THE ANALYSIS OF THE NUMBER OF PASSENGER CARS AND LORRIES INVOLVED IN ACCIDENTS AS A FUNCTION OF ROAD-SURFACE SKIDDING RESISTANCE AND HOURLY TRAFFIC VOLUME

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(shortened version)

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In 1966, a Working Group on Tyres, Road Surfaces and Skidding Accidents was set up in the Netherlands. The terms of reference of Sub-commitee V of this Working group was to establish the number of skidding accidents, and to investigate the role that road-surface skidding resistance plays in accident occurrence. A full description of the research is given in Schlösser (1977). The reasons that led to the choice of the models of analysis and a detailed description of the results of the analysis on the accident data can be found in Oppe (1977). In the present paper the interest will be focussed on the analysis of the involvement of lorries and passenger cars in accidents.

DATA

Unit of investigation is the number of lorries (passenger cars) involved in accidents during a given time period, divided by the number of vehicle kilometres of that category of vehicles driven during the same time period. These involvement ratios are computed separately for accidents classified according to road-surface skidding resistance of the road section on which the accident took place and hourly traffic volume on that road section during the time of the accident. Only accidents during rainfall are analysed. The involvement ratios are computed separately for motorways (road type I) and other primary national highways (road type II). This resulted in four tables of involvement ratios corresponding to the two types of roads and two types of vehicles. For road type I the hourly traffic volumes are divided in 20 classes with intervals of 100 vehicles per hour for each direction; for road type II into 15 classes with intervals of 200 vehicles per hour in both directions. The road sections are divided in nine skidding resistance classes corresponding to the coefficient of longitudinal force for a wet surface. The classes ranged from $\leqslant .36$ to $> .71$ in steps of .05 units of measurement.

ANALYSIS

Additive Conjoint Measurement

The intention of the analysis is to examine how the involvement ratio (I) depends on hourly traffic volume (V) and road-surface skidding resistance (R). The first assumption is that the effects of V on I and R on I are independent of each other. In a second analysis this assumption will be tested. A second assumption regards the choice between an additive model and a multiplicative model. In linear models, such as analysis of variance, it is assumed that the effects of R on I and V on I are additive; in log-linear models, such as the Poisson models mentioned later on, one assumes that the effects are multiplicative. Because the choice between both models is questionable, it is decided to use only the order information of the I-values in an additive analysis. If the optimal solution of this additive analysis results in predictions of I (I^*) that are linear with I, this means that an additive model could have been used directly on the data; a logarithmic relation between I and I^* favours a multiplicative model. The descriptive model that is used is known as Additive Conjoint Measurement (ACM). As a result of this analysis the multiplicative model turns out to be correct. A detailed description of this analysis is found in Oppe (1977).

Weighted Poisson Models

In a second analysis it is assumed that the number of vehicles involved in accidents in each cell of a table is Poisson distributed. Furthermore, the Poisson parameter of each cell is assumed to be composed of three factors, a general factor α, according to the rate of involvements, a specific volume factor (γ_j) according to the probability of a given involvement to belong to volume class j and a specific resistance factor (β_i) according to resistance class i. The product of these part parameters gives the Poisson parameter $\alpha \beta_i \gamma_j$ of the cell (i, j) in the table. The models for analysis resulting from these assumptions are in general called log-linear models, because the logarithm of the Poisson parameters is a linear function of the logarithm of the part parameters. To analyse involvement ratios instead of the number of vehicles involved, the vehicle kilometres are assumed to be correcting constants. The models used to analyse the involvement ratios are called Weighted Poisson Models (WPM). A description of these models can be found in De Leeuw and Oppe (1976).

RESULTS

Figure 1 shows the relation between the road-surface skidding resistance classes and the corresponding part parameters, for lorries at road type I and II. From this figure it can be concluded that this relation is linear. The peripheral effect for the curve of road type II is probably due to the small amount of data in skidding resistance class 1. If the relation is linear and the multiplicative model is correct then the relation between the skidding resistance classes and the corresponding involvement ratios is exponential. This means that measures taken to improve road-surface skidding resistance are effective at all levels. However, the greatest effect per level will be reached at the lower levels of skidding resistance.

Figure 2 shows the relation between the hourly traffic volume classes and the corresponding part parameters, for lorries at road type I and II. From this figure it can be seen that in general there is an increase of accident susceptibility with an increase of hourly traffic volume. For road type I the effect decreases at the higher volumes. The same effect is found for accident ratios and involvement ratios of passenger cars, but not for involvement ratios of lorries at road type II. With regard to these findings it must be noted that no observations are recorded in the traffic volume classes higher then 15 at road type II. In the lower traffic volume classes of road type I a reversed effect is found; here the accident susceptibility increases with a decrease in hourly traffic volume.

Table 1 shows the contributions of each component in the WPM-analysis. Skidding resistance seems most effective in explaining the data; the contribution of the traffic volume effect is less, but also highly significant. The interaction effect is not significant for road type I. This means that the effects of skidding resistance and traffic volume on the involvement ratios are independent of each other. This is not found for road type II. This may be caused by disturbing factors such as diversity in type of roads, influence of accidents at crossings and not separated carriageways.

Finally it may be concluded that multiplicative models seem to be more appropriate for these kinds of data than additive models.

