example in *Appendix C*. This example considers three territories (separated by dotted lines in *Figure C.1*). Each territory (in this example) consists of four or five regions; only clusters of type K1 and K2 are shown. Each region contains at least one cluster of type K2. All clusters of type K1 are connected, as is shown in *Figure C.2*. *Figure C.3* shows how K1 - K2 and K2 - K2 are connected. Firstly, each K1 connects with the nearest K2s (regardless of the region). Secondly, a K2 is connected with all K2s within the same region. Thirdly, a connection between a K2 and a K2 in another region is only made directly if the route factor is larger than 1.5. Finally the direct connections between K1s are skipped if a route factor is smaller than 1.2 (e.g. the connection between the K1s in regions A and C).

*Figure C.4* gives an example of connecting K3 and K4 clusters to K1 and/or K2 clusters. This example focuses on region R and its neighbouring regions. Connections are desired between K1 - K3, K1 - K4, K2 - K3, and K2 - K4. A connection K3 - K3 is relevant if the route factor is larger than 1.5; the same is valid for K3 - K4. This procedure still results in some redundant connections; particularly connections that are nearly running parallel to each other. Therefore, a simplification of the network is shown in *Figure C.5*.

*Table 9.2* repeats the information given in *Table 9.1*. However, the clusters K1 to K5 are now handled as 'input' (in both rows and columns), and the levels at which a connection is desired as an 'output'. Eleven out of fourteen cells deal with the level 'within a region'. This stresses the importance of planning a separate regional road network.

Which clusters belong to the same region is a matter of politics, not a matter of transport planning. In some cases, natural borders will determine which clusters form a region.

	K1	K2	K3	K4	K5
K1	Always, except for <i>route factor</i> < 1.2	Between neighbouring regions Within a region	Within a region	Within a region	<i>indirectly</i>
K2	<i>see K1-K2</i>	Between regions if <i>route factor</i> > 1.5 Within a region	Within a region	Within a region	Within a region if <i>route factor</i> > 1.5
K3	<i>see K1-K3</i>	<i>see K2-K3</i>	Within a region if <i>route factor</i> > 1.5	Within a region if <i>route factor</i> > 1.5	Within a region if <i>route factor</i> > 1.5
K4	<i>see K1-K4</i>	<i>see K2-K4</i>	<i>see K3-K4</i>	Within a region if <i>route factor</i> > 1.5	Between small clusters
K5	<i>see K1-K5</i>	<i>see K2-K5</i>	<i>see K3-K5</i>	<i>see K4-K5</i>	Between small clusters if <i>route factor</i> > 1.5

**Table 9.2.** Desired connections between clusters K1 to K5

### 9.1.2. Road classification

The final step in the procedure is to determine which road classes have to be chosen for a given level of connection. According to FGSV (2008), this choice should also depend on the presence of a built-up environment (housing areas, shopping areas), and on the influence of the road environment (mainly through direct access). *Table 9.3* contains fourteen road classes for rural areas, transition areas and urban areas. Four out of fourteen road classes are situated in the rural area; two road classes are used for the transition area.

Note that the levels of connection for the urban area are described as connections between, or within, districts and within neighbourhoods.

The A-class is intended for rural areas, without any built-up environments nearby. This road class can be applied at all levels of connection. On this road class, the continuous flow of traffic is important. The B-class is available for other connections without any built-up environments nearby. This road class will preferably connect A-roads to C-roads. The B-class should only be



applied at the higher levels of connection; these roads are also aimed at a continuous traffic flow.

The other road classes (C, D and E) should be applied in urban areas. The C-class is very much like the B-class, except for the presence of a built-up environment (but without any direct influence of the road environment).

	Rural area	Transition area	Urban area			
Built environment	No		Yes (access to and from the connection)			
Any influence of road environment	None			Partly	Largely	
Level of connection, rural area						Level of connection, urban area
Between distant regions K1-K1	A1 (I)	B1 (I)	C1 (III)	D1 (III)	-	Between distant districts
Between neighbouring regions K1-K2	A2 (I)	B2 (I)	C2 (III)	D2 (III)	E2	Between neighbouring districts
Within a region K1-K2, K1-K3, K1-K4 K2-K2, K2-K3, K2-K4 K3-K3, K3-K4 (K2-K5, K3-K5, K4-K4)	A3 (II)	-	-	D3	E3	Within a district
Between small clusters K4-K5, (K5-K5)	A4 (II)	-	-	-	E4	Within a neighbourhood

A1 to E4: road classes; (I): set of requirements for that road class

**Table 9.3.** Desired road classes for each level of connection, given the presence of a built environment and the influence of the road environment (including the set of requirements for road classes A, B, C and D)

Each road class has to meet a specific set of requirements. For this study, the requirements for road classes A, B and C are relevant:

- I. Road for motor vehicles only (mostly motorway), grade-separated intersections, speed limits on class A, 100 or 120 kph, on class B, 70 or 80 kph;
- II. Main carriageway for motor vehicles only, intersections at grade, cyclists and pedestrians may cross at intersections, speed limit 80 kph;
- III. Motor vehicles separated physically from cyclists and pedestrians, intersections at grade, cyclists and pedestrians may cross at road sections as well as at intersections, speed limit 50 kph.

Designing a road class, recognising the requirements I to III, is the final step in the planning and design procedure. This step is not part of this study.

The missing step is how to move from the network of desired connections - described above - to a network that is also inherently safe; this step will be described in *Section 9.2*.

## **9.2. Designing a road network that is inherently safe**

*Section 9.2* will deal with the design variables for designing an inherently safe road network. These variables can be positioned on three levels:

- Network level
- Road class level
- Street level

The network level is mainly related to design variables determining the network structure. Design variables on the road class level are aimed at satisfying the road class requirements. Finally, the design variables at the street level focus on arriving at a detailed design of a street (road section and intersection) that meets the requirements for all types of road users and other users of the public space (in which the street is situated).

### **9.2.1. Network level**

The network structures that will result in *low numbers of crossings*<sup>4)</sup> were summarized in *Section 2.3*; these lower numbers should result in more road safety. Some of these structures also show short distances travelled, which is also good for road safety. In general, these structures should be chosen preferentially. However, in existing networks this will be rather difficult to attain.

The *intersection density* is a design variable that will determine the locations of intersections. This location partially depends on requirements and constraints regarding human factors (minimum sight distance, assumptions about reaction times, preventing a concentration of situations that need the drivers' attention). These implications should be evaluated at the street level.

The *mesh of roads*, especially of main roads, is a design variable that influences both the intersection density and the intersection types to be applied. On the other hand, the mesh partly depends on the distribution of homes and work places in a given area. However, some freedom in choosing the mesh remains. Too big a mesh will result in high volumes on the main

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<sup>4)</sup> Crossing with regard to vehicle paths that cross each other.

roads and much rat-run traffic on local roads. Too small a mesh will limit slow traffic crossing main roads. This last can be prevented by distributing car traffic more homogeneously over the network.

A second best option is to select a road classification system that will meet the safety requirements mentioned (crossing, distance travelled) to a large extent. The road hierarchy is very important for classifying roads. Two main approaches can be distinguished (*Chapter 3*):

1. a purely hierarchical approach with a logical sequence of road classes (Swedish SCAFT);
2. a structure stemming from the existing spatial distribution of homes and work places in an area (German RAS-N/RIN).

A strictly hierarchical structure is sometimes of too theoretical a nature to be applied in practice.

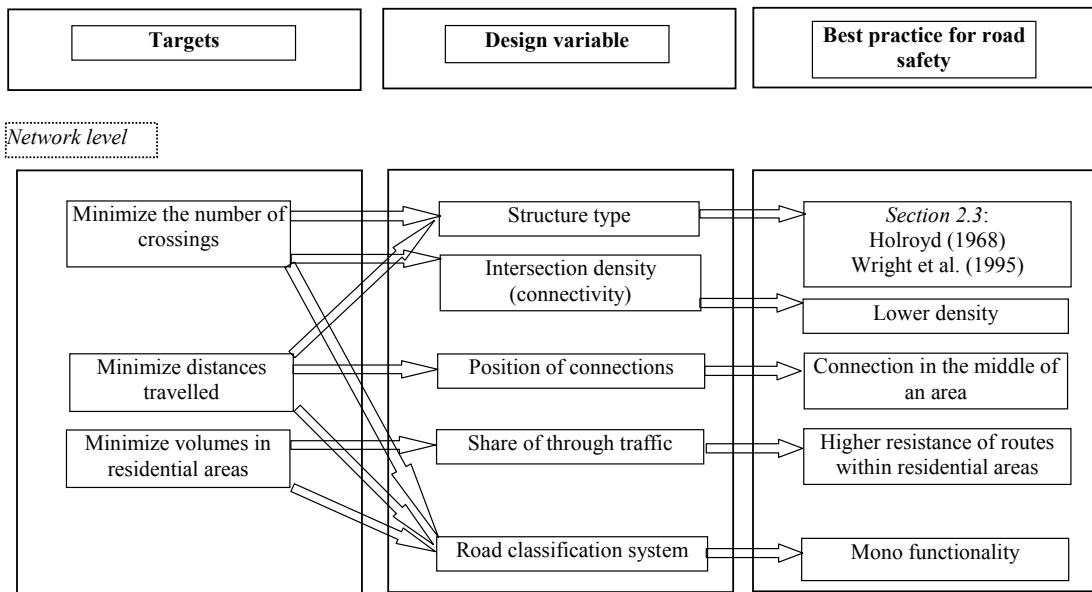
A third target at this level is the minimization of traffic volumes in residential areas. This target can be reached by road classification or by the positioning of the area accesses (*Section 5.4*). Users of access roads (especially non-motorized users) will benefit from low volumes on this type of road. That is why these roads should not be too long, should have a position at the start/end of the hierarchy, and should mainly be a destination for people living on that road. Applying these constraints will keep volumes low. When these constraints are not taken into account, the volumes will depend on the other design variables (described in this section).

*Figure 9.1* shows the targets, the design variables and the 'best practices' for the network level. The best practices are stated in *Sections 2.3, 3.3 and 5.4*.

### **9.2.2. Road class level**

The road class level applies to design variables 'within a road class'. Each road class is intended to satisfy a set of requirements among others road safety requirements. These road safety requirements will vary between road classes. The road classes have the following targets in common:

- Minimize the number of serious conflicts (lateral and opposing conflicts)
- Minimize mixing of modes at road sections (the degree of this minimization depends on the speed limit)
- Minimize speed differences

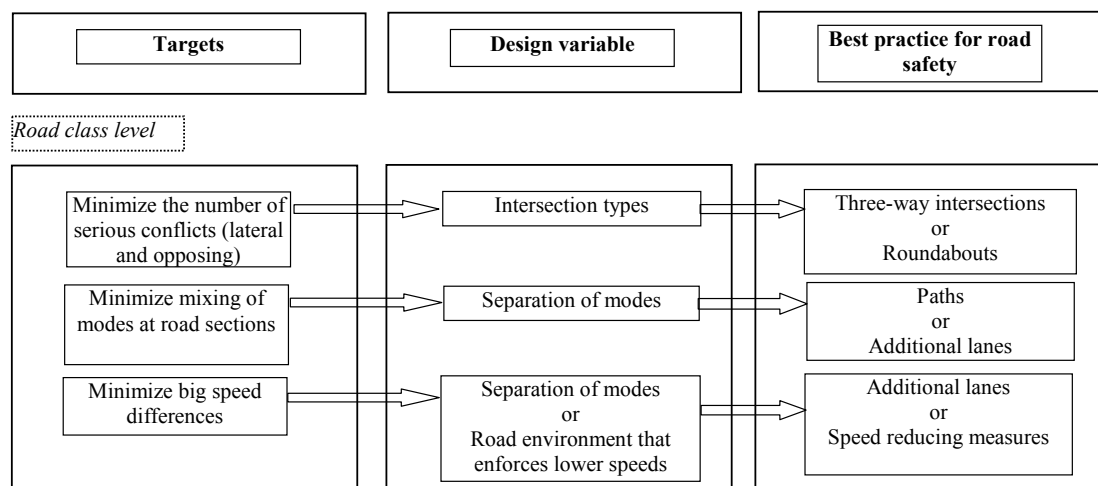


**Figure 9.1.** Targets, design variables and best practices at the network level

The design variables are intersection types, separation of modes, and road environment. The best practices were summarized in *Section 5.4*.

Three-arm intersections and roundabouts are to be preferred from a safety point of view. There can be reasons to apply signalized intersections (high volumes of conflicting flows) or four-arm intersections (spatial constraints). For the purpose of recognition, some intersection types should be characteristic for a road class, like roundabouts on distributors.

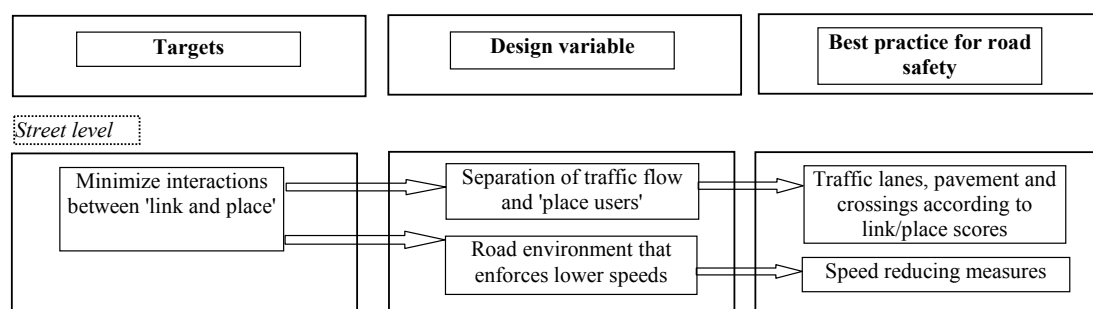
*Figure 9.2* shows the relationships between targets, design variables and best practices for the road class levels.



**Figure 9.2.** Targets, design variables and best practices at the road class level

### 9.2.3. Street level

In this study, the street level has a relatively low importance. However, a micro-simulation model also allows for 'filling in' this level. The main target is to let traffic flow as much as possible (e.g. at a low speed) and to let the users of the public space have their freedom of movement. Jones et al. (2007) proposed an extensive procedure to design a street for both purposes; they refer to traffic flow as 'link' and to the use of public space as 'place'.



**Figure 9.3.** Targets, design variables and best practices at the street level

Figure 9.3 shows a general target, the main design variables and best practices at the street level. The best practices are related to the methods proposed by Jones et al. (2007).

### 9.3. Analysing the network of the study area

A short description of the study area has already been presented in Section 7.1; see also Figure 7.1. For the network analysis, additional information will be given about the size of the clusters, and the classification of these clusters. In order to classify the sixteen clusters in this area into five types, each type should be filled with at least one cluster; see Section 9.1. This requirement can be satisfied by choosing types according to Table 9.4. This classification procedure results in three types (numbers 1, 2, and 3) containing one cluster only, and one type (number 4) containing eleven clusters; see Table 9.5. Most of the clusters in this area appear to be rather small, while some clusters are very close to each other; e.g. The Hague and Voorburg as well as Leiden and Leiderdorp.

The study area does not cover only a single existing administrative region. The Hague, Voorburg, Leidschendam and Wassenaar are part of the Haaglanden region (which also includes clusters in the south of the study area). The other clusters are located in the Leiden and Duin-/Bollenstreek

regions. The study area is situated in the western part of the 'southern wing' of the Randstad<sup>5)</sup>.

Type	Number of inhabitants
1	above 200,000
2	100,000 - 200,000
3	50,000 - 100,000
4	10,000 - 50,000
5	below 10,000

**Table 9.4.** Limits for classifying clusters

Cluster name	Number of inhabitants	Type
Den Haag / The Hague	475,580	1
Leiden	118,070	2
Voorburg	64,610	3
Katwijk	32,200	4
Leidschendam	27,750	4
Leiderdorp	26,077	4
Noordwijk	24,130	4
Oegstgeest	18,710	4
Wassenaar	17,520	4
Voorschoten	16,440	4
Sassenheim	15,260	4
Rijnsburg	14,150	4
Voorhout	13,880	4
Noordwijkerhout	12,280	4
Warmond	4,400	5
Valkenburg	3,590	5
Sum	884,647	

**Table 9.5.** Clusters, number of inhabitants (CBS Statline, 2008), and classification (according to *Table 9.4*)

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<sup>5)</sup> The Randstad covers the area in which Amsterdam, Utrecht, Rotterdam and The Hague are situated. The southern wing comprises also Dordrecht, Schiedam, Vlaardingen, and Alphen aan den Rijn.

The size of an administrative region is not very well defined. The procedure does not provide a criterion for the size of an area. What are the consequences of assuming the clusters to be in one or in two regions? Two options have been considered:

1. all clusters in one region;
2. The Hague, Voorburg, Leidschendam, and Wassenaar in one region, the other clusters in a second region.

### **9.3.1. Connecting clusters**

In both options, the clusters have been connected according to the procedure in *Section 9.1*. In *Figure 9.4* (one region) and *Figure 9.5* (two regions), all clusters of type 1 to 4 are connected. A connection begins and ends at the edge of a large cluster, or in the middle of smaller clusters. The options are quite different in terms of the number and nature of the connections. Option 1 has many long connections; in Option 2 only the shorter connections are left.

Regarding the size of both options, Option 2 is closer to the size of the existing regions in the Netherlands. Both regions in Option 2 were, for many years, physically separated by an airport. The airport having recently disappeared, the regions may be more connected in the (near) future.

### **External clusters**

External clusters can have a big influence on the connections in a region. Relevant external clusters for the study area are Rotterdam (type 1), Amsterdam (type 1), Zoetermeer (type 2), and Delft (type 3). The simulations in *Chapter 10* will show the influence of external clusters, especially on the traffic volumes. Traffic entering the study area East of Leiden has to find its way through the city of Leiden. A new road may be constructed connecting the A4 and the A44, therefore relieving Leiden of much through traffic. This new connection will create new routes for a greater area than Leiden itself.

