The structure of system safety

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THE STRUCTURE OF SYSTEM SAFETY

1. The structure of the concept 'road safety'

Lack of safety in our view is one of the negative outcomes of the traffic system in its modern motorized form. As such safety must be treated as a measurable aspect of the system. Following Hauer (1982), system safety will be defined by the expected numbers for several safety related events. Such expected numbers or certain well defined combinations thereof are characteristic properties of the safety of a certain system during a specified period of time. These characteristic properties are named variates. Appropriate examples of definitions of system safety are the expected number of accidents classified in categories for severity of outcome, such as expected fatalities or injury accidents, per year in an area. The actual observed numbers are treated as realizations of the expected numbers. These observed numbers or certain defined combinations thereof are named variables. It is a central problem of traffic safety management to estimate and enhance system safety. Fluctuations in relevant variables, due to stochastic properties of the system, can complicate the estimation of system-safety variates from the observed variables and may hide real changes in system-safety variates.
The definition of system safety is a multivariate definition. Up to now little is known of and hardly any basic research has been directed to the interrelations of these variates. Generally, fatal accidents are viewed as the best recorded and most striking variable. The debilitating difficulty, however, is that fatal accidents occur relatively rare and on statistical grounds these rare events will be irregularly spaced in time. In order to overcome this difficulty one has to enlarge the area or the observation period under equal conditions, which for the evaluation of the effect of measures on system safety is seldom possible. Other variables, like number of severe casualties, number of casualties, number of accidents or even the number of observed near misses or conflicts rather than accidents, are recorded as replacing or intermediate variables. Whether these variables are taken as some proportional approximation to the number of fatal accidents or just variables which correspond to other safety aspects have been a topic of debate (Biecheler et al. 1985 p. 316-404). Seldom explicit considerations are stated and when they do contradict between researchers; for example conflicts as proportional to accidents (Glauz & Bauer, 1985) and conflicts as different from accidents and

exposure (Hauer, 1982). The underlying structure of the relevant variables, however, can be formulated more explicitly.
We propose three different models for the structure of system safety by different formal relations of the relevant observed variables to one or more latent variates. Each observed variable is assumed to consist of a true, latent variate related part and an non system-safety related specific and or error part. Specific parts are defined as reliable parts of variables, but uncorrelated to each other. Error parts may be correlated if variables are not independently measured; for instance number of accidents includes the number of casualties and errors must be correlated, but damage-only accidents and injury accidents will have uncorrelated errors. For plausible statistical reasons we assume that the proportion of error is larger for variables with smaller numbers of observations and we assume variables to be measured independently.

The first model assumes that relevant variables are imperfect realizations of one latent factor or underlying variate for system safety. We denote this model as the <u>common factor model</u> of system safety. As such it resembles the single common factor model of intellectual ability of Spearman (Harman, 1960 ch. 7). Geometrically this model is pictured in Figure 1 for three variables, where the confounded true specific part and the error part corresponds to length of the baseline projections of vectors and the length of the vertical projected vectors to the proportionality factor with respect to the latent common factor.

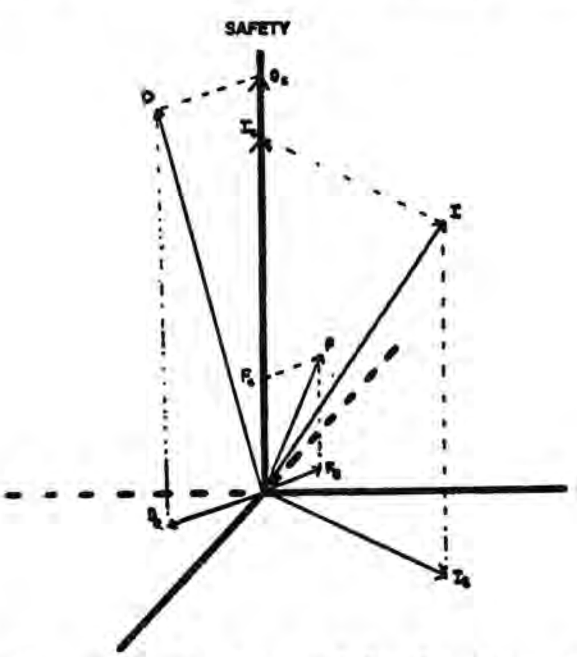

Figure 1 The common factor model of system safety

The common factor model does not take the severity order of variables or order of the accident process in account, except for the increasing relative magnitude of the error proportion and a decreasing proportionality parameter with respect to the latent factor. The specific parts of the variables are mathematically confounded with error parts in a non-repeated measurement designs of the variables. The proportions of specific parts have no prior known ordering, but in a non-repeated measurement design they are increasing with the angle of vector and component. Apart form specific parts all safety related variables are thought to be proportional realizations of one and same aspect of system safety with .