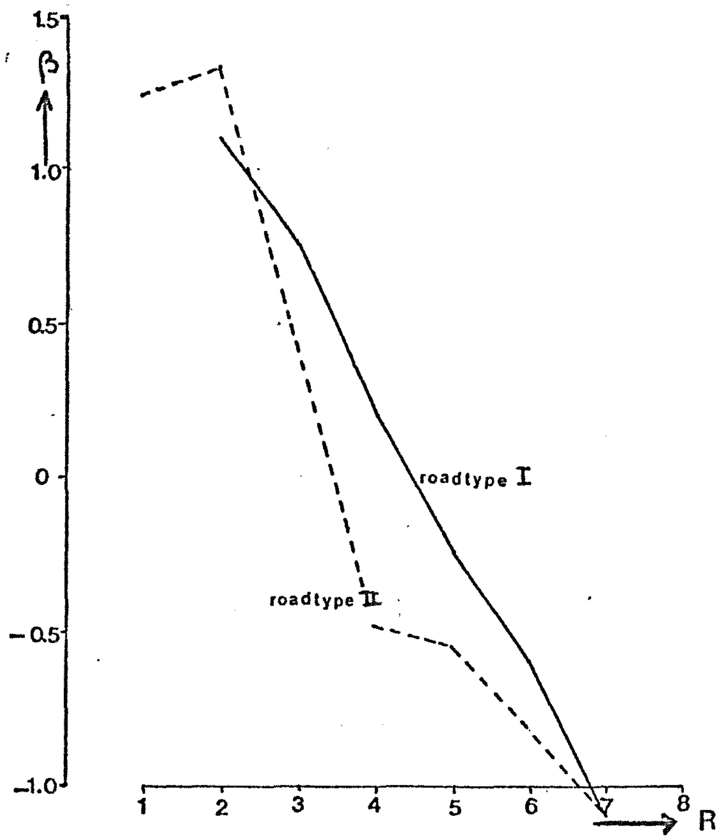

Fig. 1. Relation between the β-parameters of lorries and road-surface skidding resistance (R) for road type I and II.

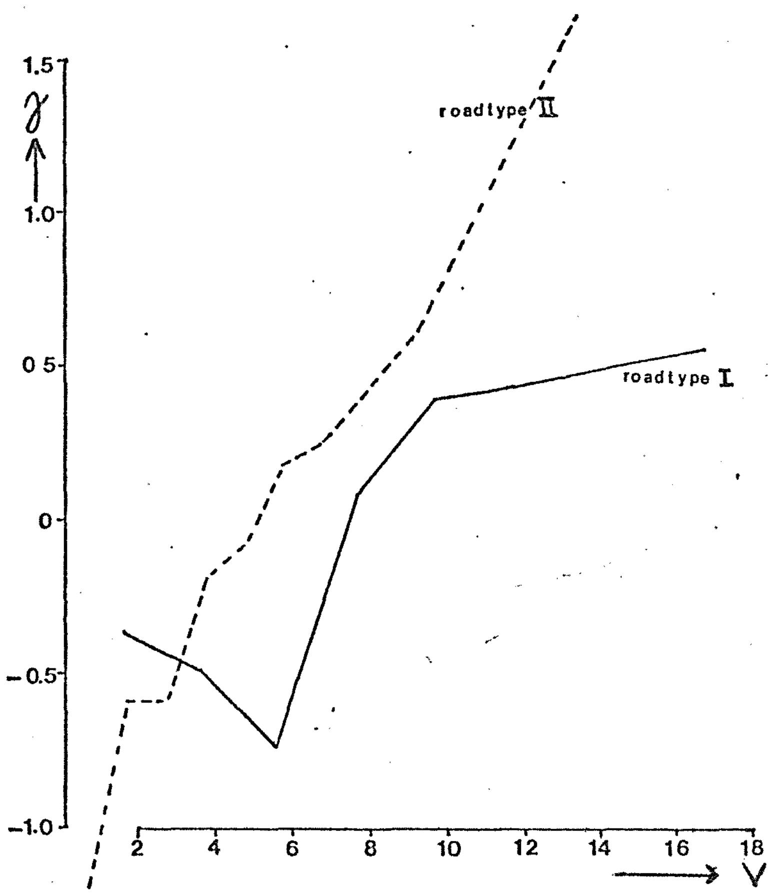

Fig. 2. Relation between the γ -parameters of lorries and hourly traffic volume (V) for road type I and II.

	Road type I				Road type II			
	lorries		passenger cars		lorries		passenger cars	
	χ^2-value	d.f.	χ^2-value	d.f.	χ^2-value	d.f.	χ^2-value	d.f.
R	92.73	5	598.62	5	233.56	6	607.22	6
V	36.25	12	142.42	12	117.87	8	255.37	9
RxV	43.07	60	112.64	60	140.89	48	365.04	54

Table 1. Chi-square values and degrees of freedom for resistance effect (R), volume effect (V) and the interaction (RxV) resulting from the WPM-analysis of the involvement ratios.

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Bishop, Y.M.M., Fienberg, S.E. & Holland, P.W. (1975). Discrete Multivariate Analysis: Theory and Practice, MIT-press, London.

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In 1966, a Working Group on Tyres, Road Surfaces and Skidding Accidents was set up in the Netherlands. The terms of reference of Sub-committee V of this Working Group was to establish the number of skidding accidents, and to investigate the extend that road-surface skidding resistance plays in accident occurrence. The following organisations were represented on the sub-committee: the State Road Laboratory RWL, Delft, the Traffic and Transportation Engineering Division Rijkswaterstaat DVK, The Hague, and the Institute for Road Safety Research SWOV, Voorburg. In order to investigate the extent of the skidding problem, accidents occurring on dry road surface were compared with those on wet surfaces during and after rainfall. The role of skidding resistance was investigated only as regards accidents during rainfall. In this latter investigation a number of variables such as speed and visibility were disregarded for practical reasons. The investigations did, however, include hourly traffic volume, traffic performance, type of road and type of vehicle.