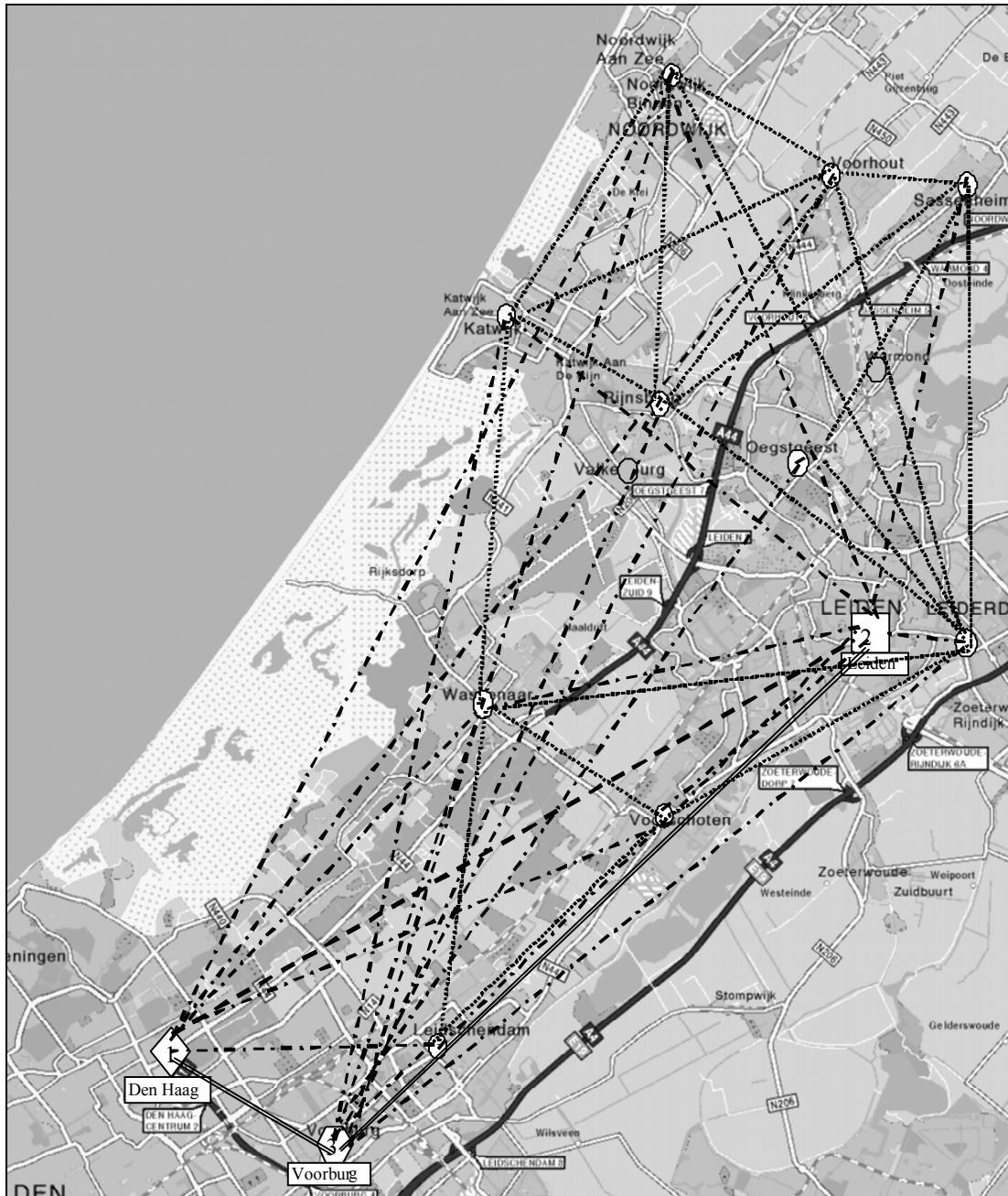
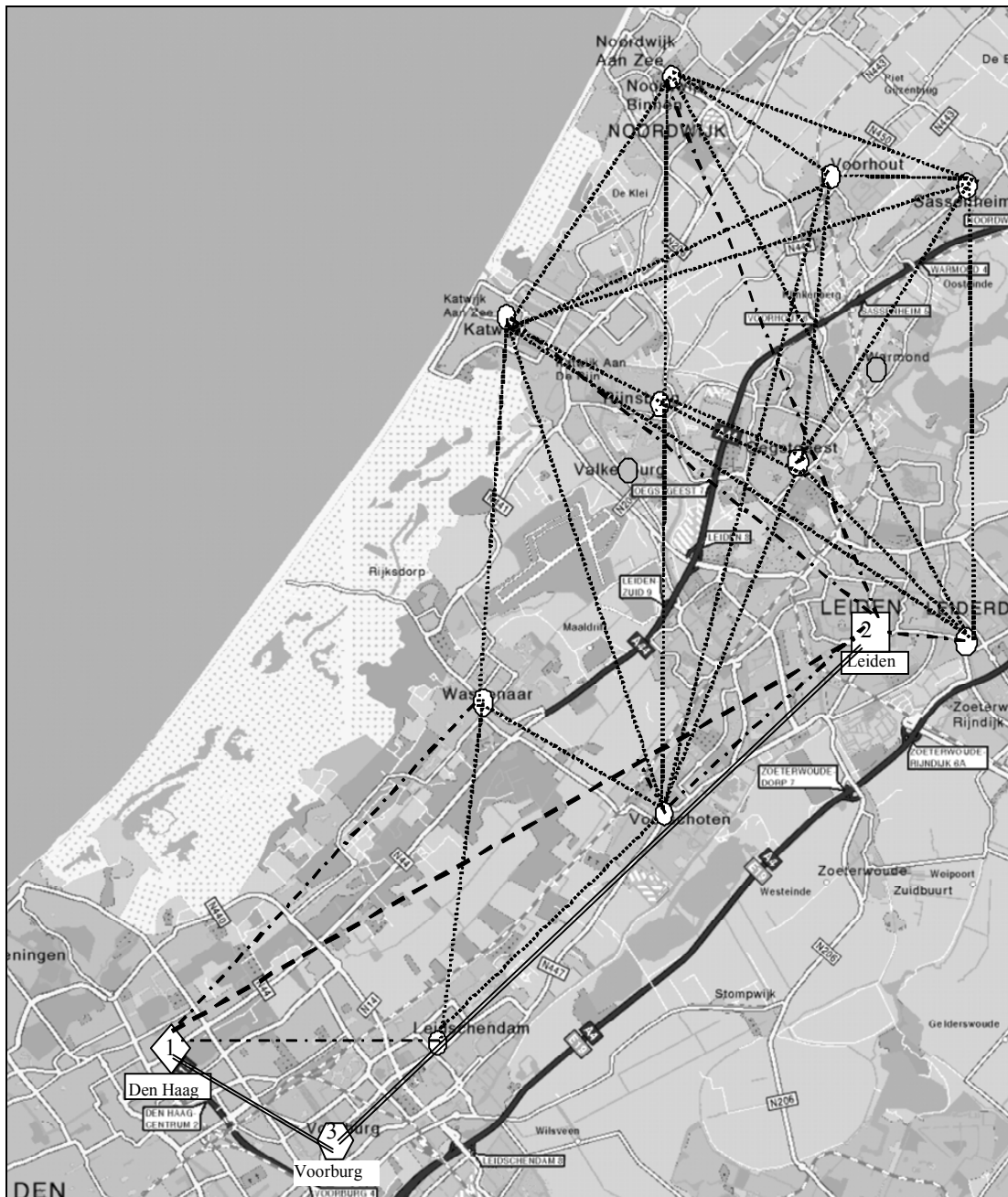


Figure 9.4. Desired connections according to Option 1

### 9.3.2. Road classification and sets of requirements

The desired connections between all clusters were classified according to the system described in Table 9.3; Table 9.6 shows the road classes and sets of requirements for Option 1, Table 9.7 for Option 2. Road class A3 is very dominant in option 1, because within a region, this road class should connect all type 4 clusters directly to larger clusters, or to other type 4 clusters (if the





**Figure 9.5.** Desired connections according to Option 2

route factor exceeds 1.5). Option 2 allows for less direct connections because, between regions, the K4-K4 connection is only desired if the route factor exceeds 1.5.

The sets of requirements belonging to the existing roads are given in *Table 9.8*. In a number of cases, two or more alternative routes are available for one connection. As shown in *Section 8.1*, these kinds of alternative routes

are actually used for the same O-D pair. However, the safety of all users of the O-D pair should be ensured. Either each of the alternative routes should meet the requirements of the connection, or road users should be directed towards the safest alternative(s).

The differences between the desired connections and the existing connections were checked for both options (one or two regions). The outcome of this check is that:

1. the desired connection is routed indirectly as well as the existing route ('-' sign in *Tables 9.9 and 9.10*);
2. the desired connection is routed indirectly while the existing route is routed directly ('+' sign);
3. the requirements for the desired connection are equivalent to the requirements for the existing connection ('=' sign);
4. the existing connection satisfies requirements better than the desired connections need to do ('>' sign).

The checks for Option 1 can be viewed in *Table 9.9*; the checks for Option 2 in *Table 9.10*. A first finding is that for many connections, in Option 1 as well as in Option 2, the existing connections are apparently of a higher quality than desired. Another result is that, in Option 2, many connections are routed directly, when they should be routed indirectly. Also, from a point of view of connectivity, the existing network appears to be of a high quality. On the other hand, many connections are handled by the same roads. Connections related to different levels (*Table 9.1*) are dependent on a small number of roads. Therefore, these roads must carry a lot of traffic, so the road network is saturated for many hours a day. Adding more capacity might go hand in hand with striving for a separate network of connections within a region.

### **9.3.3. Alternative network designs to be simulated**

The 'tool box' for alternative network designs consists of the 'integrated network design' approach (*Section 9.1*) and several design variables on the network level as well as on the road class level (*Section 9.2*). The study area network can be varied in many ways. This section considers a few alternative network designs that will most probably improve both road safety and traffic flow.

The network analysis showed many connections using the same set of main roads. An alternative structure should offer (newly built) alternative roads for relatively short interregional connections. Consequently, the density of exits and entries onto main roads can be reduced. One drawback of adding

more roads is the increasing number of intersections, possibly resulting in more conflicts and/or different types of conflicts.

Another alternative is to focus on the intersection types, changing four-way intersections either into roundabouts or into two three-way intersections. These measures should be taken on most of the major intersections of the network to be sure of finding a result on the network level.

A third alternative adds a completely new main road, while downgrading the existing main roads from A1 class to A2 class. The best location for a new road would be between the two existing main roads, next to the railway (The Hague - Leiden). The new road should only have a few exits and entries.

#### **9.4. Conclusions and recommendations**

*Chapter 9* describes a method for integrated network design. The method starts with the definition of clusters in urban areas. Consequently, these clusters are systematically connected. In the final step, the resulting desired connections will be compared to the existing connections. An application of this method to the study area showed that the standards of the existing connections are higher than the standards of the desired connections.

The application of the method showed one shortcoming. The method does not give a definition or description of the size of the area to be considered. The application showed that the optimal size of a region was about one half of the area studied.

Another issue is the number of alternative routes within one O-D pair. These alternative routes are actually used for the same purpose: connecting the O-D pair. The standards of these routes can be different. However, the safety of all users of the O-D pair should be ensured. Either each of the alternative routes must meet the requirements of the connection, or road users should be directed towards the safest alternative(s).

<b>Region LDH Desired connections</b>	Lei- den	Voor- burg	Kat- wijk	Leider- dorp	Leidschen- dam	Noord- wijk	Noord- wijker- hout	Oegst- geest	Rijns- burg	Sassen- heim	Voor- hout	Voor- schoten	Wasse- naar	Valken- burg	War- mond
Den Haag	A3 II	<i>D1 III</i>	A3 II	A3 II	<i>D1 III</i>	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	ind.	ind.
Leiden	xxxx	A3 II	A3 II	<i>D1 III</i>	A3 II	A3 II	A3 II	<i>D1 III</i>	A3 II	A3 II	A3 II	A3 II	A3 II	ind.	ind.
Voorburg		xxxxxx	A3 II	A3 II	<i>D1 III</i>	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	ind.	ind.
Katwijk			xxxxx	A3 II	A3 II	A3 II	A3 II	A3 II	<i>D1 III</i>	A3 II	A3 II	A3 II	A3 II	A4 II	A4 II
Leiderdorp				xxxxxxx	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	A4 II	A4 II
Leidschendam					xxxxxxxxx	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	A4 II	A4 II
Noordwijk						xxxxxxx	<i>D1 III</i>	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	A4 II	A4 II
Noordwijkerhout							xxxxxxx	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	A4 II	A4 II
Oegstgeest								xxxxx	A3 II	A3 II	A3 II	A3 II	A3 II	A4 II	<i>D1 III</i>
Rijnsburg									xxxxxx	A3 II	A3 II	A3 II	A3 II	<i>D1 III</i>	A4 II
Sassenheim										xxxxxx	A3 II	A3 II	A3 II	A4 II	A4 II
Voorhout											xxxxxx	A3 II	A3 II	A4 II	A4 II
Voorschoten												xxxxxxx	A3 II	A4 II	A4 II
Wassenaar													xxxxxxx	A4 II	A4 II
Valkenburg														xxxxxxx	A4 II

ind. = indirectly

**Table 9.6.** Desired connections for Option 1: road classes and sets of requirements

		L	DH	L	L	DH	L	L	L	L	L	L	L	DH	L	L
region	Two regions Desired connections	Leiden	Voorburg	Katwijk	Leiderdorp	Leidschen-dam	Noord-wijk	Noord-wijkerhout	Oegstgeest	Rijnsburg	Sassenheim	Voorhout	Voorschoten	Wassenaar	Valkenburg	Warmond
DH	Den Haag	A2 I	D1 III	ind.	ind.	D1 III	ind.	ind.	ind.	ind.	ind.	ind.	ind.	A3 II	ind.	ind.
L	Leiden	xxxxx	ind.	A3 II	D1 III	ind.	A3 II	A3 II	D1 III	A3 II	A3 II	A3 II	A3 II	ind.	ind.	ind.
DH	Voorburg		xxxxxxx	ind.	ind.	D1 III	ind.	ind.	ind.	ind.	ind.	ind.	ind.	A3 II	ind.	ind.
L	Katwijk			xxxxx	A3 II	ind.	A3 II	A3 II	A3 II	D1 III	A3 II	A3 II	A3 II	ind.	A4 II	A4 II
L	Leiderdorp				xxxxxxx	ind.	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	A3 II	ind.	ind.	ind.
DH	Leidschen-dam					xxxxxxx	ind.	ind.	ind.	ind.	ind.	ind.	A3 II	A3 II	ind.	ind.
L	Noordwijk						xxxxxxx	D1 III	A3 II	A3 II	A3 II	A3 II	A3 II	ind.	A4 II	A4 II
L	Noord-wijkerhout							xxxxxxx	A3 II	A3 II	A3 II	A3 II	A3 II	ind.	A4 II	A4 II
L	Oegstgeest								xxxxxx	A3 II	A3 II	A3 II	A3 II	ind.	A4 II	D1 III
L	Rijnsburg									xxxxx	A3 II	A3 II	A3 II	ind.	D1 III	A4 II
L	Sassenheim										xxxxxxx	A3 II	A3 II	ind.	A4 II	A4 II
L	Voorhout											xxxxxxx	A3 II	ind.	A4 II	A4 II
L	Voorschoten												xxxxxx	A3 II	A4 II	A4 II
DH	Wassenaar													xxxxxxx	A4 II	A4 II
L	Valkenburg														xxxxxx	A4 II

ind. = indirectly

Table 9.7. Desired connections for Option 2: road classes and sets of requirements

Existing connections	Leiden	Voorburg	Katwijk	Leiderdorp	Leidschendam	Noordwijk	Noordwijkerhout	Oegstgeest	Rijnsburg	Sassenheim	Voorhout	Voorschoten	Wassenaar	Valkenburg	Warmond
Den Haag	I or II	I or III	I or II	I or II	I or III	I or I-II	I or I-II	I	I-II or II	I	I	I-II or II	I or II	I-II or II	I
Leiden	xxxx	I or II	I	III	I or II	I or II	I or II	III	II	I or II	I or II	II	I or II	I or II	II
Voorburg		xxxxxxx	I	I	III	I	I	I	I	I	I-II	II	I	I	I
Katwijk			xxxxx	I-II	I	I	I	II	III	I	I-II	I-II or II	I or II	I	II
Leiderdorp				xxxxxxx	I or II	II	II	II	II	II	II	I or II	II	II	II
Leidschendam					xxxxxxx	I	I	I	I	I	I-II	II	I	I	I
Noordwijk						xxxxxxx	III	II	I	I-II	II	I-II	I or I-II	I	II
Noordwijkerhout							xxxxxxx	II	I	I-II	II	I-II	I or I-II	I	II
Oegstgeest								xxxxxx	II	I	I-II	I-II or II	I	II	III
Rijnsburg									xxxxxx	I	II	I-II	I or II	III	II
Sassenheim										xxxxxx	II	I-II	I	I	II
Voorhout											xxxxxx	II-I-II	I-II	II	II
Voorschoten												xxxxxxx	II	I-II	I-II
Wassenaar													xxxxxxx	I	I
Valkenburg														xxxxxxx	I

I or II: two routes are available for this connection

I-II: this connection consists of a route on which two sets of requirements are applicable

**Table 9.8.** Sets of requirements for existing connections

Are the existing connections OK?	Leiden	Voorburg	Katwijk	Leiderdorp	Leidschendam	Noordwijk	Noordwijkerhout	Oegstgeest	Rijnsburg	Sassenheim	Voorhout	Voorshoten	Wassenaar	Valkenburg	Warmond
Den Haag	>	>	>	>	>	>	>	>	>	>	>	>	>	+	+
Leiden	xxxx	>	>	=	>	>	>	=	=	>	>	=	>	+	+
Voorburg		xxxxxx	>	>	=	>	>	>	>	>	>	=	>	+	+
Katwijk			xxxxx	>	>	>	>	=	=	>	>	>	>	>	=
Leiderdorp				xxxxxxx	>	=	=	=	=	=	=	>	=	=	=
Leidschen-dam					xxxxxxxxx	>	>	>	>	>	>	=	>	>	>
Noordwijk						xxxxxxx	=	=	>	>	=	>	>	>	=
Noordwijkerhout							xxxxxxx	=	>	>	=	>	>	>	=
Oegstgeest								xxxxx	=	>	>	>	>	=	=
Rijnsburg									xxxxxx	>	=	>	>	=	=
Sassenheim			-: existing & desired both indirectly							xxxxx	=	>	>	>	=
Voorhout			+: existing directly; desired indirectly								xxxxx	>	>	=	=
Voorshoten			=: existing equals desired									xxxxxxxxx	=	>	>
Wassenaar			>: existing better than desired										xxxxxxx	>	>
Valkenburg														xxxxxxxxx	>

Table 9.9. Do the existing connections fulfil the sets of requirement (Option 1)

		L	DH	L	L	DH	L	L	L	L	L	L	L	DH	L	L	
region	Are the existing connections OK?	Leiden	Voorburg	Katwijk	Leiderdorp	Leidschendam	Noordwijk	Noordwijkerhout	Oegstgeest	Rijnsburg	Sassenheim	Voorhout	Voorschoten	Wassenaar	Valkenburg	Warmond	
DH	Den Haag	=	>	+	+	>	+	+	+	+	+	+	+	>	+	+	
L	Leiden	xxxxx	+	>	=	+	>	>	=	=	>	>	=	+	+	+	
DH	Voorburg		xxxxxxx	+	+	=	+	+	+	+	+	-	+	>	+	+	
L	Katwijk			xxxxxxx	>	+	>	>	=	=	>	>	>	+	>	=	
L	Leiderdorp				xxxxxxx	+	=	=	=	=	=	=	>	+	+	+	
DH	Leidschendam					xxxxxxx	+	+	+	+	+	-	=	>	+	+	
L	Noordwijk						xxxxxxx	=	=	>	>	=	>	+	>	=	
L	Noordwijkerhout							xxxxxxx	=	>	>	=	>	+	>	=	
L	Oegstgeest								xxxxxxx	=	>	>	>	+	=	=	
L	Rijnsburg									xxxxxxx	>	=	>	+	=	=	
L	Sassenheim		-: existing & desired both indirectly									xxxxxxx	=	>	+	>	=
L	Voorhout		+: existing directly; desired indirectly									xxxxxxx	>	-	=	=	=
L	Voorschoten		=: existing equals desired										xxxxxxx	>	>	>	>
DH	Wassenaar		>: existing better than desired												xxxxx	>	>
L	Valkenburg														xxxxxxx	>	

Table 9.10. Do the existing connections fulfil the sets of requirement (Option 2)



## **10. Adapting the network structure to improve safety**

This chapter shows the effect of road network structure and road classification on road safety. The previous *Chapter 9* provided the means and methods for designing network structures. *Chapter 10* uses these means and methods to vary both the network structure and the road classification systematically. To this end, a micro-simulation model will be used. Whether a network structure is good for road safety can be shown through the output variables of the simulation model. An important factor for the resulting effects on road safety is induced by the changes in route choice. The micro-simulation model used - *S-Paramics* - comprises a series of assumptions and choices for the modelling of route choice; these are summarized in *Section 10.1*.

Finally, the simulation model was applied to the study area. The results are given in *Section 10.2*.

### **10.1. Route choice in S-Paramics**

In the simulations (*Section 10.2*), attempts were made to influence route choice. How routes are chosen in S-Paramics will be described first; the description is derived from SIAS (2005).

In S-Paramics, each vehicle tries to find the shortest route from the road section on which it is located to its destination zone. The shortest route is the one for which the general journey costs are lowest. Each time a vehicle enters a new road section, the route is evaluated again on the basis of the general journey costs that are 'stored' in route tables.

#### **10.1.1. Road hierarchy and familiarity**

The road hierarchy in a network can be used to change the journey costs on special road sections for familiar and unfamiliar vehicles. The road hierarchy in a network is made up of major and minor road sections.

Major road sections are signposted; the true costs of travelling on them are known to familiar and unfamiliar vehicles.

The minor road sections are non-signposted. The familiar vehicles perceive the journey costs on minor road sections as being the same as the true costs. Unfamiliar vehicles have a lower awareness of minor road sections; they

view the journey costs on these road sections as being twice the true costs. These 'penalty costs' make it less likely that these unfamiliar vehicles will choose routes along minor road sections and they will therefore tend to stay on the signposted road sections (i.e. the major road sections).

### **Familiarity**

Familiarity with the road network has a fundamental influence on route choice in a hierarchical road network. If this directly influences the quantity of vehicles passing along routes with and without signposting, it is important to calibrate the level of familiarity properly. The standard familiarity value for all vehicles is 85%. This means that 85% of the vehicles make *no* distinction between the costs of *major* and *minor* road sections. The other 15%, the unfamiliar vehicles, view the costs on *minor* road sections as higher and will be more inclined to travel along *major* road sections.

The level of familiarity can be set separately for each vehicle type. For example, if a model includes taxis, it would be quite possible to set the familiarity at 100% because taxi drivers usually know the road network well.