This contribution is not a report on the research. This is given in Schlösser (1977).

The reasons that led to the choice of the models and a detailed description of the results of the analysis of the accident data can be found in Oppe (1977). In the present paper interest will be focused on the analysis of the involvement of lorries and passenger cars in accidents.

The concept 'lorry' is used here to denote all kinds of vehicles used to transport goods, such as delivery vans, heavy trucks, trailers, and buses. A passenger car may have a trailer or may be a minibus.

The analysis is based on the assumption that traffic can play a part in accident occurrence in two ways. On one hand, if there is more traffic the expected number of accidents will increase due to the larger number of accident-susceptible road users; in other words, exposure increases. Thus, the number of accidents is likely to increase proportionately to traffic performance. On the other hand, at higher traffic volumes the accident hazard will increase for every individual road user; i.e. accident-susceptibility increases.

The analysis is adjusted for the extent to which exposure plays a part. For this purpose, the number of vehicles involved in accidents during a given time period, on a given road section, are divided by the number of vehicle kilometres driven during that time period on that road section. These involvement ratios are analysed. Besides the adjustment for vehicle kilometres, hourly traffic volume is used to explain the difference in accident ratios, in order to ascertain the influence of traffic volume on accident susceptibility. Therefore the involvement ratio is described as a function of both road-surface skidding resistance and hourly traffic volume. It is reasonable to assume that the increase in accident susceptibility will not be the same on all roads. Consequently, roads were divided into two types.

Type I comprises motorways: roads with split level junctions and separate carriageways, each with at least two lanes and generally one shoulder. Type II comprises other primary national highways, mainly single-carriageway roads with two lanes, level junctions and occasional slow moving vehicles.

Chapter I

DATA

The involvement data required for the research were obtained from Rijkswaterstaat (Department of Roads and Waterways).

The locations, times and dates of the accidents and whether or not it was raining are recorded.

For road type I the hourly traffic volumes are divided into 20 classes with a width of 100 vehicles per hour for each direction; for type II into 15 classes with a width of 200 vehicles per hour in both directions. The coefficient of longitudinal force for a wet surface is determined for each road section. These coefficients are divided into 9 skidding resistance classes with a width of 0.05 units of measurements from $\leqslant 0.36$ to > 0.71.

From the location, date and time, the appropriate skidding resistance and hourly volume class is determined for each accident. Since the highest resistance class also includes accidents on wet surfaces during dry weather, it is completely eliminated from the investigation.

From the length of the road, the distribution of hourly traffic volumes and duration of rainfall, the number of vehicle kilometres is calculated for each combination of skidding resistance and hourly volume class, separately for workdays and weekends and adjusted for month and year.

Next, the involvement ratio is determined for each resistance - volume combination by dividing the number of involvements by the relevant number of vehicle kilometres.

This results in four tables of involvement ratios corresponding to the two types of roads and two types of vehicles.

Chapter II

ANALYSIS

The intention of the analysis is to examine how the involvement ratio (I) depends on hourly traffic volume (V) and road-surface skidding resistance (R).

The first assumption for the descriptive model is that the effects of V on I and R on I are independent of each other. Because the specific nature of both relations is not known and probably not linear, no restriction on the nature of these functions will be put on the model.

Furthermore it is not certain whether the effects of V on I and R on I are additive as assumed in linear models (such as linear regression models or analysis of variance) or multiplicative as is assumed in log-linear models (such as the Poisson models mentioned later on). According to the additivity assumption, the dependent variable (I) can be written as a (weighted) sum of the independent variables R and V.

As regards this assumption the following can be said: Suppose the probability of a given accident occurring on a road surface belonging to skidding resistance class i ($i = 1, \ldots, m$) is indicated as $p(R_i)$, and the probability of this accident occurring in hourly volume class j ($j = 1, \ldots, n$) is indicated as $p(V_j)$. If we assume that both probabilities are independent of each other (which means that the probability distribution over the resistance classes is the same for every volume class and vice versa), it follows that the probability of an accident for the combination of hourly volume class i and skidding resistance class j can be written as the product of the (marginal) probabilities $p(V_j)$ and $p(R_i)$, viz:

$$p(R_i \cap V_j) = p(R_i) \cdot p(V_j)$$

This consideration should lead to the choice of a multiplicative model instead of an additive model.

Chapter III

ADDITIVE CONJOINT MEASUREMENT

The ACM model does have the requirement of additivity, but multiplicity can be converted into additivity by using a logarithmic transformation. In the ACM model arbitrary functions f on R and g on V are allowed to describe I (or a logarithmic transformation of I) as a function of R and V.

For every I_{ij} value belonging to the combination (R_i, V_j):

$$I_{ij} = \alpha + \beta_i + \gamma_j \tag{1}$$

So far, two alternatives have been mentioned for applying ACM. The first possibility is to apply the analysis directly to involvement ratios; the second is to apply it to their logarithms. Another possibility, based on a method by Kruskal (1965), is to make an analysis seeking for the monotone non-descending transformation of I which, if filled in for I, gives a solution of equation (1). If it is subsequently examined which monotone transformation leads to the better fit of the ACM model, the above arguments regarding additivity or multiplicity can still be verified. For example, if the monotone transformation is a linear transformation, ACM could have been applied directly; a logarithmic transformation would favour a multiplicative model.