These choices and assumptions in S-Paramics will actually serve the purpose of this study. That is because this study would like to offer all the alternative routes to most of the 'road users' (vehicles in this kind of model); the value of 85% is a reasonable assumption. It means that most of the vehicles will view all available roads as an alternative route. During rush hour, such a high value can be expected because of the many trips that are made everyday. This value of 85% was used to calibrate the model described in *Section 6.1*.

#### **10.1.2. General costs**

The general journey costs and the road category can be set for each individual road section.

#### **General journey costs of a road section**

The journey costs of an individual road section can be calculated using the general cost comparison. This represents a combination of factors that drivers take into consideration when choosing between various routes. The most important factors are time and distance. If a toll is charged for using certain parts of a road, these costs will also be taken into account.

The general journey costs  $GK$  of a road section are measured in time, distance and (if imposed) toll charges. These types of costs are widely used (Ortúzar & Willumsen; p. 324).  $GK$  can be weighted by means of coefficients, depending on the road category and the familiarity of the road users with the

road network. The base costs for links  $GK$  is calculated using the Generalised Cost Equation (GCE):

$$GK = a \times T + (60 \times b \times D) + c \times P$$

in which  $a$  is the time coefficient,  $b$  the distance coefficient,  $c$  the toll coefficient,  $T$  the travel time in minutes,  $D$  the link length in miles and  $P$  the toll in monetary cost units. The default values are 1 for  $a$ , 0 for  $b$  and  $c$ .

The general journey costs  $GK$  of a road section can be set to the same (*generic*) value for all vehicles or they can be set *by vehicle type*.

By way of example, the general journey costs associated with a 1-kilometre road section with a journey time of 120 seconds for different coefficients  $a$ ,  $b$  and  $c$  are shown in *Table 10.1*.

a	b	c	GK
1	0	0	120
0	1	0	60
0.5	0.5	0	90

**Table 10.1.** Example of general journey costs  $GK$  for different coefficients  $a$ ,  $b$  and  $c$

The General Cost Equation is particularly relevant if tolls are charged. For this study, both the distance coefficient and the toll coefficient are set to 0. Only the travel time  $T$  is used as a cost factor, as is widely accepted (Höfler, 2006).

### General journey costs of a road category

In addition to calculating the general journey costs of an individual road section as described above, one can also calculate the general journey costs for a road category. This determines the general journey costs for all road sections that fall into a certain road category. This is done in precisely the same way as described above.

If an individual road section falls into a category for which the general journey costs are e.g. 2 and, furthermore, it is allocated a specific value of e.g. 3 that applies only to this road section, then the final general journey costs are 6 ( $GK$  of the category multiplied by  $GK$  of the individual road section). For a minor road section, the costs are 6 for familiar vehicles and 12 for unfamiliar vehicles. *Table 10.2* gives some examples of how  $GKCs$  (general

journey costs of categories) and *GKW*s (general costs of an individual road section) influence the costs for familiar and unfamiliar vehicles.

Link type	<i>GKC</i> General costs of a category	<i>GKW</i> General costs of an individual road section	Familiar	Unfamiliar
Major	1 <sup>*)</sup>	1 <sup>*)</sup>	1	1
Minor	1 <sup>*)</sup>	1 <sup>*)</sup>	1	2
Major	2	1	2	2
Minor	2	1	2	4
Major	2	2	4	4
Minor	2	2	4	8
Major	3	2	6	6
Minor	3	2	6	12

<sup>\*)</sup> default value for link type

**Table 10.2.** Example of general journey costs for familiar and unfamiliar vehicles on major and minor road sections for a combination of *GKC*s and *GKW*s

This option in S-Paramics was not used in this study because no information is available to determine whether adding *GKC*s would be useful for the route choice in the study area.

### 10.1.3. Route tables

The route tables are filled in using the general journey costs of the road sections. The route costs are equal to the sum of the general journey costs of the road sections that form part of the route. Route tables give vehicles the opportunity of calculating the costs of a route choice at each junction along the route. When a vehicle approaches a junction, it consults the relevant route table and, after deciding whether to apply *perturbation* and/or *dynamic feedback* (see hereafter), the vehicle selects the route that has the lowest journey costs to the destination.

In all cases, there are two route tables in a model in S-Paramics: one table contains the costs for vehicles that are familiar with the road network (familiar vehicles) and the other table contains the costs for vehicles that are unfamiliar with the road network (unfamiliar vehicles). Familiar vehicles have a different perception of a route through the network to unfamiliar

vehicles. This is achieved by making use of a road hierarchy in the network and by calibrating familiarity.

In addition, a separate route table can be created for each type of vehicle, thereby producing a set of route tables. Each route table is calculated each time a simulation is started.

#### 10.1.4. Assignment methods

The following assignment methods are possible in S-Paramics:

- All-or-nothing assignment
- Stochastic assignment
- Dynamic assignment
- Stochastic Dynamic assignment

Mayer & Miller (2001; p. 284) also distinguish the equilibrium assignment method. The stochastic assignment adds a stochastic component to an equilibrium assignment.

##### **All-or-nothing assignment**

In a one-off operation based on an empty network at the start of a simulation, the *all-or-nothing* assignment determines the general journey costs for all possible routes associated with an OD relationship. The route with the lowest general journey costs is seen as the *shortest* route. All vehicles that travel from a given origin to a given destination will then make use of this shortest route.

The *all-or-nothing* assignment was not applied in this study. This type of assignment does not express the complicated route choices in the networks to be simulated.

##### **Stochastic assignment**

In the stochastic assignment, *perturbation* is used. Application of perturbation means that a variance is applied to the general journey costs of a route whenever vehicles have to choose between routes and do not want to make use of an *all-or-nothing* assignment.

When a route choice has to be made, a vehicle calculates the general journey costs  $GK$  of each possible route and then takes a random *perturbation* of these costs according to the formula below to calculate the new generalised journey costs  $GK_{new}$ ; see for example Willumsen (2008). The route with the lowest new general journey costs  $GK_{new}$  is chosen.

$$GK_{new} = GK + (GK \times var / 100)$$

in which  $- perturbation \leq var \leq + perturbation$ .

The variance, *var*, can be calculated in one of two ways: by means of the Percentage algorithm or the Square Root algorithm.

With the *Percentage algorithm*, the probability is taken into account that the new general journey costs lie within a margin of P% above or below the actual costs GK. A *perturbation* level of 5 (default value) leads to a variance of 5% on the general journey costs GK.

The *Square Root algorithm* perturbs the general journey costs by making use of the *Burrell* technique (Burrell, 1968), based on the following comparison:

$$C' = C + (((N - 5) * P) / 500) * \sqrt{C}$$

in which  $C'$  is a random journey time,  $C$  is the actual journey time,  $N$  is a random number (from 0 to 10) and  $P$  is the perturbation factor (whole number >0).

For example, if the *perturbation factor*  $P$  equals 100, then the costs will vary by up to  $\pm\sqrt{C}$ .

The *Burrell* technique is widely accepted as a reliable way to calculate journey costs (Ortúzar & Willumsen, 2002), so this study uses the *square root algorithm* as part of the *stochastic* assignment.

### **Dynamic feedback assignment**

In the dynamic feedback assignment, road users who are familiar with the road network take into consideration the congestion in the network when calculating the journey costs of a road section and of routes.

Where an all-or-nothing assignment calculates the journey costs on the basis of an empty road network, the dynamic feedback assignment calculates the journey costs of a road section on the basis of the delay imposed by congestion in a constantly revised (dynamic) cost calculation.

Road sections that have low journey costs based on calculation for an empty network, and therefore attract a lot of traffic, will, in the course of time, produce higher journey costs due to higher concentrations and possibly even congestion. As a result, alternative routes become more attractive. If the congestion decreases, the journey costs of these road sections will decline and become more attractive again.

In the dynamic feedback assignment, the various route tables are constantly recalculated for each feedback interval.

The frequency of the feedback can be set using the *feedback interval*. This means that the journey costs are recalculated every 1, 5 or 10 minutes (for example) and are used to evaluate the route choice for each individual vehicle.

To avoid excessive variance in the route choice during the simulation period, a *feedback factor* is used. This factor takes into account the degree of change in the journey costs, and it is used to recalculate the choice of route. It is applied as follows:

$$V_{new} = a * V_{current} + (1 - a) * V_{previous}$$

in which  $a$  is the feedback coefficient,  $V$  the costs of a given movement (from link to link),  $V_{new}$  the costs to be used for route choice calculations,  $V_{current}$  the costs from the current feedback period and  $V_{previous}$  the costs from the previous feedback period.

A high feedback factor leads to a higher proportion of delays that are fed back in the simulation and therefore lead to a greater chance of route revision. The standard setting for the feedback factor is 0.50.

The *dynamic feedback* assignment assumes that drivers have knowledge of the journey costs at a given moment. This can only be true if specific information is sent periodically to each vehicle. In the simulations described in *Section 7.1*, this feedback assignment was not used. However, for finding the theoretical effects of such a feedback, some of the simulations in *Section 10.2* have been performed by using a *dynamic feedback* assignment.

### **Stochastic dynamic assignment**

The stochastic dynamic assignment uses both *perturbation* and *feedback* and is therefore the dynamic feedback assignment, together with a varying perception of the actual general journey costs (*perturbation*). It is used in precisely the same way as the stochastic assignment.

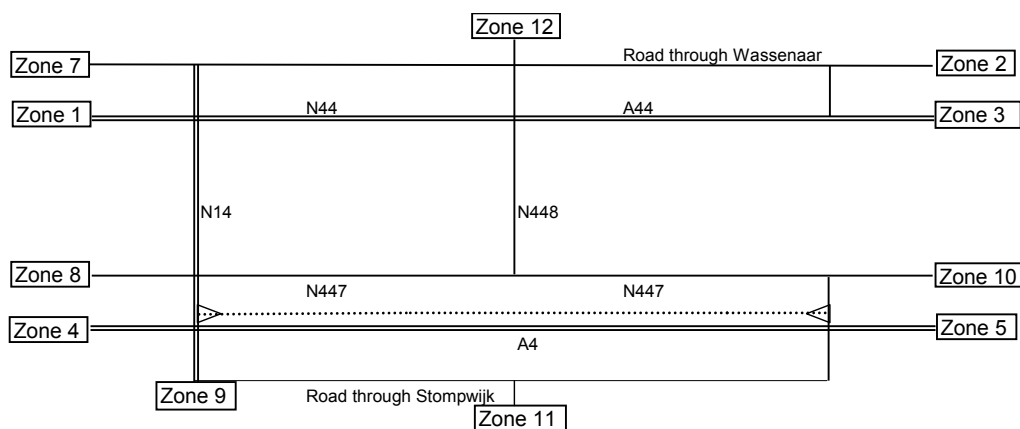
This type of assignment was not used in this study because it mixes the effects of perturbation and feedback. This would interfere with the goal of the simulations: to *separate* the effect of perturbation from the effect of feedback.

## **10.2. Simulations and analyses**

### **10.2.1. Network structure for simulations**

The (main) road network of the study area is shown in *Figure 7.1*. The baseline structure for the simulations in this *Section 10.2* was derived from this network. This structure comprises the main road structure of the study area: five parallel roads are modelled (A4, N44, N447, road through

Wassenaar, road through Stompwijk) as well as the three roads (N14, N448, N206) perpendicular to these five roads; see *Figure 10.1*.



**Figure 10.1.** Baseline structure for simulations (including O-D zone names)

The network as shown in *Figure 7.2* is not used for the simulations of the network structures. That network had to represent the real network as much as possible in order to be able to make a connection with the accident data. The baseline structure, however, can be simpler and less realistic because different structures will be compared with each other, apart from the real network.

		Destinations											Sum
		1	2	3	4	5	7	8	9	10	11	12	
Origins	1	-	500	500	100	400	100	100	400	0	0	0	2,100
	2	500	-	100	100	100	100	100	0	0	0	0	1,000
	3	1,500	100	-	100	100	100	100	500	0	0	0	2,500
	4	100	100	100	-	2,000	100	100	500	0	0	0	3,000
	5	1,000	100	800	2,000	-	100	100	500	0	0	600	5,200
	7	100	100	100	100	100	-	100	200	0	0	0	800
	8	100	100	100	100	100	100	-	100	100	0	0	800
	9	500	0	500	500	500	200	100	-	0	0	0	2,300
	10	0	0	0	0	0	0	100	0	-	0	0	100
	11	0	0	0	0	0	0	0	0	0	-	0	0
	12	0	0	0	0	0	0	0	0	0	0	-	0
	Sum	3,800	1,000	2,200	3,000	3,300	800	800	2,200	100	0	600	17,800

**Table 10.3.** Origin-destination zones in the network: number of vehicles per hour



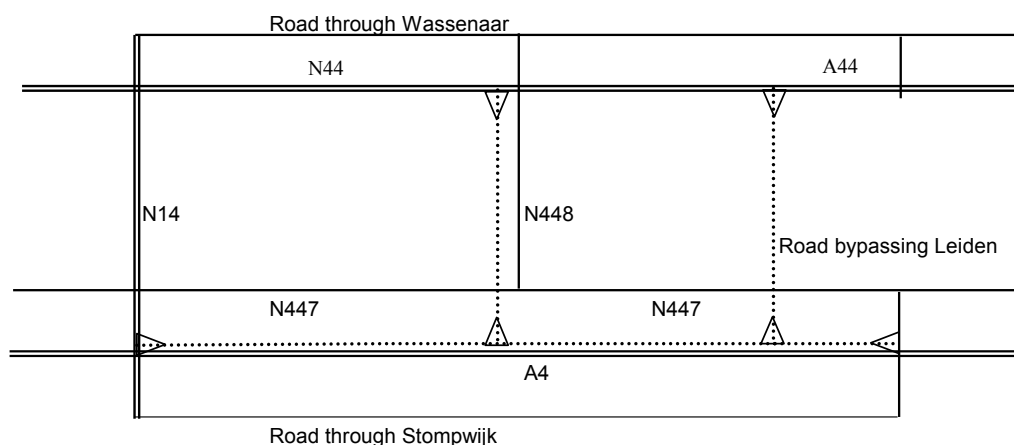
Eleven origin-destination zones were defined to generate traffic in the network; see *Table 10.3* and *Figure 10.1*. Most of the vehicles are headed towards The Hague (specifically towards zones 1 and 4). A substantial number of vehicles are directed from zone 5 towards zones 3 and 12. The numbers of vehicles do not have any relation to the real O-D pairs. Nevertheless, the proportions of the numbers of vehicles are representative for this area and these roads.

### 10.2.2. Network variations

Two variations were designed:

1. The baseline structure extended with two connections between A4 and N44 as well as a minor road next to the A4 (*Figure 10.2*);
2. The structure according to variation 1 extended with a 'central road' (*Figure 10.3*).

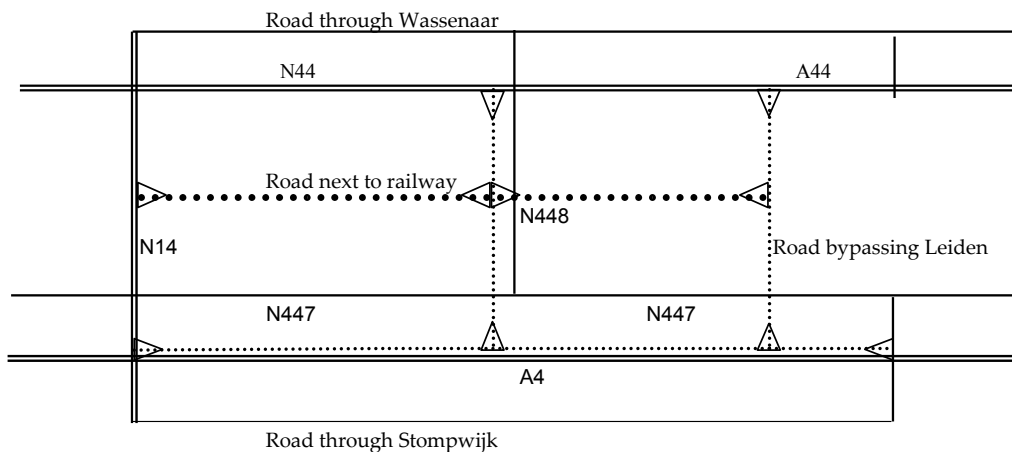
The locations and the numbers of the zones were not changed, neither were the numbers of vehicles between the zones.



**Figure 10.2.** Variation 1: Road structure, including two connections between A4 and N44

Variation 1 is intended to complement the existing structure by connecting the two main roads. The A4 is connected indirectly to the N44/A44 to prevent regional traffic from using the A4.

Variation 2 provides even more capacity to the network in order to relieve the N44 and N447. However, the connection of this central road to the N14 needed a special design because of the large flow of intersecting vehicles. In the final design, the intersecting flows are grade separated.



**Figure 10.3.** Variation 2: Road structure, including both two connections between A4 and N44 and a road next to the railway

### 10.2.3. Simulation runs

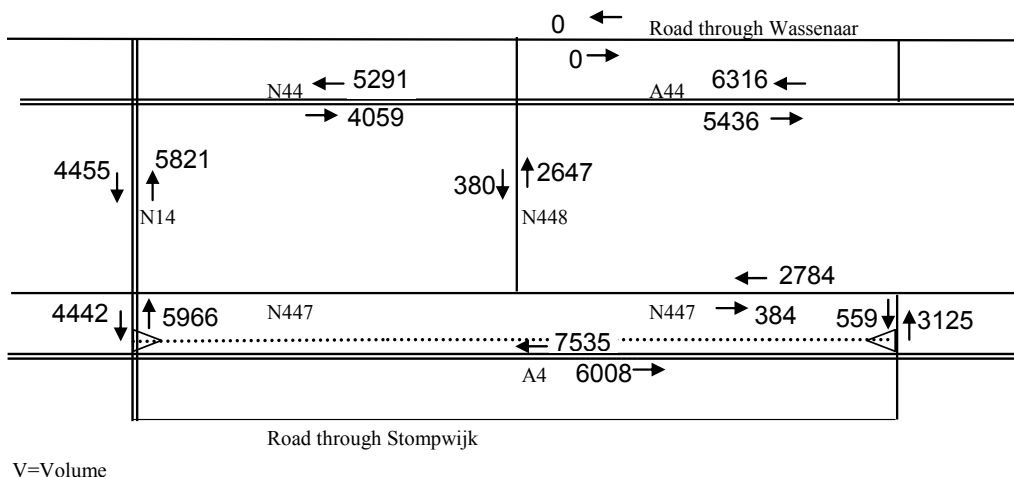
The simulations for the baseline structure and the two variations had the following characteristics; see also *Section 10.1.4*:

- Ten runs for each structure
- Perturbation factor  $P = 50$  for 85% of the vehicles
- Variance,  $var$ , by means of the square root algorithm
- No feedback

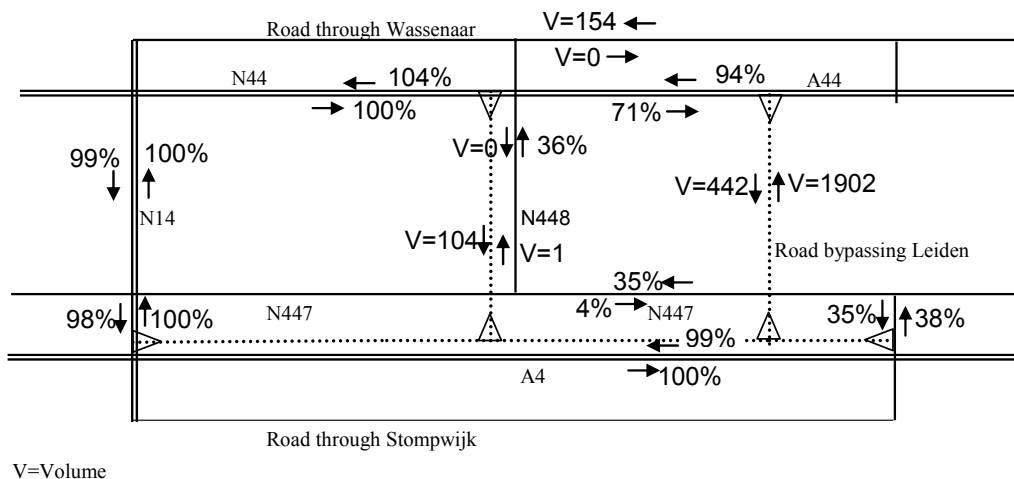
Each simulation run covered a period of two hours. During this two-hour period, all vehicles departed from their origin zones. To make this happen, the number of lanes had to be increased at the exits of some busy zones. In addition, some entries of main roads had to be lengthened. Finally, some road sections had to be widened (by adding one lane). These alterations apply to both the baseline structure and the variations. Consequently, the differences between the three variations are exclusively related to the availability of the connections.