Formulated somewhat more exactly, this method amounts to the following: Suppose f and g are known, then for each I_k and I_l there are values I^*_k and I^*_l such that

$$I^*_k = f(R_k) + g(V_k) \geqslant I^*_l = f(R_l) + g(V_l)$$

if, and only if $I_k \geqslant I_l$

in which k and l are indices continuing through the resistance-volume combinations (1,1), ..., (1,n), ..., (m,n).

As a rule, such a transformation will be possible only up to a certain level. An effort will thus have to be made to find the transformation for which the model gives the best possible description of the data.

As a criterion for optimum description, a least-squares criterion is chosen. In other words, let I^+_k be the value belonging to a given monotone transformation. And I^*_k the appropriate prediction of I^+_k fitting best with model (1); then the monotone non-descending transformation is sought for which the sum of the discrepancies (S) between the I^+_k and I^*_k values is as possible. Or, more precisely, for which:

$$S = \min_{I^+} \min_{\langle f,g \rangle} \left[\sum_k (I^+_k - I^*_k)^2 \Big/ \sum_k (I^*_k - \bar{I}^*)^2 \right]$$

The denominator in this expression is merely a scale factor. In an iterative process seeking the best fitting monotone transformation, the I values themselves are chosen as the initial configuration.

By comparing the value of S found with this initial configuration (S_d) with S_{mon} of the motone transformation, it is possible to examine how far the solution can be improved if we allow a monotone transformation of I. If we also apply the analysis to the log-I values, we again obtain initial solution with matching S_{log} which, compared with S_d, shows whether it is better to speak of an additive or multiplicative model, while S_{log} compared with S_{mon} (identical of course for both initial situations) again shows how this solution can be improved.

If the hypothesis concerning multiplicity is correct, we expect

$$S_d > S_{log} = S_{mon}$$

Results*

Figures 1 to 4 give the ACM_{mon} solutions for the values of function f in formula

$$I^*_{ij} = f(R_i) + g(V_j)$$

for the four tables of involvement ratios mentioned earlier. In Figure 1, representing the function values of lorries for road type I, the size of the parameters decreases linearly with the class value.

If the multiplicative model is correct (i.e. if the montone transformation is found to be logarithmic) this means that the relationship between involvement ratio and skidding resistance class is exponential. As a result the measures taken to improve the road-surface skidding resistance will have a decreasing effect on road safety, going from class 2 to class 7.

The same linear relation although less clear is found for the data represented by Figure 2, 3 and 4. The peripheral effects may be caused by the smaller numbers of observations in these classes. If we delete class 1 and 8 for road type II then the linearity is clearer.

For road type I these classes are excluded because the respective situations hardly exist for that road type.

Figures 5 to 8 give the ACM_{mon} solutions for the values of function g in the formula.

The curves in these figures are not as smooth as in the Figures 1 to 4. As will be seen later, this is merely caused by the large number of volume classes.

In general it can be said that accident susceptibility increases with hourly traffic volume. For road type I, both for passenger cars and lorries, there are peripheral effects of the curves. In this case, however, it is unlikely that these are caused by the small number of observations per class alone.

For checks on the fit of the model we refer to Oppe (1977) again. It is argued there that the multiplicative model seems to be correct.

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* The computerprogramme ACM, written in PLI by J. de Leeuw, Leyden State University, dept. Datatheory, was used to analyse the data.

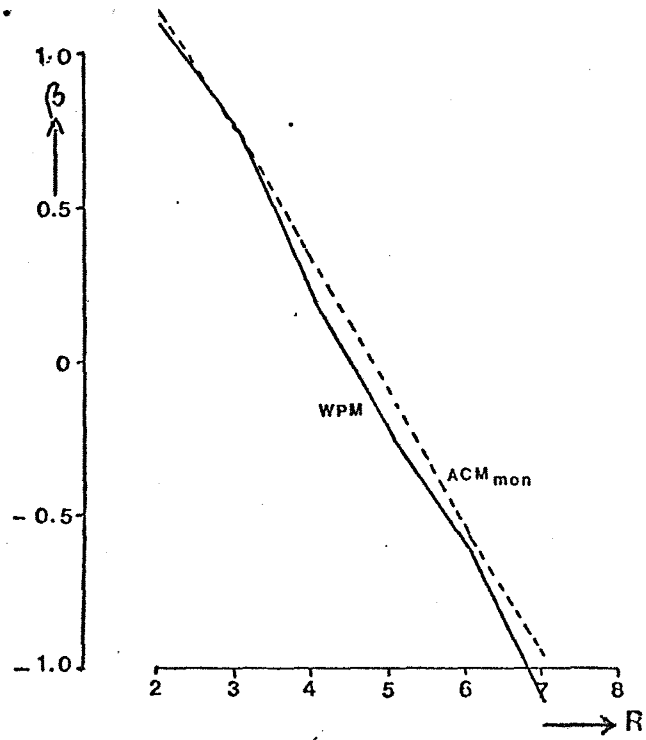

Fig. 1. Lorries at road type I.