### 10.2.4. Volumes on major links by structure

The volumes on the major links of the baseline structure are shown in *Figure 10.4*. The vehicles can only use a small number of routes. The right-hand sides of the N447 and the N448 are used by vehicles driving from zone 5 to zone 2 and to zone 3. The road through Wassenaar and the left-hand side of the N447 are hardly used, mainly due to the perturbation factor and the lack of feedback.



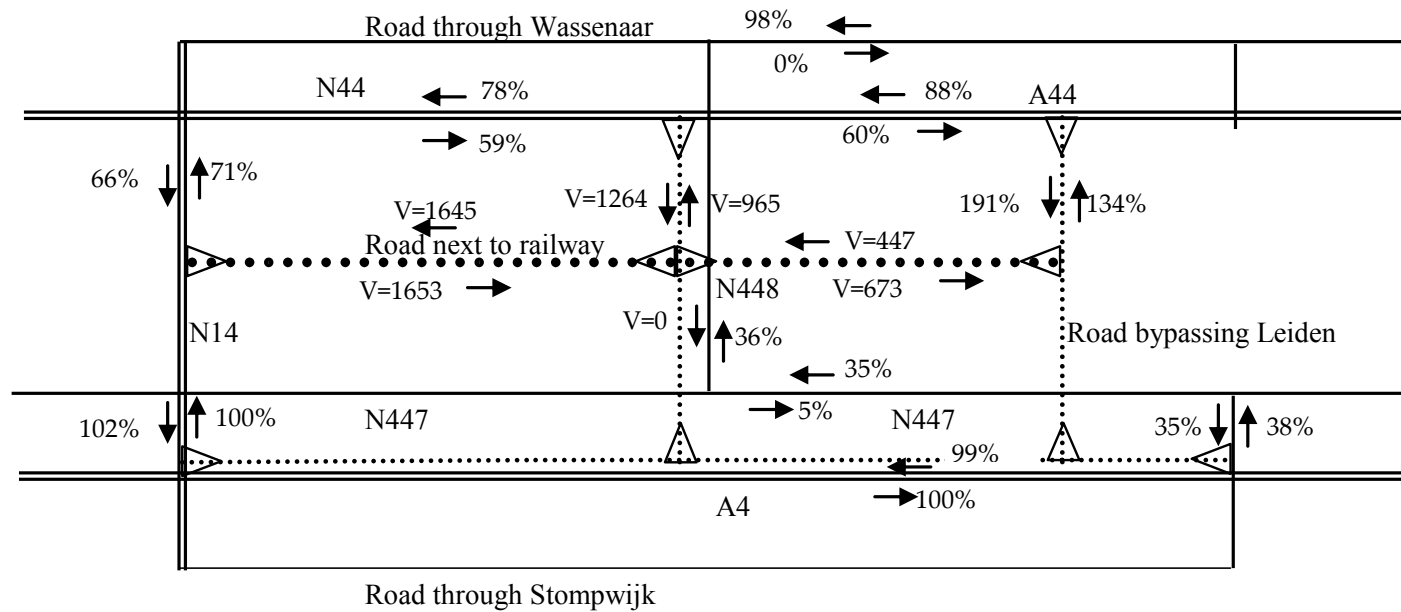
**Figure 10.4.** Baseline structure: volumes for major links (for both directions, in number of vehicles per two hours)



**Figure 10.5.** Variation 1: volumes for major links (for both directions, in percentage of baseline structure or in number of vehicles, V, per two hours)

In respect of the use of the N448 and the right-hand-side of the N447, the volumes in Variation 1 are quite different from the baseline structure; (see *Figure 10.5*). The road bypassing Leiden as well as a small part of the road parallel to the A4, take over the traffic from zone 5 to zone 2 and to zone 3. The new road parallel to the N448 does not have a clear function in this variation.

In Variation 2, the situation changes even more due to the introduction of the 'road next to the railway'; see *Figure 10.6*. Many vehicles use that road in stead of the N44. This new road ends at the road bypassing Leiden; that is also why that road becomes much busier. The upper part of the road parallel to the N448 is also used by traffic heading for the N44.



V=Volume

**Figure 10.6.** Variation 2: volumes for major links (for both directions, in percentage of baseline structure or in number of vehicles, V, per two hours)

### 10.2.5. Conflict numbers, conflict types

Using the approach in *Chapter 7*, the conflicts (numbers and types) were derived from the output of the simulations. The output numbers (conflicts or flows) for each variation are the average of ten simulation runs. The sums of the numbers of conflicts were calculated for each variation; see *Table 10.4*. These conflicts are only related to three-arm and four-arm intersections (called nodes in S-Paramics). There are rather small differences between the structures regarding their total numbers (column Sum in *Table 10.4*). The variations have a lower number of conflicts than the baseline structure. The indices in *Table 10.5a* show that variation 2 has about ten percent fewer conflicts than the base structure.

Simulation structure	RearEnd	Lateral	Frontal	Converging	Sum	FlowNode
Baseline structure	2,585	8,098	9,203	1,141	21,027	254,181
Variation 1	2,200	9,040	8,064	1,143	20,446	248,807
Variation 2	1,978	8,039	7,531	1,171	18,718	244,559

**Table 10.4.** All intersections (nodes<sup>6)</sup>): number of conflicts for each conflict type, total number of conflicts, and total number of vehicles passing the intersections ('Flownode')

The conflicts are also segregated into conflict types: rear-end, lateral, frontal and converging (*Table 10.4*). The most severe conflicts are the lateral and frontal ones; the numbers for these conflicts were taken together in *Table 10.5b*. In addition, for these types of conflicts, variation 2 has about ten percent fewer conflicts than the baseline structure. Variation 1 and the baseline structure have nearly the same numbers of conflicts.

Simulation structure	RearEnd	Lateral	Frontal	Converging	Sum	FlowNode
Baseline structure	100	100	100	100	100	100
Variation 1	85	112	88	100	97	98
Variation 2	77	99	82	103	89	96

**Table 10.5a.** Indices for conflict types, total number of conflicts, and total number of vehicles passing the intersections (baseline structure = 100)

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<sup>6)</sup> S-Paramics uses the word 'node' for all connections of links. Only nodes with at least three arms have been used for the analyses; these nodes are preferably called 'intersections'.

Simulation structure	Sum of lateral and frontal	
	Numbers	Indices
Baseline structure	17,301	100
Variation 1	17,104	99
Variation 2	15,570	90

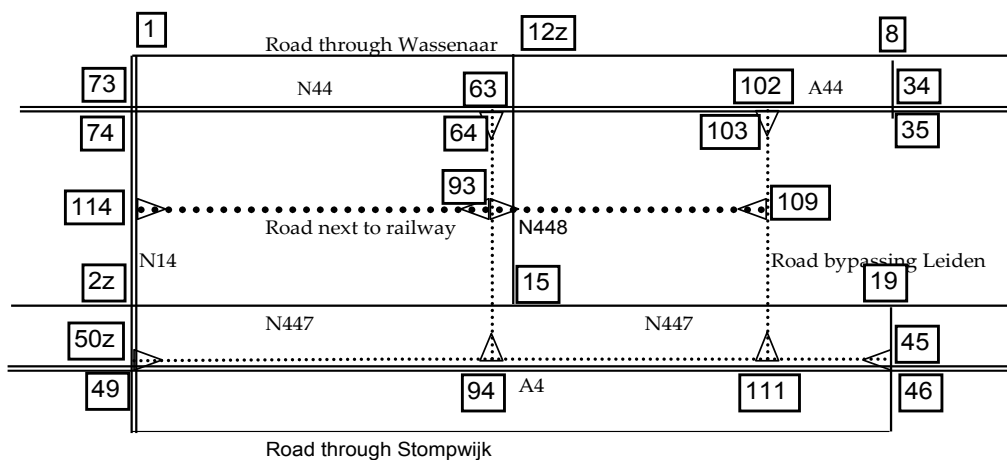
**Table 10.5b.** Numbers and indices for the sum of lateral and frontal conflict types (baseline structure = 100)

### Differences of specific intersections (nodes)

Some of the intersections, having three arms, are exits or entries. These kinds of intersections only show converging conflicts or rear-end conflicts. The intersections that could possibly show frontal and lateral conflicts (because of the directions of the conflicting flows) are shown in *Figure 10.7*; they are selected for *Tables D.1a and D.1b in Appendix D*. Not all flows on these intersections appear to result in (serious) conflicts; on some intersections, only rear-end conflicts have happened. *Tables 10.6a to 10.6c* show that the differences between the selected intersections (nodes) and the total set of intersections mainly relate to the differences in the rear-end conflicts.

On some intersections (34, 35, 45, 46, and 49), the conflicts shift from frontal in one variation to lateral in another variation. Intersection 19 has many rear-end and frontal conflicts in the baseline structure; the flows on this intersection are much lower in the variations, so the number of conflicts decreases and the type changes into lateral.

Most of the intersections show quite high numbers of conflicts; such figures may well be used for quantitative safety analyses.



**Figure 10.7.** Selected intersections (or nodes); some intersections do not exist in the baseline structure (see also *Appendix D, Tables D.1a and D.1b*)

	RearEnd	Lateral	Frontal	Converging	Sum	FlowNode
Selected nodes	1,889	7,955	9,203	1,141	20,189	103,643
All nodes	2,585	8,098	9,203	1,141	21,027	254,181
Percentage sel. nodes	73.1	98.2	100.0	100.0	96.0	40.8

**Table 10.6a.** Baseline structure - selected nodes versus all nodes: numbers of conflicts for each conflict type, total number of conflicts, and total numbers of vehicles passing the intersections

	RearEnd	Lateral	Frontal	Converging	Sum	FlowNode
Selected nodes	1,723	8,868	7,799	1,143	19,533	98,648
All nodes	2,200	9,040	8,064	1,143	20,446	248,807
Percentage sel. nodes	78.3	98.1	96.7	100.0	95.5	39.6

**Table 10.6b.** Variation 1 - selected nodes versus all nodes: numbers of conflicts for each conflict type, total number of conflicts, and total numbers of vehicles passing the intersections

	RearEnd	Lateral	Frontal	Converging	Sum	FlowNode
Selected nodes	1,592	8,039	7,377	1,171	18,179	101,100
All nodes	1,978	8,039	7,531	1,171	18,718	244,559
Percentage sel. nodes	80.5	100.0	98.0	100.0	97.1	41.3

**Table 10.6c.** Variation 2 - selected nodes versus all nodes: numbers of conflicts for each conflict type, total number of conflicts, and total numbers of vehicles passing the intersections

### 10.2.6. Conflicts related to traffic flow (conflict risk)

The numbers of conflicts, as shown in *Table 10.4*, are divided by the numbers of vehicles passing the intersections; see *Table 10.7*. In this way, the conflict risk is calculated. The conflict risk values are indexed with relation to the baseline structure; see *Table 10.8*. Variation 1 has a much higher risk of lateral conflicts than the baseline structure. Because of the much lower risks of rear-end and frontal conflicts, the average risk ('Sum' in *Table 10.7*) of Variation 1 equals the average risk of the baseline structure. Variation 2 clearly has a lower risk than the other two variations. However, Variation 2 also does not show a better result for lateral conflicts.

Simulation structure	RearEnd	Lateral	Frontal	Converging	Sum
Baseline structure	10.2	31.9	36.2	4.5	82.7
Variation 1	8.8	36.3	32.4	4.6	82.2
Variation 2	8.1	32.9	30.8	4.8	76.5

**Table 10.7.** Conflict risk for each conflict type, related to the total numbers of vehicles passing the intersections (divided by 1,000); see absolute numbers in *Table 10.4*

Simulation structure	RearEnd	Lateral	Frontal	Converging	Sum
Baseline structure	100	100	100	100	100
Variation 1	87	114	90	102	99
Variation 2	80	103	85	107	93

**Table 10.8.** Indices regarding conflict risk for each conflict type, related to the total numbers of vehicles passing the intersections (baseline structure = 100)

### 10.2.7. Dynamic assignment: feedback in stead of perturbation

The previous simulations used a stochastic assignment (*Section 10.2.3*), by using a perturbation factor. The effect of the assignment method on the route choice was examined by using a dynamic assignment for two structures (baseline and variation 2). For that purpose, the perturbation in the S-Paramics models was switched off, and the feedback was turned on. The feedback was set to ten minutes, so the routes of all vehicles in the network were recalculated regularly with an interval of ten minutes. The baseline structure does not have many alternative routes, so the dynamic assignment hardly results in any shift to other routes. However, some changes in flows can be observed. On a few routes, the numbers of passing vehicles increase to a small extent (between 50 - 300 vehicles), meaning that the flow improves. It appears that more vehicles have reached their destination within the period of the simulation run (two hours). The dynamic assessment for variation 2 does not show any change. Apparently, the greater numbers of alternative routes (compared to the baseline structure) have the same effect on both assignment methods (perturbation and feedback).

The numbers of conflicts were calculated for the dynamic assignment runs. The indices for these conflict numbers are given in *Tables 10.9a and 10.9b*. The effect of feedback on the numbers of conflicts in variation 2 is very small. However, the effect on the baseline structure is very large for the rear-end



conflicts. This is probably the effect of the larger numbers of vehicles finishing their routes, resulting in more conflicts with other vehicles.

Simulation structure	RearEnd	Lateral	Frontal	Con-verging	Sum	Sum of lateral and frontal	Passing vehicles
Baseline structure	100	100	100	100	100	100	100
Baseline structure, incl. feedback	249	102	105	100	121	104	101
Variation 2	77	99	82	103	89	90	96
Variation 2 incl. feedback	77	100	83	103	90	91	96

**Table 10.9a.** Indices for conflict types, total number of conflicts, and total number of vehicles passing the intersections (baseline structure = 100)

The effect is less marked for the lateral and frontal conflicts: 4% more of these conflicts for the baseline structure, given a small increase (1%) in the number of passing vehicles (*Table 10.9b*).

Simulation structure	Sum of lateral and frontal	
	Numbers	Indices
Baseline structure	17,301	100
Baseline structure, incl. feedback	17,920	104
Variation 2	15,570	90
Variation 2 incl. feedback	15,679	91

**Table 10.9b.** Numbers and indices for the sum of lateral and frontal conflict types (baseline structure = 100)

### 10.3. Conclusions and recommendations

Three network structures (baseline, variations 1 and 2) were modelled by way of the S-Paramics micro-simulation package. The modelling of the three network structures (using stochastic assignment) showed rather small differences in the resulting numbers of conflicts. Both variations resulted in a lower number of conflicts (3- 11%) than the baseline structure. The reduction of the numbers of 'serious' conflict types (lateral and frontal) varied from one to ten percent. Although the number of intersections in variation 2 is higher than in the baseline structure, the number of serious conflicts decreased. This

is also due to adding alternative routes, resulting in lower traffic densities on existing routes.

Generally, adding additional main roads to a main road structure will improve traffic flow. Road safety will benefit from spreading traffic over a greater number of roads. However, the cost effectiveness of the increase in road length is still a matter to be considered.

Not all flows on the intersections appeared to result in (serious) conflicts; on some intersections, only rear-end conflicts occurred.

The effect of feedback (dynamic assignment in stead of stochastic assignment) on the numbers of conflicts in the baseline structure is very large considering the increase in the numbers of rear-end conflicts. Because of the feedback, the flow increases, resulting in more vehicles conflicting with each other.

The effect of feedback on variation 2 is very small, for both traffic volumes and conflict numbers.

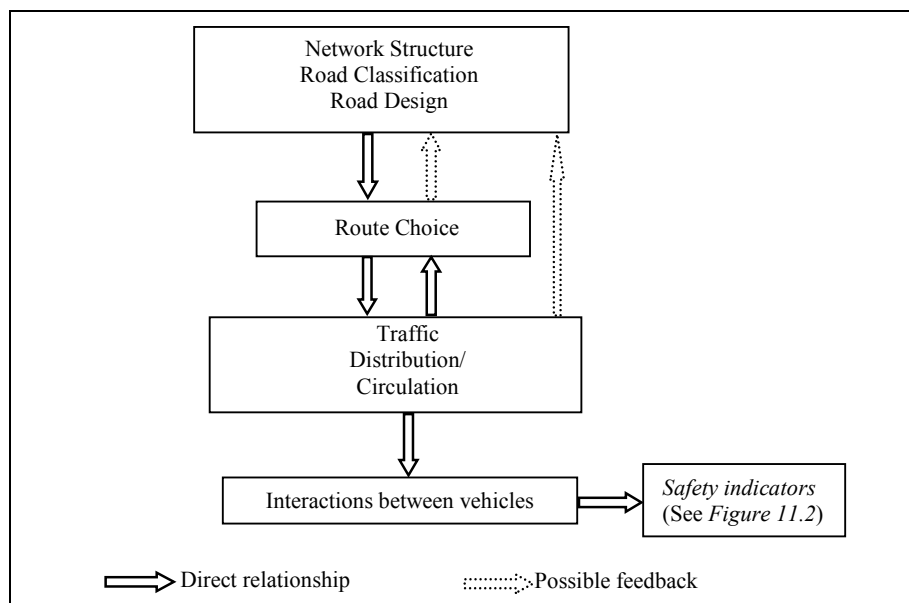
Most of the intersections show quite high numbers of conflicts, much higher numbers than crash data do. Such higher numbers could be used for quantitative safety analyses. Safety evaluations of network structures could very well be performed by using conflict numbers and risk values.

## 11. A safe mixture of network structure, traffic circulation and route choice

This chapter will show the overall concept of finding safety effects from different variables that, on the one hand, operate on different spatial levels and, on the other hand, are very much related to each other. The concept consists mainly of two parts: the integrated network design and the evaluation of safety effects using safety indicators. Other variables act between these two parts: route choice, traffic distribution and interactions of vehicles. *Section 11.1* describes the way in which network structure and safety indicators are connected by these other variables. *Section 11.2* explains the procedure for getting from network design to evaluating its safety effects.

### 11.1. From network structure to safety indicators

The task for network structure, road classification and road design is to bring together the aims of the road authority and the aims of the road user. The safety indicators are the direct outcome of the interactions between vehicles. In between network structure and safety indicators are route choice, traffic distribution (or traffic circulation), and interactions between vehicles: see *Figure 11.1*.



**Figure 11.1.** Schematic representation of the relations between network structure, route choice and traffic distribution

*Route choice* was described in *Chapter 4*. The most important findings (*Section 4.5*) are that travel time and trip length are without any doubt the most important factors in route choice. Road safety is not an issue in route choice matters. The road environment (urban planning aesthetics, scenery) will also influence route choice. Drivers prefer a less congested route as well as (parts of) routes on motorways; they also prefer good road and weather conditions, less stress, and less idle stops. Motorways are very much preferred; they are associated with low stress levels. The number of selected routes depends on the type of area (rural or urban) as well as on the volumes on the main road network. Most drivers use two or three routes.

*Traffic distribution* is the consequence of network structure, road classification, road design, and route choice; it was described in *Section 3.3*. Road classification should help road users to make trips safely and quickly. Road design, among other factors, is a prerequisite for homogeneity within road classes. The road user should be able to understand from the road characteristics and from actual traffic situations (recognisability) how to behave and what behaviour can be expected from other road users (predictability). Road classification should assist the road user in this driving task.

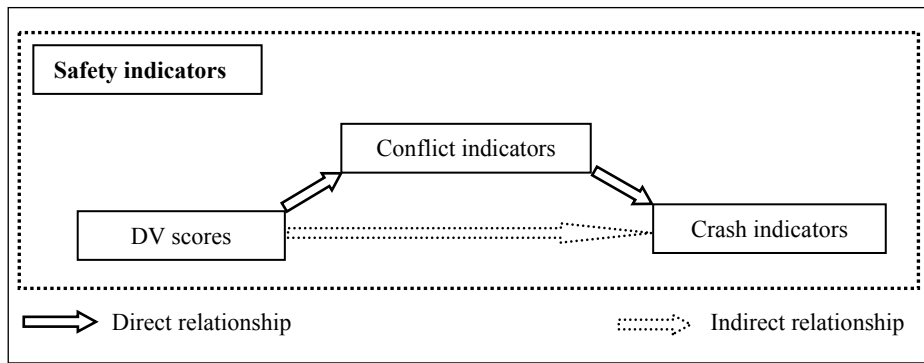
*Interactions between vehicles* with respect to the safety indicators to be derived, was described in *Section 6.3*. The interactions between vehicles to be looked at are frontal, lateral, rear-end, and converging conflicts. However, the frontal and lateral conflicts are the most important interactions for safety evaluations.

### **Safety indicators**

In this study, three types of safety indicators are used: DV scores, conflict indicators, and crash indicators. A greater part of this study focussed on showing (quantitative) relations between these indicators.

Conflict indicators appear to be related to crash indicators (*Chapter 7*). In general, the more conflicts, the more crashes. This is also valid for conflict density (resulting in a higher crash density) and conflict risk (higher crash risk).

DV scores are related to conflict indicators (*Chapter 8*); see *Figure 11.2*. A higher DV score means better compliance with the requirements of Sustainable Safety. A higher DV score goes together with fewer conflicts, lower conflict density and lower conflict risk.



**Figure 11.2.** Schematic representation of the relationships between different types of safety indicators

The conflict indicators are involved in both relations; they are the intermediate variable between DV scores and crash indicators. So DV scores are related *indirectly* to crash indicators (Figure 11.2).

## 11.2. Network Safety Procedure

Both the application of the integrated network design and the application of the safety indicators, (referred to above), are part of one procedure or tool that is meant to find safety effects as a result of changes in the variables shown in Figure 11.1. This procedure, called *Network Safety Procedure* hereafter, consists of eight steps: see also Figure 11.3.

### Step 1

The first step of the procedure, designing a network that meets the requirements of the clustering method, is described by Dijkstra (2010); see also Section 9.1. The (housing) clusters in a region are connected according to specific rules, resulting in a number of desired connections. The network structure is composed of the desired connections. However, some connections are redundant and may be removed from the final network; see the example in Section 9.1 (as well as in Appendix C). The connections in the network structure are already assigned to road classes. However, the final road classification is also dependant on characteristics of the road environment (Section 9.1). The road classes should satisfy a set of requirements as regards the road design.

### Step 2

As a consequence, in Step 2, this outcome can be compared with the existing network. This comparison will possibly show the deficiencies (or surpluses)

of the existing network. To that end, the connections in the existing network should be classified according to the actual road design. This actual road design is compared to the requirements that were the outcome of Step 1. An example of such a comparison is described in *Section 9.3*.

### **Step 3**

Step 3 designs the future network structure, called baseline network structure. *Section 9.2* provides the basic elements for this step. The design focuses on three levels: network, road class and street level. The targets, design variables and best practice for road safety are presented for each level of the road network. The best practice for road safety will help to develop the design at the levels relevant to the study method chosen. For example, a micro-simulation model will require the design of many details. Best practise will assist in taking this step.

*The foregoing three steps are the components of the integrated network design. The next steps, 4 to 8, are the way to evaluate the safety effects of network structures.*

### **Step 4**

Step 4 prepares the calculations for Step 5. There are two options for Step 4. The first option, building a micro-simulation model, will make it possible to calculate conflict indicators. *Section 7.1* shows how such a model is built. A derivative result of this modelling is the output that can be used for calculating route scores. The second option is the preparation of the data to be able to calculate route scores without using a simulation model. This option is used in *Section 8.1*.

### **Step 5**

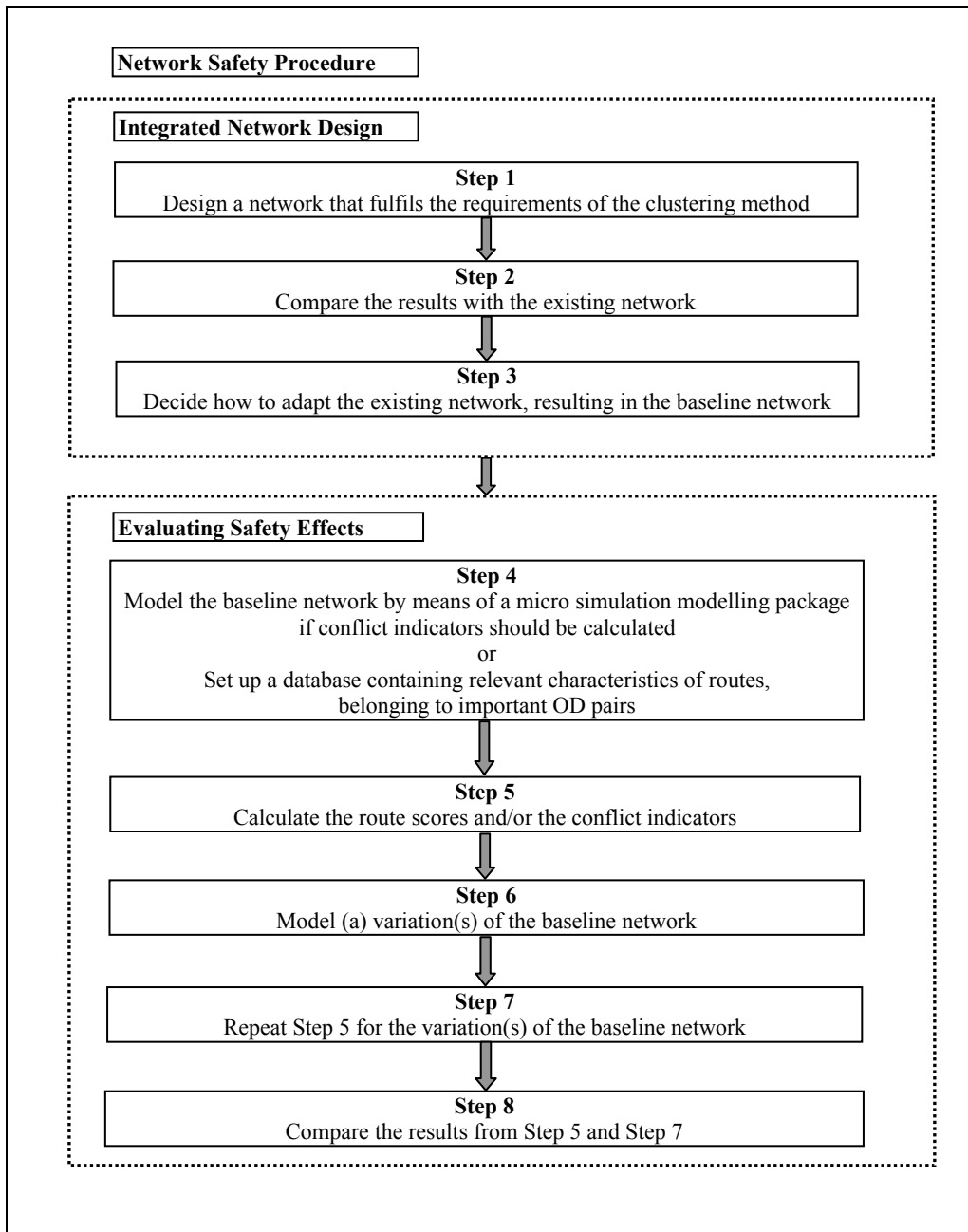
In Step 5, the conflict indicators and/or route scores are actually calculated. The calculation of conflict indicators is automated by using algorithms of the SAS package (SAS, 2005). The route scores can also be calculated using these SAS algorithms. In the aforementioned second option the route scores are calculated by using a spread sheet; see also *Section 8.1*.

### **Step 6**

Step 6 focuses on designing variations of the baseline structure. These variations can be the result of evaluating Step 3, or may come from new insights. This step is applied in *Section 9.2*.

## Steps 7 and 8

Step 7 is the same as Step 5 while Step 8 is a repetition of Step 6.



**Figure 11.3.** Schematic representation of the procedure for finding the safety effects of changes in the variables shown in *Figure 11.1*

## **12. Conclusions, discussion, recommendations**

This study focused on the effects of changing route choices on road safety. These changes in route choice are the result of (intended) changes in the structure of the road network. Alternatively, these changes could be the consequence of different traffic circulation, e.g. by adapting a traffic signal system. Thirdly, these changes might be the result of instructions to car drivers through their navigation systems or their route guidance signs. In this study, new methods have been developed in order to find the safety effects of changes in network structure, traffic circulation and route choice. Combining these methods resulted in a procedure that enables a traffic planner to find the effects of the mutual influence of these three variables on road safety.

### **12.1. Conclusions**

#### **12.1.1. Methods and safety indicators**

##### **Integrated network design and road classification**

In the Netherlands, the methods for arriving at a network structure and a road classification are not a foregone conclusion. The design principles and rules of thumb are mostly based on practical experience. The scientific foundation for this set of principles, requirements and rules is very frail.

A series of requirements was formulated in Sustainable Safety with the purpose of improving the functioning of the road network safety and efficiency. The method of 'integrated network design' was developed to test whether the road network meets these requirements. Firstly, this method focuses on the difference between desired and existing connections in the road network. Different types of clusters (ranging from cities to villages) should be connected in a structured way. In reality, the road network will differ from the ideal structure. The next step is to check the difference between the desired and existing relative position of each connection within the road network. The final road classification depends on these relative positions. Road safety is a crucial part of this classification procedure.

##### **Route score - conflict indicator - crash indicator**

This study used several safety indicators to find the effects of changes in route choice. These indicators show a specific aspect of the safety of a route



(an unbroken series of road sections and intersections). The route score describes the general characteristics of a route. A conflict indicator is calculated by means of a micro-simulation model. This indicator expresses the seriousness of conflicts between motor vehicles on and near intersections. A crash indicator is one of the characteristics of recorded crashes.

### **Safety as a motive for route choice**

Car drivers mention 'fastest route' and 'shortest route' as main preferences for their route choice. The next preference is 'prior knowledge about a route'. Car drivers hardly ever take 'safety of a route' into consideration when choosing a route. These results can be found in many studies on route choice.

### **12.1.2. Relevance for road safety policy and road safety research**

#### **Road networks in general**

Indicators based on the number of crossing or conflicting vehicles and the type of these conflicts are relevant if road structures need to be selected for increased road safety. Literature shows a number of indications of some road structures having low numbers of crossing vehicles. On the other hand, these structures can have longer distances travelled, which means more exposure to risk. In theory, some structures have low numbers of crossings as well as short distances travelled.

#### **Road safety aspects of network structure and road classification**

Countermeasures regarding network structure and road classification appear to result in crash or casualty reductions ranging from 40 to 80 percent. In most cases, safety on the surrounding roads hardly worsened, because additional measures were taken:

- The level of through traffic in a square sized residential area (grid network), is determined by the number and the position of the connections of the local network to the external network. Connections in the middle of the sides offer the fastest through routes (no detours). Connections at the angular points will result in through routes as long as routes along the surrounding roads. The latter route will be more attractive because of the higher speed limits on these roads. The more sides of an area are connected, the shorter the trip length for local traffic (origin or destination within the area).
- Several traffic measures in a residential area (one-way traffic, street closures, barring some turning directions on intersections, internal zoning, and speed reducing provisions) will mostly diminish through traffic because of the higher resistance of the through routes. Both the

local environment and road safety will benefit from these measures. Traffic volumes on the surrounding roads will mostly increase. The increasing traffic volume on the surrounding main roads should be balanced by the improvements in the areas.

- A regional network classified according to Sustainable Safety will most probably result in a lower number of casualties than a traditional network. The large numbers of roundabouts in the Sustainable Safety network will decrease the amount of vehicle hours spent waiting at signals.

### **Relation between route score - conflict indicator - crash indicator**

A direct relation was found between the number of calculated conflicts and the number of crashes. The numbers of conflicts are also directly related to the route score. The number of conflicts is a variable in both relations. That is why the route score is indirectly related to the number of crashes. Consequently, the route score is relevant for road safety research.

### **Route score and conflict indicator**

A high value for the route score is related to a lower number of conflicts, to a lower conflict density, and to a lower conflict risk. In addition, on a selection of routes containing only the longer routes, a high value for the route score is related to a lower number of conflicts.

### **Calculating route scores**

The route score consists of a number of safety criteria. Each criterion can be weighted. The route scores change slightly if the weighting of the criteria is adapted. These changes are quite small; resulting in hardly any change between the routes within one OD pair. The weightings are apparently not necessary to improve the relation between route score and conflict indicators.

### **Route score and travel time**

The routes within one OD pair are compared to each other by means of the route scores. This comparison shows that the fastest route does not always have the highest route score. The route with the highest volumes does not always have the highest route score either.

The number of vehicles on the routes within one OD pair cannot always be explained by the mean travel time. A shorter travel time is related to fewer conflicts on a route.

These results depend on the given road network in the study area. Adapting the structure and characteristics of this network will change these results.

### **Influencing route choice**

Prior to a trip, most drivers take note of traffic information, mostly by radio, television or Internet. This information will largely determine route choice or departure time. The traffic information en route comes from radio, personal observation, variable message systems, and, for some drivers, a navigation system. A substantial proportion of drivers change their route because of this information.

The expected total effect of navigation systems is: less exposure at the expense of some loss of attention to the other road users.

### **12.1.3. Applications**

#### **Network structure and conflict indicators**

Simulations using different network structures showed small differences in the number of conflicts. The vehicle flows are spread more evenly over the network in the network variation with a number of additional connections. This variation has the lowest number of conflicts as well as a lower conflict risk. However, the road length is considerably longer.

The effect of feedback (dynamic assignment instead of stochastic assignment) on the numbers of conflicts in the baseline structure is very large considering the increasing numbers of rear-end conflicts. Because of the feedback, the flow increases, resulting in more vehicles conflicting with each other.

This method, using conflict indicators, produces large numbers of conflicts on most of the intersections. These numbers are much higher compared to the numbers of crashes on intersections. Therefore, this method will show more solid statistical results than crash analyses.

#### **Integrated network design**

The application of an integrated network design method to the study area showed that many connections use roads which have a much higher position in the road network than desired according to the method. This conclusion was supported in other (foreign) studies. This finding clearly shows the structure of the road network in the Netherlands: many main roads (motorways) facilitating as many connections as possible, disregarding the distance between the origin and destination of these connections.

The application of the method showed one shortcoming. The method does not give a definition or description of the size of the area to be considered. The application showed that the optimal size of a region was about one-half of the area studied.

Another issue is the number of alternative routes within one O-D pair. These alternative routes are actually used for the same purpose: connecting the O-D

pair. The standards of these routes can be different. However, the safety of all users of the O-D pair should be ensured. Either each of the alternative routes should satisfy the requirements of the connection or road users should be directed towards the safest alternative(s).

## **12.2. Discussion and reflection**

This study started with a project titled 'Route choice in a road network'. This originated from the notion that route choice is an intermediary between road network design and actual traffic circulation. A route is an important element in transport and traffic research, and also for road safety research. Firstly, because the total numbers of routes show the actual use of the road sections and intersections in a road network. Secondly, the route shows the sequence of road sections and intersections that a driver experiences when travelling from origin to destination. The focus of this study turned to safety indicators which could relate to a route.

In this study, an attempt was made to connect different worlds; the world of transport network design, the world of route choice research, the world of micro-simulation modelling, and finally, the world of surrogate safety measures (conflict indicators). This attempt originates from the early days of road safety practice and research when the Swedish government published guidelines (1968) aimed at an integrated approach to network planning, housing, and road safety. However, it took many years before tools became available that allowed the expected effects of network design and traffic circulation (including route choice) on road safety to be quantified. An important tool for this task - the micro-simulation model - was used in this study. These kinds of models are usually only available in a commercial setting. The user is confronted with a black box. Research would benefit from micro-simulation models that are transparent to users.

The importance of road classification for road safety purposes seems to be underestimated. In the Netherlands, the methods for classifying roads could be improved substantially. This study proposes a method for classifying roads. Whether this method really benefits road safety will have to be the subject of further research.

Another important issue in this study is the safety indicators (surrogate safety measures). All safety indicators, other than crash figures, are still being researched. A great deal of study is needed before crash figures can be replaced by other safety indicators. However, the conflict indicators in micro-simulation models appear to be a promising approach in finding adequate and accurate safety indicators.

## 12.3. Recommendations

### 12.3.1. Practice purposes

This study shows that, in existing road networks, the safest route does not always coincide with the fastest route. However, car drivers tend to choose the fastest route. Therefore, the fastest routes should be converted to routes that are also the safest.

The use of micro-simulation models should be encouraged because they are suited to showing the safety effects of changes in road networks as well as in traffic circulation. This will require the programming of modules that can convert the output of a micro-simulation model into safety indicators.

The safety criteria of route choice should be incorporated into navigation systems. A test is recommended to discover the effects of the actual advantages for safety.

The method of integrated network design should be applied to more areas than the present study area. This may show whether the results depend on the (type of) area. From these findings, the issues of generalization and practical application should be resolved.

A robust road network is a road network that is less vulnerable to incidents than a regular network. In a robust road network, the motorways should be reserved for long distance travel, while the other main roads should be used for regional purposes. This functional separation will improve both traffic circulation and safety.

Methods for designing road structure and for classifying roads should have a more scientific background. This study provides a basis for using the method of an *integrated network design*.

This study resulted in a *Network Safety Procedure*. This procedure can be applied to finding the safety effects of the combination of changes in network structure, road classification and traffic circulation (including route choice).

Road safety will benefit from spreading traffic over a greater number of roads. However, the cost effectiveness of the increase in road length is still a matter to be considered.

A safety evaluation of network structures can very well be performed by using conflict numbers and risk values.

### **12.3.2. Research purposes**

It should become clear how micro-simulation models determine the position of a vehicle in the intersection area. This should be related to the level of detail needed for calculating conflicts.

The conflicts on signalized intersections are difficult to determine in micro-simulation models. Red-light running is not simulated, resulting in a lower number of lateral conflicts than are actually observed. There is a higher proportion of rear-end conflicts because of the many vehicles driving slowly in line. For both reasons, signalized intersections need to be examined more intensively.

The present micro-simulation model does not simulate all types of conflicts. This applies to longitudinal conflicts involving bicycles and to single vehicle conflicts (driving off the road). It should be possible to determine the contribution of these conflict types to the total number of conflicts. This could be done directly (comparable to other conflict types) or indirectly (through additional indicators).

This study did not focus on the issue of 'real' conflicts (observed in reality). These real conflicts will presumably differ from the calculated conflicts in the model. The terminology and typology of observed real conflicts was partly used for calculating conflicts in the model. Observations of real conflicts may give more insight into the nature of conflicts in a given model.

It is still unknown what would happen if a greater number of drivers using a navigation system changed their routes. This would certainly affect the traffic circulation in the road network. This is a matter to be studied.

Models like S-Paramics are, largely, black boxes. To know more about what happens 'inside', non-commercial models should be developed.