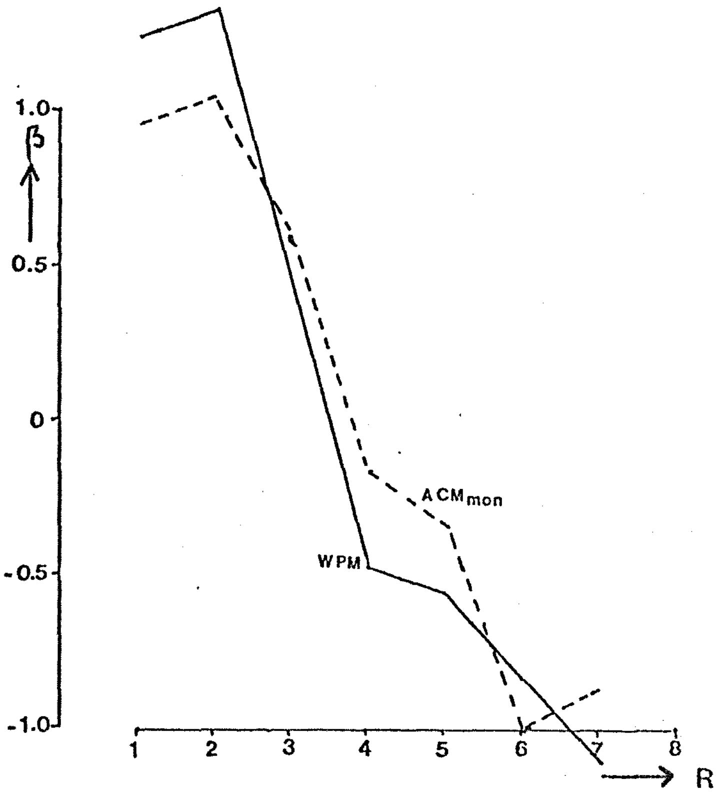

Fig. 2. Lorries at road type II.

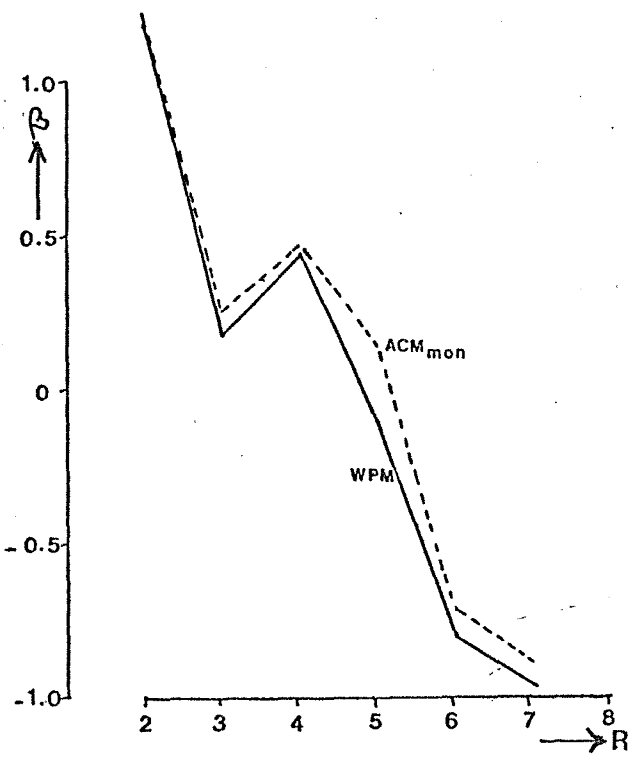

Fig. 3. Passenger cars at road type I.

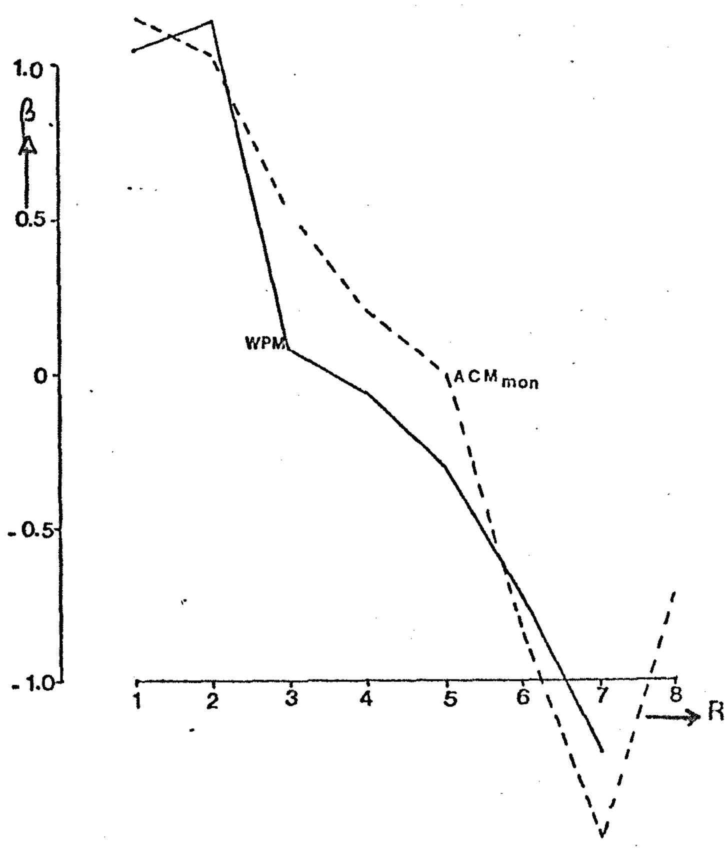

Fig. 4. Passenger cars at road type II.

Relation between the β-parameters and road-surface skidding resistance (R) as found from the ACM- and the WPM-analysis.

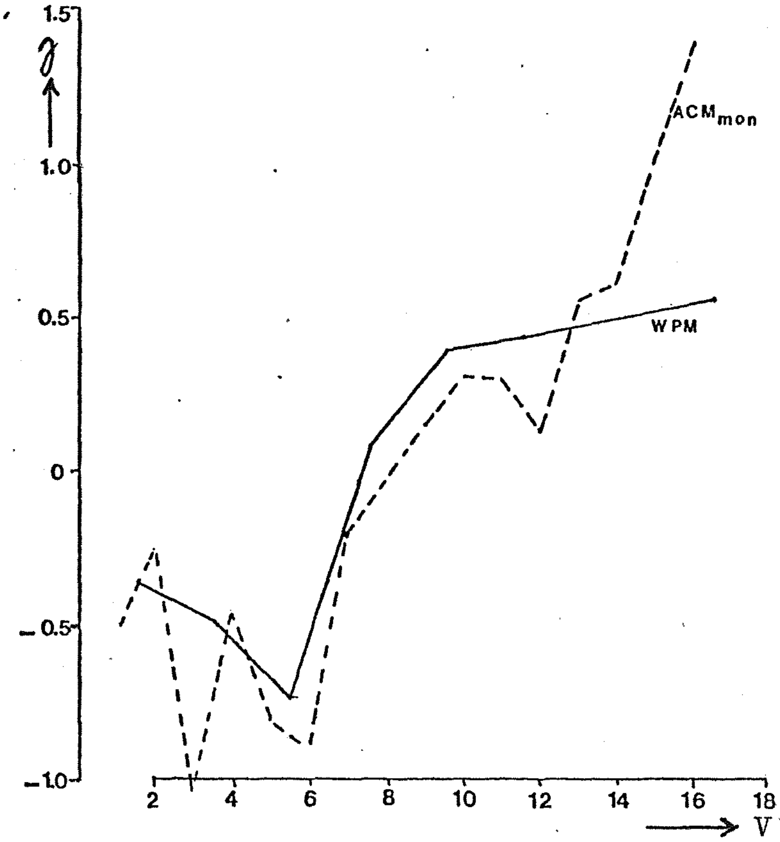

Fig. 5. Lorries at road type I.

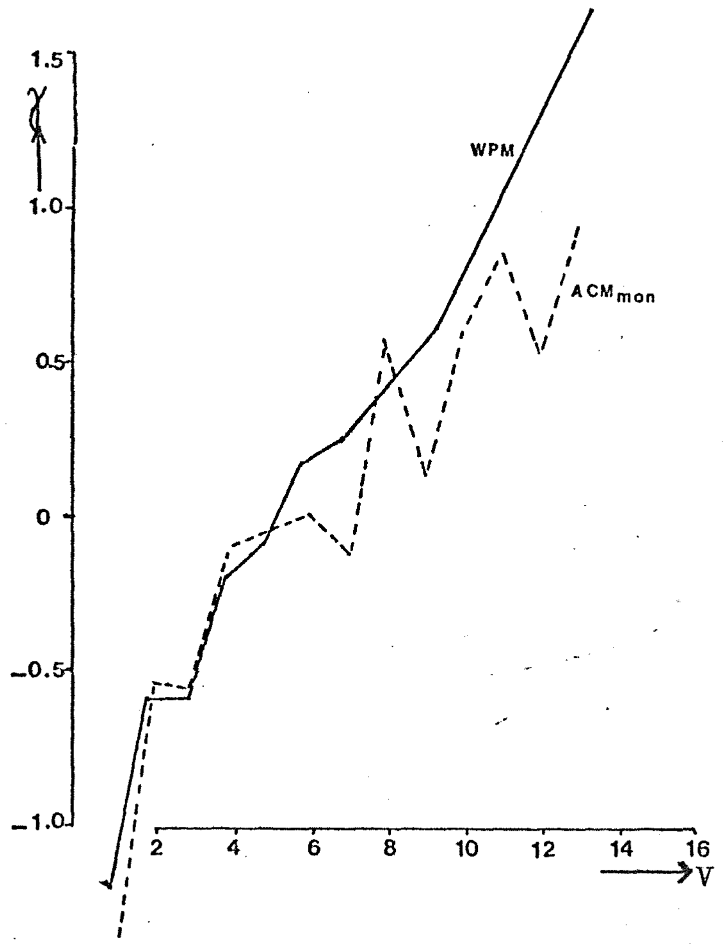

Fig. 6. Lorries at road type II.

Relation between the γ-parameters and hourly traffic volume (V) as found from the ACM- and WPM-analysis.