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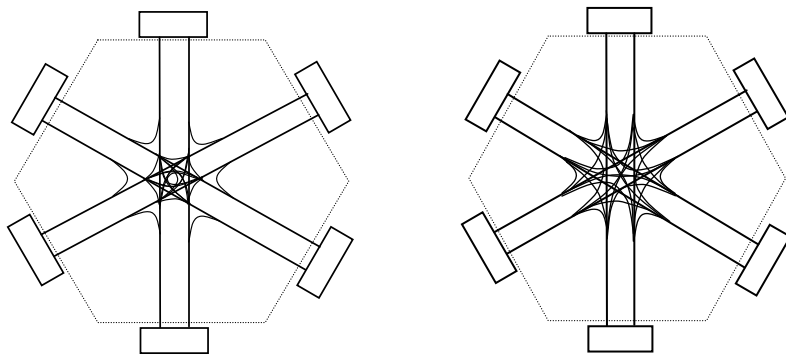
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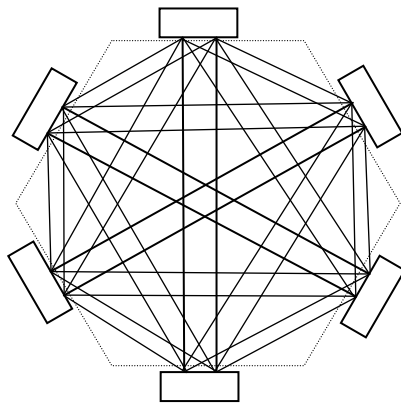
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## Appendix A. Traffic circulation systems

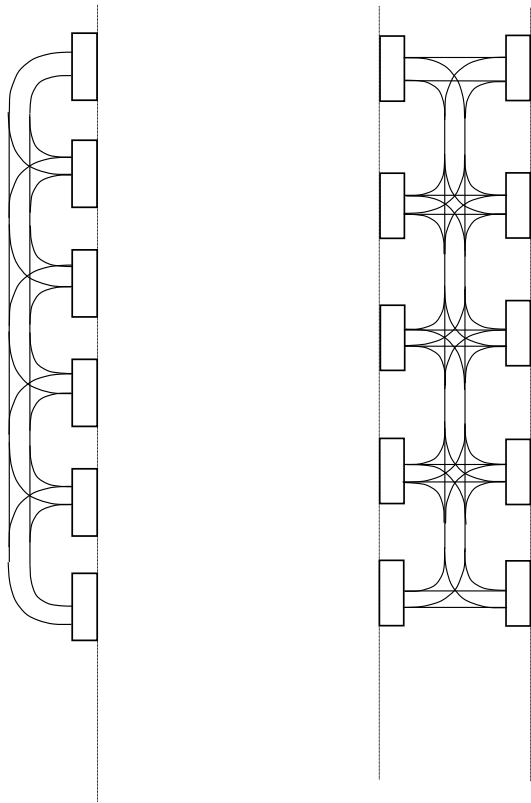
Traffic systems described by Wright et al., 1995



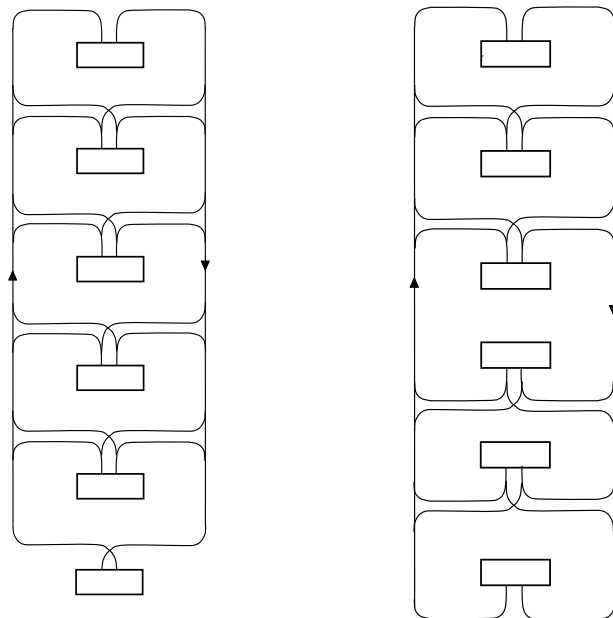
**Figure A.1.** Circulation systems corresponding to routing patterns SIOT and SNIOT



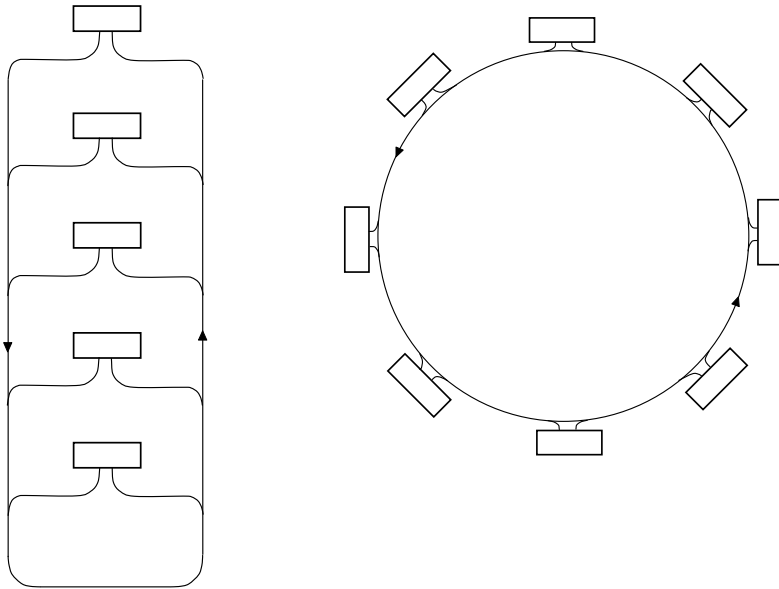
**Figure A.2.** Circulation system corresponding to routing pattern CVP



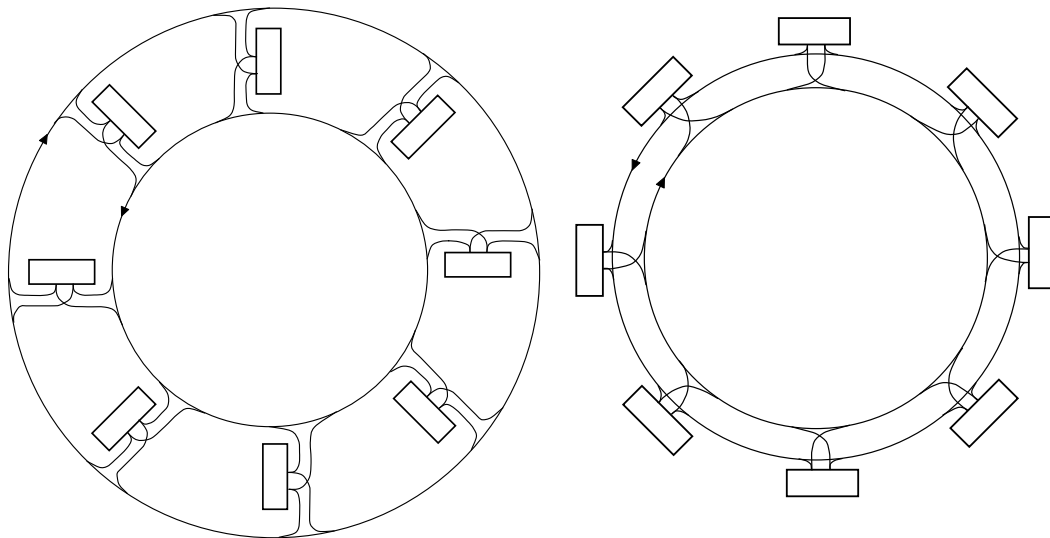
**Figure A.3.** Circulation systems corresponding to routing patterns TWC and TWS



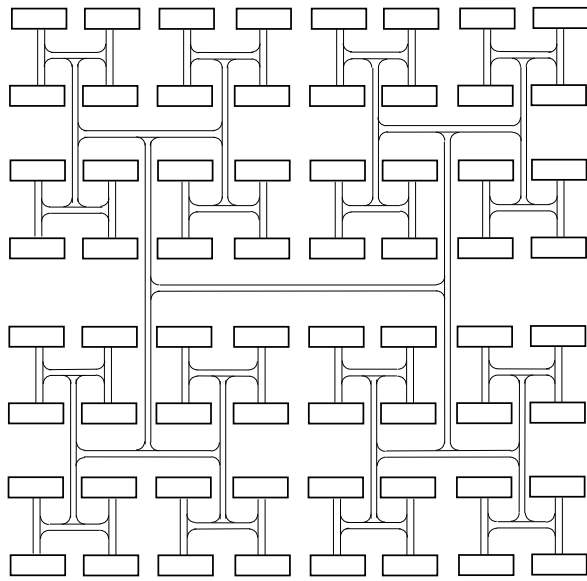
**Figure A.4.** Circulation systems corresponding to routing patterns 2OWCU and 2OWCS





**Figure A.5.** Circulation systems corresponding to routing patterns NL and OWR

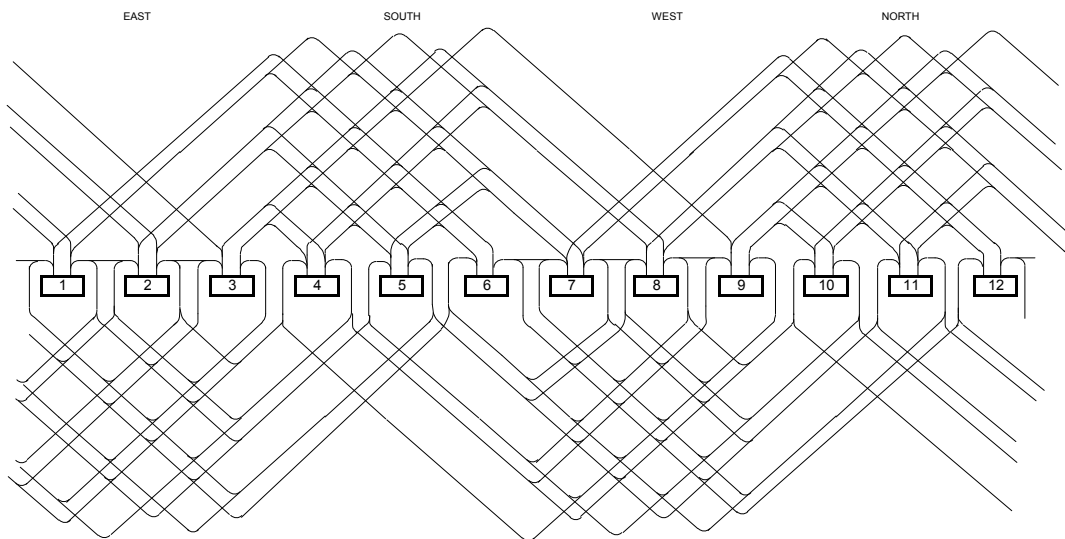


**Figure A.6.** Circulation systems corresponding to routing patterns 2OWR, TWRES and TWRMCS

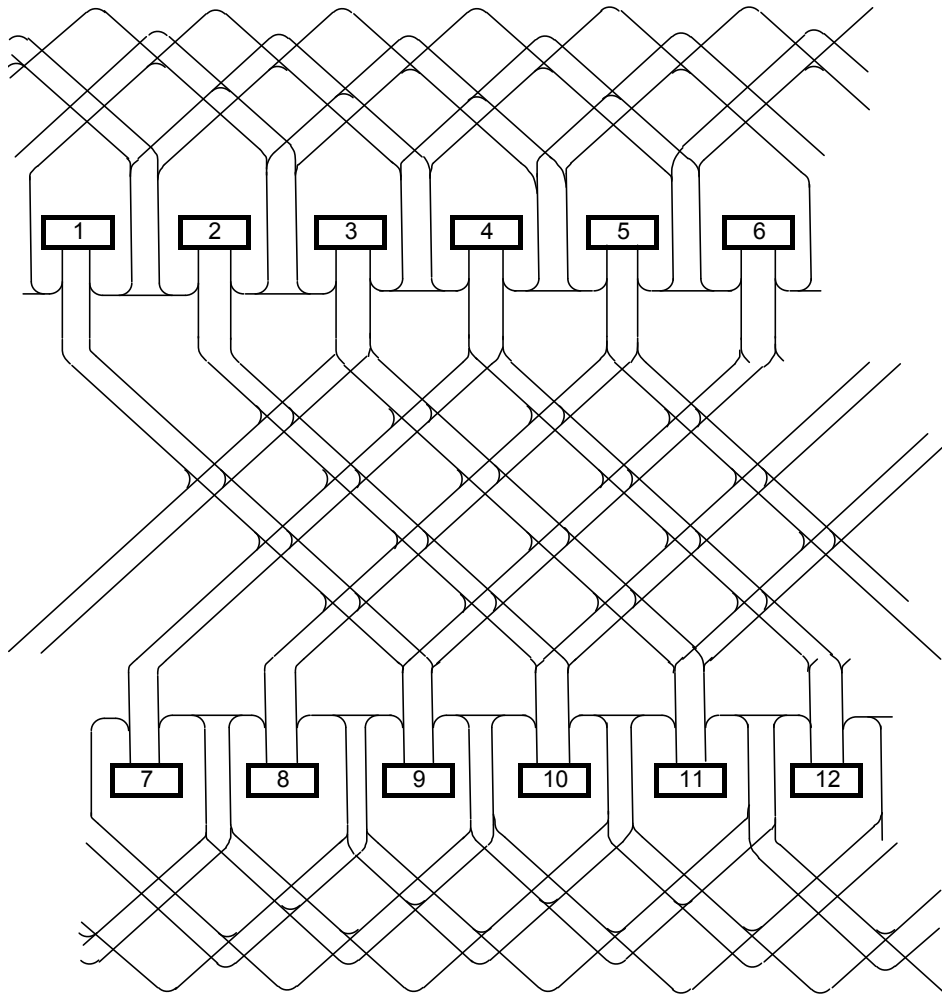


Each intersection is depicted as:   
 This represents an intersection with traffic flows as follows: 

**Figure A.7.** Circulation system corresponding to routing pattern BT

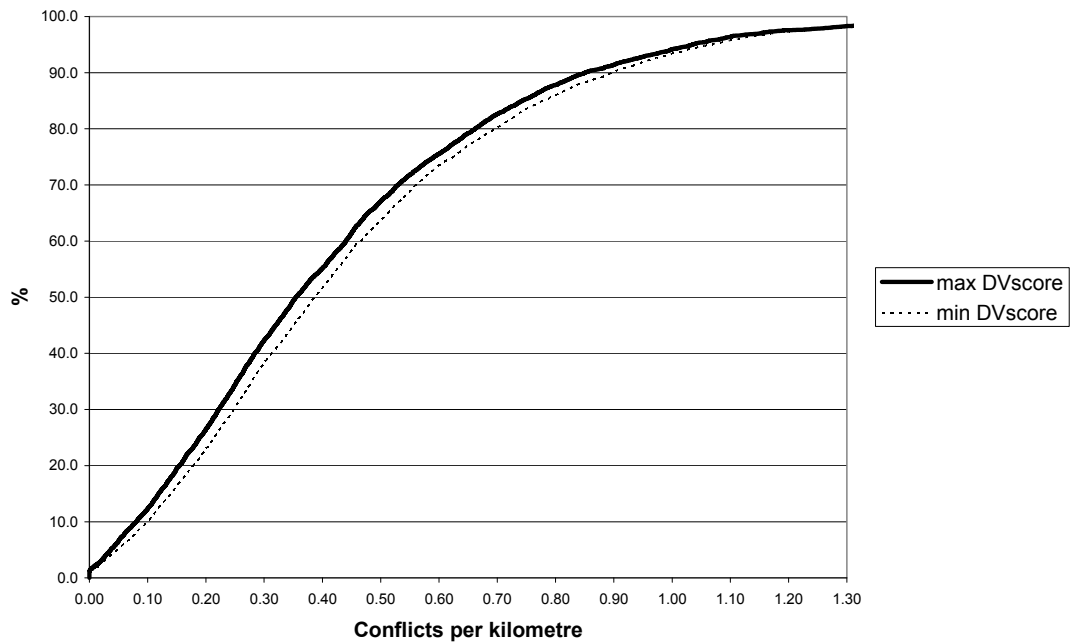


**Figure A.8.** Circulation system corresponding to routing pattern NSEW

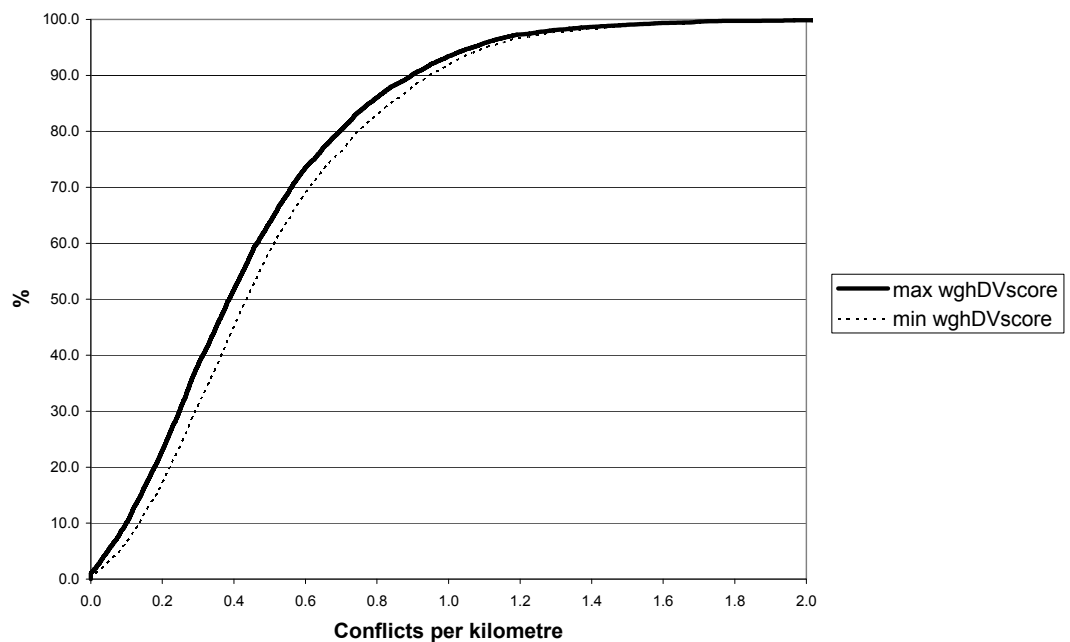


**Figure A.9.** Circulation system corresponding to routing pattern CCP

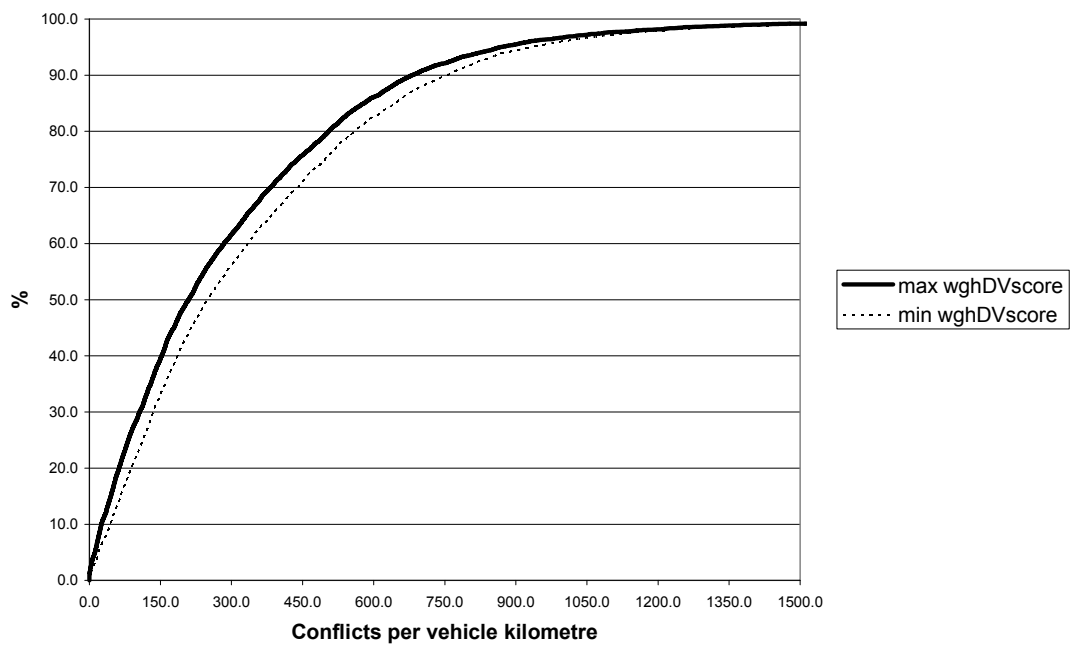
## Appendix B. Distribution of conflict scores



**Figure B.1.** Distribution of the number of conflicts per unit of length, regarding minimum and maximum DV scores within an OD pair



**Figure B.2a.** Distribution of the number of conflicts per unit of length, regarding minimum and maximum wghDV scores within an OD pair



**Figure B.2b.** Distribution of the number of conflicts per vehicle kilometre, regarding minimum and maximum wghDV scores within an OD pair