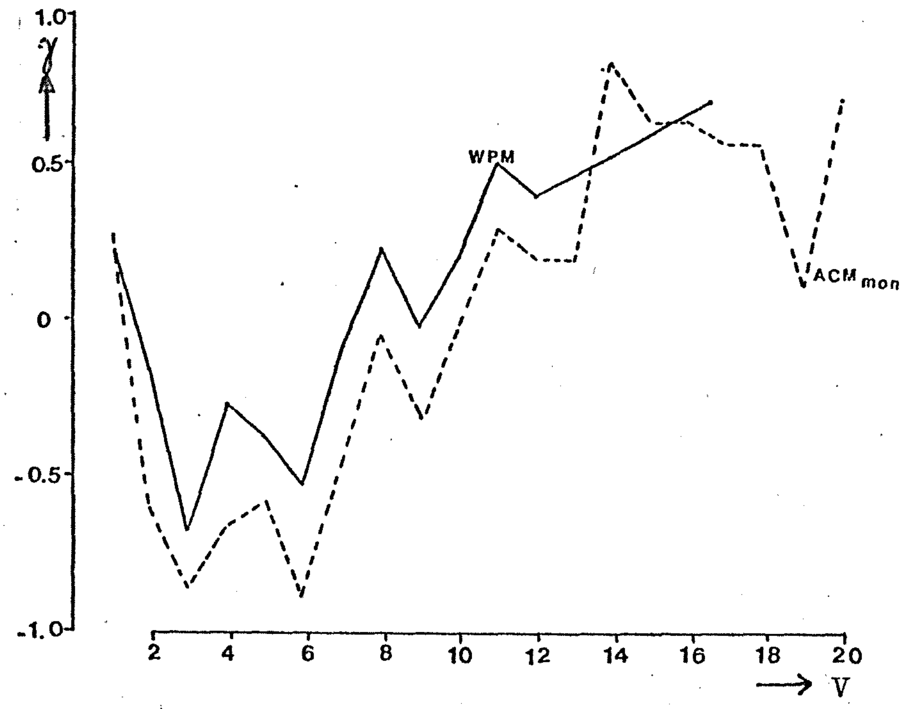

Fig. 7. Passenger cars at road type I

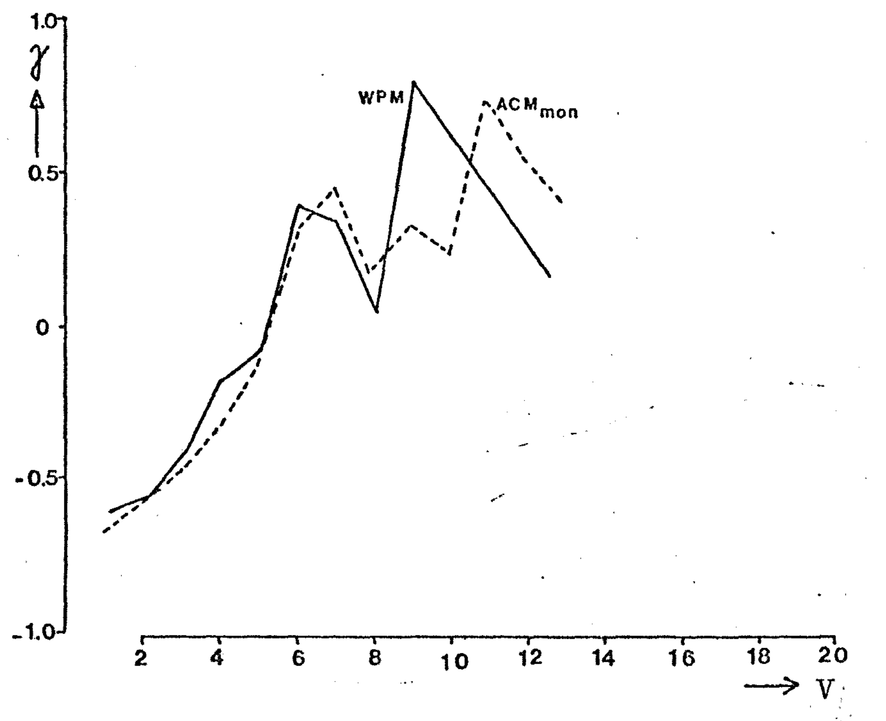

Fig. 8. Passenger cars at road type II

Relation between the γ-parameters and hourly traffic volume (V) as found from the ACM- and WPM-analysis.

Chapter IV

STOCHASTIC INTERPRETATION OF THE MULTIPLICATIVE MODEL

Assuming that the occurrence of accidents can be described as a Poisson process with parameter λ and that the accidents are multinomially distributed over the skidding resistance and traffic volume classes while the volume and resistance variables have a mutually independent influence on the accident hazard, then:

(1) For each resistance class R_i with multinomial probability p_i and each volume class V_j with multinomial probability q_j, accidents can be described as a Poisson process with parameters λp_i and λq_j.

(2) For each cell X_{ij} the accident distribution is a Poisson distribution with parameter $\mu_{ij} = \lambda . p_i q_j$.

<u>Log-linear models</u>

In recent years methods of analysis have been developed especially for data collected in the form of contingency tables. The subdivision of the data into traffic volume and skidding resistance classes described above is an example of such a tabulation.

If it can in fact be assumed for the values in the cells of the contingency table that they are Poisson distributed, these methods can be employed. Within these Poisson models one describes the Poisson parameters, which may differ from cell to cell, in terms of the variables of the contingency table. The multiplicative model mentioned above is a specific example of this. The Poisson parameter for each cell is described as composed of three part-parameters: a general parameter (identical for each cell) λ, one (identical for each cell in one row of the contingency table) p_i, and one (identical for each cell in one column) q_j.

In other words, restrictions are imposed on the ultimate Poisson parameter of every cell with regard to the position in the row and column of that cell in the contingency table. However, it is only one choice from a number of possible restrictions. If we say, for instance, that road-surface skidding resistance has no influence at all on accidents, viz. that all p_i's are the same, the model could be simplified. For each cell, its Poisson parameter would then be equal to λq_j (one general part-parameter and one part-parameter for the location of the cell in a column).