# Appendix C. Examples of integrated network design

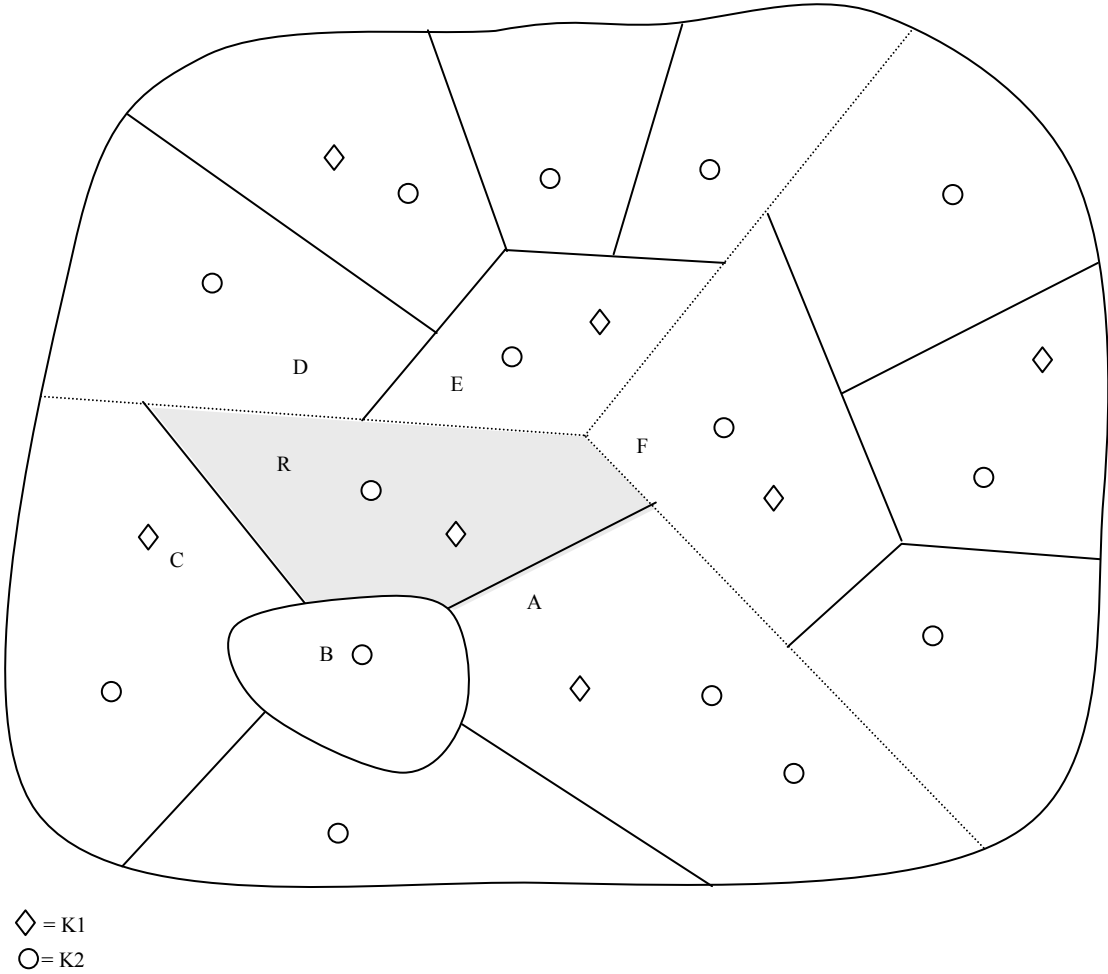
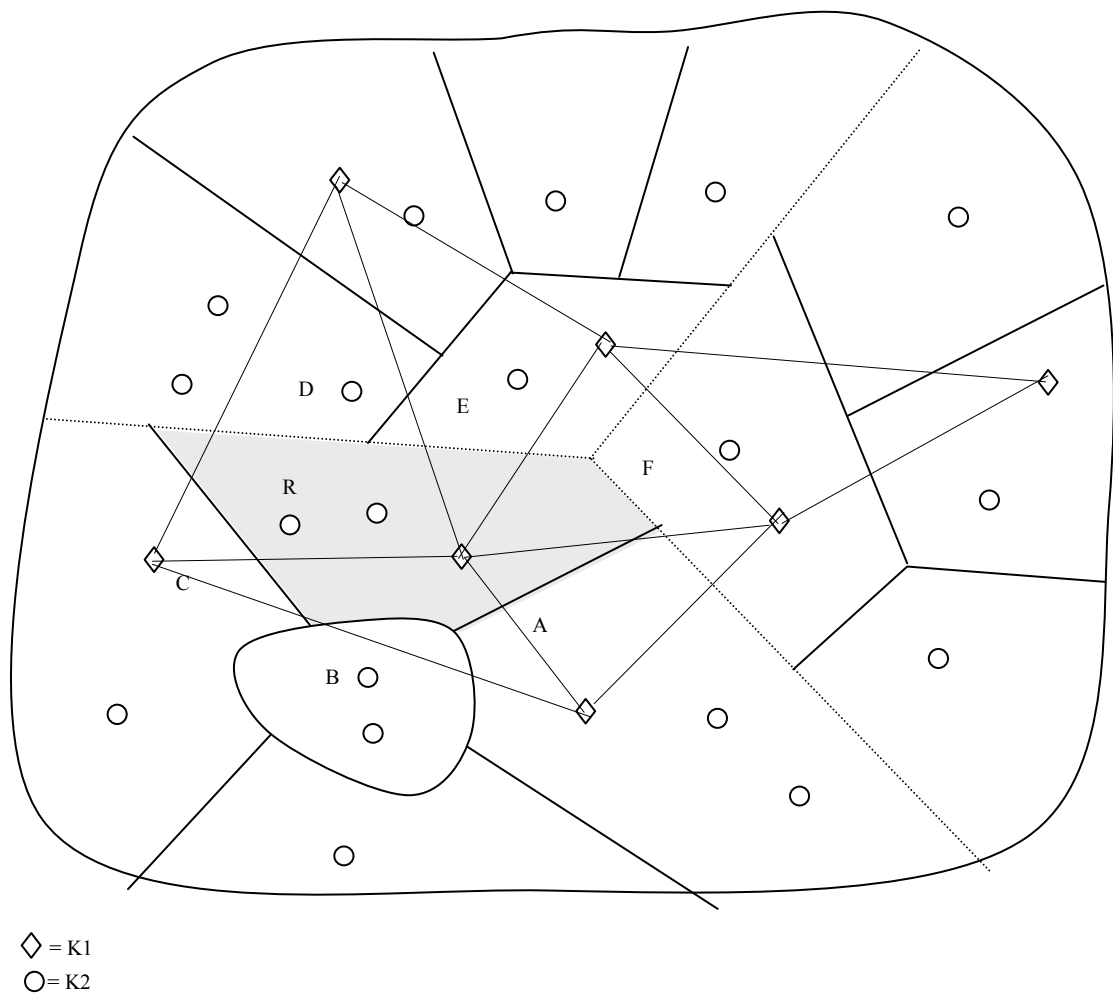
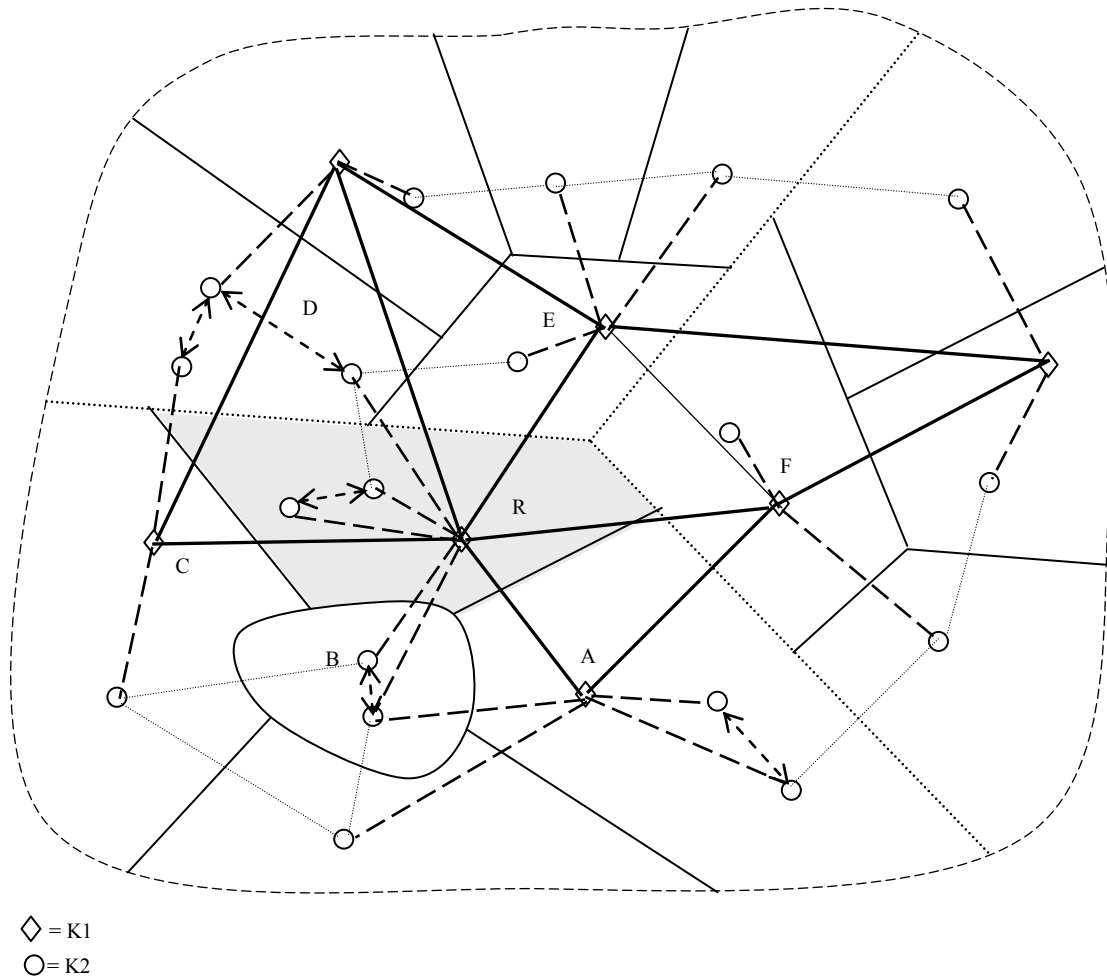


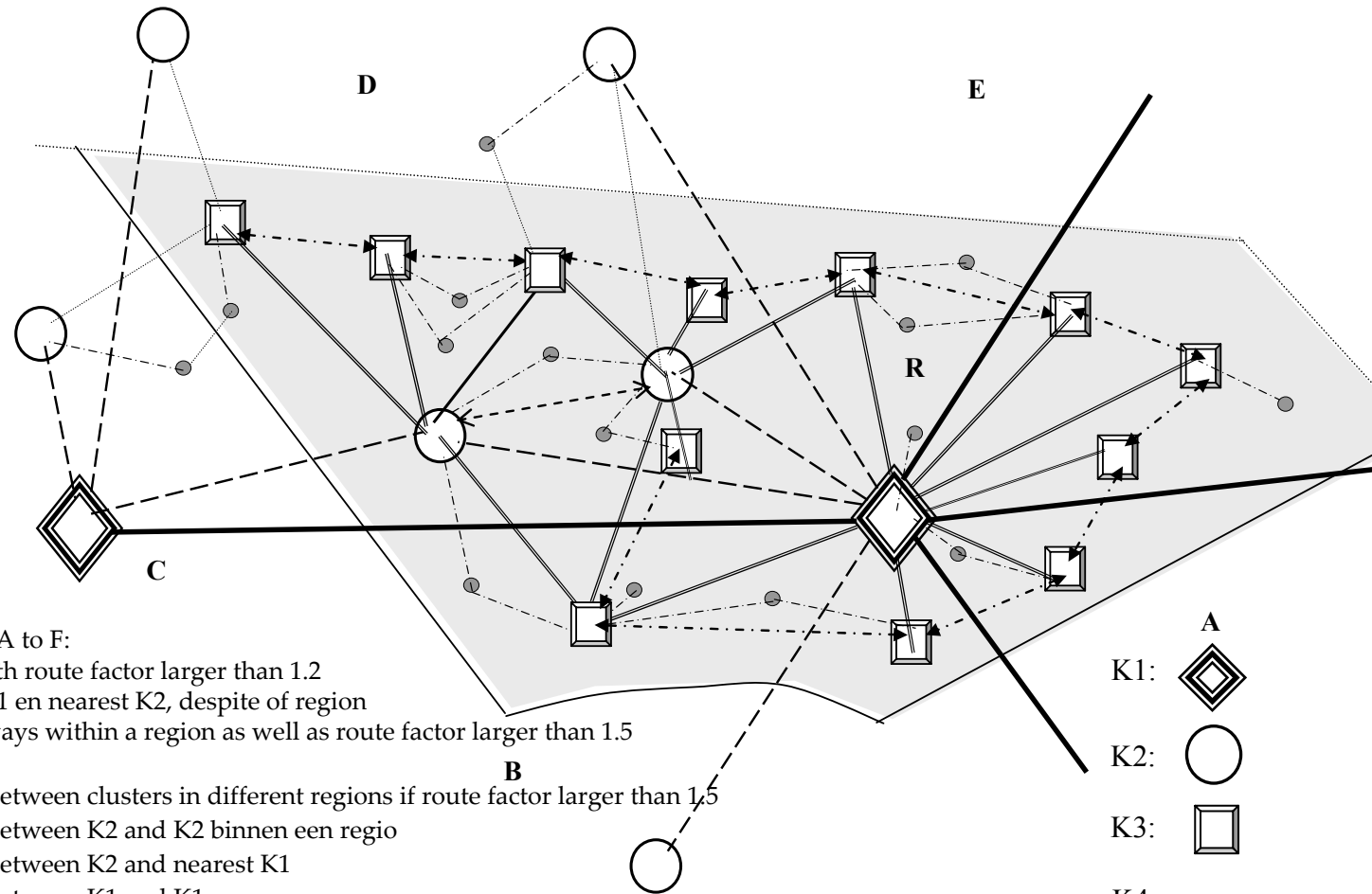
Figure C.1. Distant regions, regions, and clusters types 1 and 2



**Figure C.2.** Desired connections between cluster types 1



**Figure C.3.** Desired connections between cluster types 1 and 2



Regions R, and regions A to F:

Connections K1 - K1 with route factor larger than 1.2

Connections between K1 en nearest K2, despite of region

Connections K2 -K2 always within a region as well as route factor larger than 1.5

..... = connection between clusters in different regions if route factor larger than 1.5

<---> = connection between K2 and K2 binnen een regio





--- = connection between K2 and nearest K1

— = connection between K1 and K1

==== = connection between K3 and K2 or K1

◄.....► = connection between K3 and K3 if route factor larger than 1.5

-·-·-· = connection between K4 and K1, K2 or K3

- A
- K1: 
- K2: 
- K3: 
- K4: 

**Figure C.4.** Desired connections in region R between cluster types 1, 2, 3, and 4

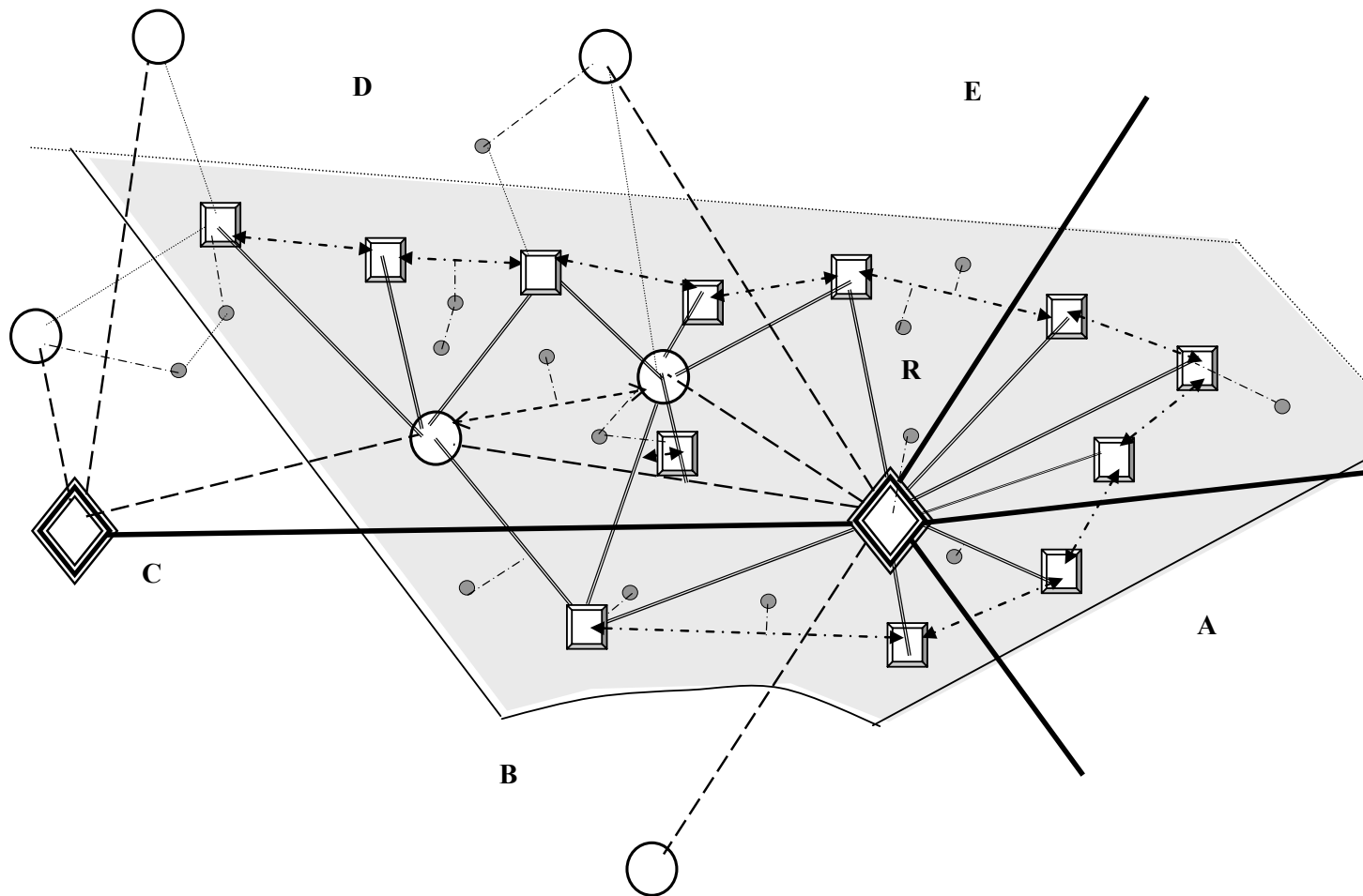


Figure C.5. Simplified version of Figure C.4

## Appendix D. Selected nodes

Simulation structure	Node	Rear End	Lateral	Frontal	Converging	# Arms	Flow Node
Variation 2	1	11				3	3,105
Variation 1	1	8				3	3,092
Baseline structure	1	9				3	3,067
Variation 2	8	71	261			3	4,001
Variation 1	8	61	257			3	4,001
Baseline structure	8	114				3	3,823
Variation 2	15	76				3	1,007
Variation 1	15	74				3	1,002
Baseline structure	15	40		2		3	3,181
Variation 2	19	4	292	3		3	1,401
Variation 1	19	6	293	4		3	1,399
Baseline structure	19	363	93	789		3	3,705
Variation 2	34	28	102			4	4,008
Variation 1	34	30	99			4	4,007
Baseline structure	34	27		90		4	3,823
Variation 2	35	26	42			3	2,030
Variation 1	35	24	41			3	2,029
Baseline structure	35	22		41		3	1,846
Variation 2	45	126	375			4	4,155
Variation 1	45	177	380	2		4	4,269
Baseline structure	45	10		358		4	4,245
Variation 2	46	1	54			4	545
Variation 1	46	1	53			4	555
Baseline structure	46	1		55		4	530
Variation 2	49	8		1,478	1,171	4	10,078
Variation 1	49	8		1,478	1,143	4	10,060
Baseline structure	49	7	1,481		1,141	4	10,011
Variation 2	63		2			3	1,278
Variation 1	63		2			3	106
Baseline structure	63			196		4	1,436

**Table D.1a.** Selected nodes 1-63: numbers of conflicts for each conflict type, total number of conflicts, number of arms, and total numbers of vehicles passing (see also *Figure 7.3*)

Simulation structure	Node	Rear End	Lateral	Frontal	Converging	# Arms	Flow Node
Variation 2	64					4	2,236
Variation 1	64					4	106
Baseline structure	64					4	3,011
Variation 2	74	120	282	486		4	5,746
Variation 1	74	121	379	684		4	8,873
Baseline structure	74	119	665	379		4	8,925
Variation 2	93	1	81	58		4	3,364
Variation 1	93					4	105
Baseline structure	93	5				4	3,065
Variation 2	94					3	1
Variation 1	94					3	104
Baseline structure	(94)					n.a.	-
Variation 2	102	5	3			3	853
Variation 1	102	1				3	445
Baseline structure	102					3	0
Variation 2	103					4	3,406
Variation 1	103					4	2,347
Baseline structure	103					4	0
Variation 2	104	5				3	9,757
Variation 1	104	6				3	10,392
Baseline structure	104	2				3	11,944
Variation 2	109	18	298			3	3,427
Variation 1	109					3	2,363
Baseline structure	109					3	0
Variation 2	111		2			3	2,328
Variation 1	111		2			3	2,389
Baseline structure	111					3	0

**Table D.1b.** Selected nodes 64-111: numbers of conflicts for each conflict type, total number of conflicts, number of arms, and total numbers of vehicles passing (see also *Figure 7.3*)

Simulation structure	Node	Rear End	Lateral	Frontal	Converging	# Arms	Flow Node
Variation 2	114	219		4		3	8,877
Variation 1	114	10		2		3	10,324
Baseline structure	114	7	4			3	10,369
Variation 2	12z	36	95			4	1,106
Variation 1	12z	34	85			4	1,107
Baseline structure	12z					4	1,041
Variation 2	2z	172	4,623	1,937		4	12,095
Variation 1	2z	163	4,428	1,888		4	11,907
Baseline structure	2z	176	1,872	4,515		4	11,962
Variation 2	50z	576	1,490	2,182		4	10,025
Variation 1	50z	588	1,605	2,130		4	9,951
Baseline structure	50z	566	2,181	1,506		4	9,926

**Table D.1c.** Selected nodes 114-50z: numbers of conflicts for each conflict type, total number of conflicts, number of arms, and total numbers of vehicles passing (see also *Figure 7.3*)





## Summary

The subject of this study is about the influence of network structure and road classification on road safety. Road safety, or unsafety, is usually expressed as the number of crashes or casualties. It is not evident how one can relate what happens at street level to the decisions regarding network design and the elaboration of this design. Traffic circulation can be regarded as the link between these two levels. Behind traffic circulation is the individual who decides to travel from a point of origin to a destination, using a particular route. The route is the starting point for this study. That is because network structure and road classification are important preconditions for traffic circulation and route choice, while the intersecting routes will determine the crash locations. This study will therefore focus on the effects of changing route choices on road safety. The changes in route choice may be the result of:

1. (intended) changes in the structure of the road network
2. a change in traffic circulation, e.g. on account of an alteration of a traffic signal system or of congestion on the main roads
3. instructions to car drivers through navigation systems or route guidance signs

These changes, adaptations and instructions aim to improve the traffic and transport system as a whole. This study is undertaken to find the effect of the changes/instructions enumerated above on the safety of all road users in the road network. This study will show whether an improvement can be attained and how it can be attained.

In this study, an attempt was made to connect different worlds; the world of transport network design, the world of route choice research, the world of micro-simulation modelling, and finally, the world of surrogate safety measures (conflict indicators).

The topic of this study was inspired by the functional requirements of Sustainable Safety, in particular that the shortest and safest route should coincide. Would it be possible to determine whether this requirement can be fulfilled? For answering this question, one needs a method that can represent several safety aspects of trips and routes. Existing methods only show the safety of either intersections or road sections. New methods had to be developed for answering the aforementioned questions. These methods are able to show the results of the improvements for road safety and for traffic

flow. The methods can predict the results before the improvements will actually be implemented.

The topic relates to the following five main research areas: road networks, use of the road network, routes and route choice, influencing route choice, and safety aspects of the four previous areas. These main research areas have been subdivided into eight subjects of this study.

1. *Characteristics of transportation networks and road networks; influence on both the generation of traffic and the circulation of traffic in the road network*

Indicators based on the number of crossing or conflicting vehicles and the type of these conflicts are relevant if road structures need to be selected for increased road safety. Literature shows a number of indications of some road structures having low numbers of crossing vehicles. On the other hand, these structures can have longer distances travelled, which means more exposure to risk. In theory, some structures have low numbers of crossings as well as short distances travelled.

2. *Road network structure and road classification: their influence on traffic circulation and its road safety aspects*

In the Netherlands, the methods for arriving at a network structure and a road classification are not a foregone conclusion. The design principles and rules of thumb are mostly based on practical experience. The scientific foundation for this set of principles, requirements and rules is very frail.

A series of requirements was formulated in Sustainable Safety with the purpose of improving the functioning of the road network safety and efficiency. In this study, the method of 'integrated network design' was developed to test whether the road network meets these requirements.

3. *Route choice in road networks; options to influence route choice*

Car drivers mention 'fastest route' and 'shortest route' as main preferences for their route choice. The next preference is 'prior knowledge about a route'. Car drivers hardly ever take 'safety of a route' into consideration when choosing a route. Prior to a trip, most drivers take note of traffic information, mostly by radio, television or Internet. This information will largely determine route choice or departure time. The traffic information en route comes from radio, personal observation, variable message systems, and, for some drivers, a navigation system. A substantial proportion of drivers change their route because of this information.

The expected total effect of navigation systems is: less exposure at the expense of some loss of attention to the other road users.

4. *Road safety aspects of road network structure and road classification; results from modelling studies and evaluation studies*

Countermeasures regarding network structure and road classification appear to result in crash or casualty reductions ranging from 40 to 80 percent. In most cases, safety on the surrounding roads hardly worsened, because additional measures were taken.

5. *Detecting the effects on road safety by changes in route choice; methodological issues and review of different types of studies*

From a series of methods, it can be concluded that a few methods are suited for studying road safety effects of changes in the use of the road network, caused by adaptations of the network structure and/or road classification. The effects of these changes on route choice, in particular, determine the choice of method. These methods are: key safety indicators, crash prediction models, comparing features to requirements, and surrogate safety measures (used in micro-simulation models). Only surrogate safety measures will show output for the safety of individual routes.

6. *More detailed analysis of road safety indicators; simulated conflicts and recorded crashes*

The estimated numbers of conflicts between vehicles in a micro-simulation model (S-Paramics) have been calculated here according to a specified method. The number of conflicts at junctions and the number of passing motor vehicles appear to be quantitatively related to the number of observed crashes for all junctions. The goodness of fit of this relationship could be statistically confirmed.

Models like S-Paramics are, to a great extent, black boxes. For research purposes, the internal modelling of vehicle movements and interactions should be clearer.

The model does not yet take traffic other than motor vehicles into account. Addition of cyclist and pedestrian movements is, however, desired.

7. *More detailed analysis of road safety indicators; simulated conflicts, route characteristics and route criteria*

The route score consists of a number of safety criteria. Each criterion can be weighted. The route scores change slightly if the weighting of the criteria is adapted. The numbers of conflicts are directly related to the route score. The weightings are not necessary to improve the relation between route score and conflict indicators.

A high value for the route score is related to a lower number of conflicts, to a lower conflict density, and to a lower conflict risk.

8. *Changing route choice for more safety; adapting road structure.*

The application of an integrated network design method to the study area showed that many connections use roads which have a much higher position in the road network than desired according to the method. This conclusion was supported in other (foreign) studies. This finding clearly shows the structure of the road network in the Netherlands: many main roads (motorways) facilitating as many connections as possible, disregarding the distance between the origin and destination of these connections.

### **Recommendations**

This study shows that, in existing road networks, the safest route does not always coincide with the fastest route. However, car drivers tend to choose the fastest route. Therefore, the fastest routes should be converted to routes that are also the safest.

The importance of road classification for road safety purposes seems to be underestimated. In the Netherlands, the methods for classifying roads could be improved substantially. This study proposes a method for classifying roads: integrated network design. Whether this method really benefits road safety will have to be the subject of further research. This method should be applied to more areas than the present study area. This may show whether the results depend on the (type of) area. From these findings, the issues of generalization and practical application should be resolved.

Road safety will benefit from spreading traffic over a greater number of roads. However, the cost effectiveness of the increase in road length is still a matter to be considered.

Another important issue in this study is the safety indicators (surrogate safety measures). All safety indicators, other than crash figures, are still being researched. A great deal of study is needed before crash figures can be replaced by other safety indicators. However, the conflict indicators in micro-simulation models appear to be a promising approach in finding adequate and accurate safety indicators.

The safety criteria of route choice should be incorporated into navigation systems. A test is recommended to discover the effects of the actual advantages for safety.

## Samenvatting

Deze studie gaat over de invloed van netwerkstructuur en wegategorisering op verkeersveiligheid. Verkeersveiligheid, of -onveiligheid, wordt meestal uitgedrukt in aantallen slachtoffers of ongevallen. Het is niet duidelijk hoe men gebeurtenissen op straat kan relateren aan beslissingen op het niveau van het wegennet of aan de uitwerking daarvan. Verkeerscirculatie beschouwt men als de verbinding tussen beide niveaus. Achter deze verkeerscirculatie zit de individuele verkeersdeelnemer die beslist om van herkomst naar bestemming te reizen, via een specifieke route. De route is het startpunt van deze studie. Dat is omdat netwerkstructuur en wegategorisering belangrijke voorwaarden zijn voor de verkeerscirculatie en de routekeuze. Terwijl de snijpunten van de gekozen routes de ongevalslocaties bepalen. De studie zal daarom focussen op de veranderingen in routekeuze op verkeersveiligheid. Veranderingen in routekeuze kunnen plaatsvinden door:

1. (geplande) veranderingen in de netwerkstructuur;
2. verandering in verkeerscirculatie, bijvoorbeeld door een aanpassing van een verkeersregelininstallatie of door congestie op hoofdwegen;
3. aanwijzingen aan autobestuurders door een navigatiesysteem of door aanwijzingen langs de weg.

Deze veranderingen, aanpassingen en aanwijzingen zijn bedoeld om het verkeerssysteem als geheel te verbeteren. Deze studie is uitgevoerd om het effect vast te stellen van bovengenoemde veranderingen of aanwijzingen op de verkeersveiligheid van alle weggebruikers. Deze studie toont aan of een verbetering wordt bereikt en zo ja, op welke manier.

In deze studie is geprobeerd verschillende werelden te verenigen: de wereld van het ontwerp van vervoersnetwerken, de wereld van het routekeuze-onderzoek, de wereld van microsimulatiemodellen, en ten slotte, de wereld van de niet-ongevalgegevens, meestal aangeduid met conflictindicatoren ('surrogate safety measures').

Het onderwerp van deze studie is geïnspireerd door de functionele eisen van Duurzaam Veilig, in het bijzonder de eis dat de veiligste en snelste route moeten samenvallen. Is het mogelijk om vast te stellen of aan deze eis kan worden voldaan? Om deze vraag te kunnen beantwoorden is een methode nodig die uitdrukking geeft aan verschillende veiligheidsaspecten van verplaatsingen en routes. Bestaande methoden laten alleen de veiligheid van wegvakken of kruispunten zien, zelden de aaneenschakeling van beide

elementen. Nieuwe methoden moesten worden ontwikkeld om de voorgaande vraagstelling aan te pakken. Deze methoden maken het mogelijk om het effect van verbeteringen te laten zien op zowel de veiligheid als de doorstroming van het verkeer. De methoden geven een prognose van de resultaten voordat de verbeteringen daadwerkelijk tot stand zijn gebracht. Deze studie richt zich op de volgende onderzoeksgebieden: vervoersnetwerken en wegennetten, gebruik van het wegennet, routes en routekeuze, beïnvloeding van routekeuze, en verkeersveiligheidsaspecten van de voornoemde gebieden. Deze onderzoeksgebieden zijn onderverdeeld in de volgende acht onderwerpen.

1. *Kenmerken van vervoersnetwerken en wegennetten; invloed op de vervoersvraag en op de verkeerscirculatie in het wegennet*

Of een netwerkstructuur voldoende verkeersveilig zal zijn, kan men nagaan door indicatoren te hanteren die een schatting geven van het aantal kruisende of conflicterende voertuigen en/of van de voorkomende conflicttypen. De literatuur laat zien dat in sommige netwerkstructuren een gering aantal kruisende voertuigen mag worden verwacht. Anderzijds zijn de afgelegde afstanden dan meestal groter; dat betekent meer blootstelling aan gevaar. Er zijn echter netwerkstructuren die zowel een gering aantal kruisende voertuigen als kortere afgelegde afstanden vertonen.

2. *Netwerkstructuur en wegategorisering; hun invloed op de verkeerscirculatie en hun verkeersveiligheidsaspecten*

In Nederland is het nog geen uitgemaakte zaak welke methoden geschikt zijn om de netwerkstructuur en de wegategorisering respectievelijk te ontwerpen en vast te stellen. De gehanteerde ontwerpprincipes en vuistregels zijn voornamelijk gebaseerd op praktijkervaring. De wetenschappelijke onderbouwing voor deze principes, eisen en vuistregels is zeer zwak.

In Duurzaam Veilig is een pakket van eisen geformuleerd met als doel het wegennet veiliger en efficiënter te laten functioneren. In deze studie is de kernenmethode ontwikkeld om na te gaan of het wegennet voldoet aan de gestelde eisen.

3. *Routekeuze in wegennetten; mogelijkheden om routekeuze te beïnvloeden*

Autobestuurders noemen 'snelste route' en 'kortste route' als de belangrijkste voorkeuren bij hun routekeuze. De derde voorkeur is 'voorgaande kennis over een route'. Autobestuurders letten bij hun routekeuze zelden op 'veiligheid op een route'. Voorafgaand aan een verplaatsing nemen de meeste bestuurders kennis van verkeersinformatie via radio, televisie of internet.

Deze informatie bepaalt in hoofdlijnen de vertrektijd en de routekeuze. De verkeersinformatie onderweg verkrijgt men via de radio, eigen observatie, dynamische route-informatie en, voor sommigen, het navigatiesysteem. Een aanzienlijk deel van de bestuurders verandert de route op grond van deze informatie.

Het verwachte totale effect van navigatiesystemen is: minder blootstelling aan gevaar ten koste van enig verlies aan aandacht voor andere weggebruikers.

4. *Verkeersveiligheidsaspecten van netwerkstructuren en van wegategorisering; resultaten uit modelstudies en evaluatiestudies*

Maatregelen op het niveau van netwerkstructuur en wegategorisering hebben in de praktijk geleid tot grote dalingen (40 tot 80 procent) in het aantal verkeersslachtoffers. In de meeste gevallen is de onveiligheid op de omliggende wegen van deze aangepaste gebieden nauwelijks verslechterd doordat aanvullende maatregelen waren genomen.

5. *Het veiligheidseffect van een veranderde routekeuze vaststellen; methodologische kwesties en een overzicht van diverse studies*

Uit een aantal verschillende studies kan worden afgeleid dat er enkele geschikte methoden zijn om de veiligheidseffecten te bepalen van veranderingen in het gebruik van het wegennet. Dit betreft veranderingen die veroorzaakt zijn door aanpassingen van de netwerkstructuur en/of de wegategorisering. De hier gezochte methoden moeten inzicht bieden in het effect van veranderingen op de routekeuze. Deze methoden zijn: risicocijfers, 'crash prediction models', vergelijking van verkeersvoorzieningen met de gestelde verkeerskundige eisen, en veiligheidsindicatoren die in microsimulatiemodellen worden gebruikt ('surrogate safety measures'). Alleen de laatstgenoemde methode laat de veiligheid van individuele routes zien.

6. *Gedetailleerde analyse van veiligheidindicatoren; gesimuleerde conflicten en geregistreerde ongevallen*

De aantallen conflicten tussen voertuigen in het hier gebruikte microsimulatiemodel (*S-Paramics*) zijn geschat volgens een methode die in deze studie is beschreven. Het aantal geschatte conflicten op kruispunten is gerelateerd aan het aantal geregistreerde ongevallen op die kruispunten. Hiertussen blijkt een kwantitatieve relatie te bestaan; dit is statistisch onderbouwd.

Modellen zoals *S-Paramics* zijn in grote mate een 'black box'. Voor onderzoeksdoeleinden zou er meer duidelijkheid moeten komen over de



modellering van de bewegingen van de voertuigen en van de onderlinge reacties tussen de voertuigen.

In het gebruikte model zijn alleen motorvoertuigen beschouwd. Toevoeging van fietsers en voetgangers is wenselijk.

7. *Gedetailleerde analyse van veiligheidsindicatoren; gesimuleerde conflicten, kenmerken van routes en routecriteria*

De zogeheten routescore bestaat uit een aantal veiligheidscriteria. Elk criterium kan worden voorzien van een weegfactor waardoor de onderlinge verhoudingen tussen de weegfactoren veranderen. De routescores veranderen in geringe mate bij toepassing van deze weegfactoren. De routescores zijn direct gerelateerd aan het geschatte aantal conflicten per route. Het gebruik van weegfactoren beïnvloedt deze relatie nauwelijks.

Een hoge waarde van de routescore zou theoretisch overeen moeten komen met een laag aantal conflicten, met een lage conflictdichtheid en met een laag conflictrisico. Dit blijkt volgens de geanalyseerde gegevens het geval te zijn.

8. *De routekeuze veranderen om de veiligheid te bevorderen; aanpassing van de netwerkstructuur*

De toepassing van de kernenmethode op het studiegebied laat zien dat veel verbindingen tussen kernen via wegen verlopen die een veel hogere functie in het netwerk hebben dan voor die verbindingen (volgens de methode) gewenst is. Deze conclusie is ook in andere (buitenlandse) studies getrokken. Deze bevinding laat zien dat het Nederlandse wegennet een structuur heeft die bestaat uit relatief veel autosnelwegen met veel aansluitingen en dat veel routes via deze wegen lopen, ongeacht de afstand van verplaatsing.

### **Aanbevelingen**

Deze studie laat zien dat in bestaande wegennetten de veiligste route niet altijd via de snelste route loopt. Autobestuurders kiezen echter meestal voor de snelste route. Daarom zouden de snelste routes moeten worden aangepast zodat ze ook de veiligste worden.

Het belang van wegcategorisering voor veiligheidsdoeleinden wordt onderschat. In Nederland kan de methode om wegen te categoriseren flink worden verbeterd door de kernenmethode toe te passen. Of deze methode daadwerkelijk de veiligheid zal verbeteren verdient nadere studie. In deze studie is de methode toegepast op één studiegebied; toepassing op meer gebieden is gewenst. Daaruit zal blijken of de methode generaliseerbaar is. Vervolgens is een bredere toepassing aan de orde.

De verkeersveiligheid is er mee gediend om het verkeer over verschillende routes te spreiden. Onderzoek is gewenst naar de maatschappelijke kosteneffectiviteit hiervan.

In deze studie zijn veiligheidsindicatoren gebruikt, met name conflict-indicatoren en routescores. Alle veiligheidsindicatoren, anders dan ongevallencijfers, zijn (internationaal) onderwerp van onderzoek. Uit de resultaten van dat onderzoek moet blijken of het verantwoord is om veiligheidsindicatoren in plaats van ongevallencijfers te hanteren. Uit deze studie blijkt dat conflictindicatoren sterk gerelateerd zijn aan ongevallencijfers. Dit is een belangrijke stap op weg naar adequate veiligheidsindicatoren.

De hier gehanteerde veiligheidscriteria voor routekeuze kunnen ingebouwd worden in navigatiesystemen. In een pilotstudie kunnen de werkelijke effecten hiervan op veiligheid worden onderzocht.



## Curriculum Vitae

Atze Dijkstra was born in Groningen, on 19 November 1954. He studied civil engineering at the Delft University of Technology. After his graduation, he worked as a researcher at the Transportation and Traffic Engineering Section of the Faculty of Civil Engineering. In 1983 he joined the SWOV Institute for Road Safety Research as a researcher, a post he fulfilled until 1992. His main research projects dealt with the analysis of the safety aspects of bicycle facilities, the evaluation of 30 km/h zones, and the analysis of quantitative relations between road characteristics (of main rural and urban roads) and crash indicators. When he left SWOV in 1992, he was a project manager responsible for the research programme 'Designing safer roads'.

From 1992 until 1996 he worked as a researcher and research manager at the OTB Research Institute for Housing, Urban and Mobility Studies (an institute of the Delft University of Technology). His work focused on both goods transport by rail (evaluation of the existing capacity of the rail infrastructure), and on internal goods transport, using the Maasvlakte (Port of Rotterdam) as a case study.

He rejoined the SWOV as a senior researcher in 1996. From 1996 to 1998 he was the project manager of several work packages in European research projects regarding bicycle and pedestrian facilities (ADONIS), and regarding the design of road infrastructure (SAFESTAR). SAFESTAR was also the platform from which Road Safety Audits in the Netherlands were launched. He set up the national course for road safety auditors; a course that has been presented every year since 2001.

From 1999 to 2003 he was the manager of the research programme 'Road design and road safety'. Within this programme he set up and supervised the evaluation of the newly built 60 km/h zones. In this period, Atze was a member of a number of national working groups (organized by CROW) on various geometrical and related topics (incl. road humps, bicycle facilities, pedestrian crossings).

At the end of 2003 Atze started working on the project 'Route choice in a road network' which ultimately resulted in his thesis. This eight-year project was an opportunity for him to get extensively acquainted with the intricacies of micro-simulation modelling. During this period, he also wrote many fact sheets, evaluated the safety of bicycle facilities at roundabouts, and studied the effects of a robust road network on road safety.



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