The most general form in which the parameters can be written is:

$$\mu_{ij} = \lambda . p_i . q_j . r_{ij}$$

or, if we take the logarithm:

$$m_{ij} \ (= \log \mu_{ij}) = \alpha + \beta_i + \gamma_j + \delta_{ij} \qquad (2)$$

in which the terms after the = sign indicate the logarithms of the factors in the previous expression.

Models which try to give such a representation of the Poisson parameters μ_{ij} are therefore known as log-linear models. A detailed description is given in Goodman (1970), Haberman (1974) and Bishop, Fienberg & Holland (1975).

The ACM model applied to the log-data is in fact also a log-linear model, but without stochastic interpretation. The multiplicative model comparable with model (1) imposes the additional restriction that $\delta_{ij} = 0$, for all combinations (i, j). The data in the contingency table can always be reconstructed perfectly with the aid of (the saturated) model (2). It is then in fact assumed that each cell has a specific Poisson parameter.

It can now be checked, for instance, whether the (non-saturated) multiplicative model $m_{ij} = \alpha + \beta_i + \gamma_j$ represents the data significantly worse than model (2).

An example of applying such a type of analysis to road traffic problems (but with a differing model description) is found in Rasch (1973).

Weighted Poisson models

The application of log-linear models to contingency tables in which accidents are given seems warranted: the assumption that the numbers of accidents represent an independent Poisson distribution is considered acceptable by many researchers. If we are dealing with accident ratios instead of accidents such an analysis is not directly applicable. De Leeuw (1975) describes a more general model applicable to Poisson distributed variables corrected by dividing the variables by a constant. In other words: Poisson distributed variables are first weighted before being analysed. The accident ratios can be regarded as such weighted variables. A drawback to this is that strictly speaking vehicle kilometres are not correcting constants but in fact stochastic variables themselves. The variance of the variables, however, is many times smaller than that of the accident variables, and the drawback will not be very important in practice. Furthermore, using involvement ratios instead of accident ratios may have some influence on the assumption of independence of the observations. However, this seems to be of little importance especially with regard to lorries. A next drawback applying to all log-linear analyses is that the model is only verifiable asymptotically, which means that it is applicable if enough accidents per cell have been collected for analysis. In the present case, this condition certainly does not apply to each cell, which makes the model difficult to test.

However, the test statistics will at least give an indication of the effects. A detailed description and an example of using weighted Poisson models can be found in De Leeuw & Oppe (1976).

Results*

The WPM-analysis of the data for road type I relates to skidding resistance classes 2 to 7.

Because of the small numbers of observations, especially for lorries, some traffic volume classes are taken together. For lorries this results in classes 1 + 2, 3 + 4, ..., 11 + 12 and a residual class 13 to 20. For passenger cars only the residual classes 13 to 20 are taken together.

For road type II the skidding resistance classe 8 is deleted.

For lorries the traffic volume classes 8 to 11 and 12 to 15 are taken together.

Figures 1 to 4 again represent the values of the function f. The agreement with the ACM-solutions are obvious.

From Figure 5 to 8 we see that summing up over the traffic volume classes results in more stable curves.

In these cases the overall agreement with the ACM-solutions is also fair.

For road type I it may be concluded from Figure 5 and 7 that, although in general involvement increases with traffic volume, at lower volumes there is a reversed tendency. Furthermore, at higher volumes the effect becomes smaller.

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* The WPM-programme, written in PLI by the author was used for the log-linear analysis.

The peripheral effects are not found for road type II.

To test the linearity of the f-curves, standard normal statistics are computed to separate linear and higher order components of the curves. The results are given in Table 1. From this table it can be concluded that the linear component is highly significant. The second and third degree components are not, while some of the higher degree components are.

The overall effects of road-surface skidding resistance and hourly traffic volume are given in Table 2. From this table it can be concluded that the effect of road-surface skidding resistance is the most important and highly significant factor in explaining the data.

The effect of hourly traffic volume is also highly significant.

For road type I there is no interaction found between both variables with regard to the involvement ratios for lorries. The same result was found earlier with regard to the accident ratios. This means that the R- and V-effects are independent of each other. For passenger cars a significant interaction is found. However, compared with the main effects this effect is rather small.

For road type II the interaction effects are both significant. No systematic trend in this effect could be found. A possible explanation for the interaction may be found in the diversity in type of road for this class.

	Road type I	Road type II
lorries	linear: -7.21 h.o. : -.78, -.13, -.44, -.12	linear: -12.54 h.o. : 1.43, 1.95, -4.23, 1.35, 1.60
passenger cars	linear: -14.63 h.o. : .38, -1.20, 4.94, -2.36	linear: -15.95 h.o. : -.01, -.20, -3.70, 3.62, -1.97

Table 1. Standard normal scores for the linear and higher order components of the resistance curves as found from the WPM-analysis.

	Road type I				Road type II			
	lorries		passenger cars		lorries		passenger cars	
	χ^2-value	d.f.	χ^2-value	d.f.	χ^2-value	d.f.	χ^2-value	d.f.
R	92.73	5	598.62	5	233.56	6	607.22	6
V	36.25	12	142.42	12	117.87	8	255.37	9
RxV	43.07	60	112.64	60	140.89	48	365.04	54

Table 2. Chi-square values and degrees of freedom for resistance effect (R), volume effect (V) and the interaction (RxV) resulting from the WPM-analysis of the involvement ratios.

LITERATURE

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