We may take the known severity order or the accident-process order of variables as a source for a priori consideration in the multi-dimensional model building for structural relations of variables with latent components of system safety. Such multi-dimensional models arise if we hypothesize that adjacent variables in the rank order have more in common than remote variables. This can be conceived in two different ways.

The second model assumes that the relevant expected variables can be ordered along the mixture of two latent factors or underlying components. The first component is most closely represented by one extreme at the ordering as the expected number of fatalities or fatal accidents for the system. This component stands for the amount of destructive energy absorbed in safety related events; for instance in resolving conflicts or in accidents of increasing severity. Going down along the ordering of fatalities, to severe injuries, to light injuries, to damage-only accidents, to "near misses" or conflicts, to encounters with conflict opportunity and even further to exposure as number of possible encounters, we may think of traffic density aggregated over points in time and space as the representative of the second component at the other extreme of the ordering. This component stands for the expected frequencies of combinations of the relevant elements for safety related events. The second model states that every expected variable in the traffic safety domain is a weighted combination of these two components: frequency of combinations of relevant elements and destructive energy absorbed by conflicting elements. Moreover the weights for the ordered variates of the variables for one component are reversed in order for the other component. Geometrically this is shown in Figure 2 , where the length of the vectors corresponds to the latent component related proportion of the variables.

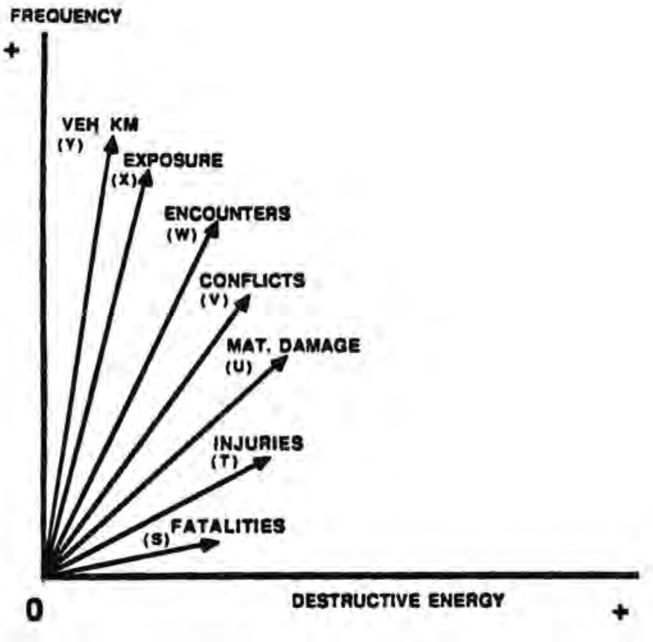

Figure 2 The ordered two-component model of system safety

As in the first model we assume larger error proportions for variables with smaller numbers, hence for variables on more severe outcomes of events. These error parts are not shown in figure 2 but are to be imagined as vector projections on axes perpendicular to the plane. In this model we assume no specific parts in the variables. This second model is called the ordered two component model.

The third model assumes that the relevant expected variables can be ordered along a cumulative hierarchy of latent components. For example an injury accident presupposes vehicle damage which in turn presupposes a traffic conflict and that presupposes an opportunity for conflict. No dimensionality constraints are at forehand clear. Guttman (1955) analyzed these kinds of structures and named them as an additive simplex, circumplex and radex. These metric structures have by definition as many component dimensions as variables. Guttman (1966), however, also showed that, by non-metric multidimensional order analysis of such structures, the compression into a two-dimensional configuration is possible for the radex structure and that a uni-dimensional order representation is possible for the additive simplex. The unidimensional order of the traffic-safety variables can be translated in a hierarchy of latent component contributions to the variables. Each subsequent variable in the ordering is assumed to contain, apart from error, parts of the components of the prevailing variables and a part of a new component. This yields the so-called additive simplex structure. We will refer to our third model as the additive multi-component model of system safety. Again no specific parts are assumed and independently measured variables are assumed to have uncorrelated errors with error proportions of magnitudes inverse to magnitude of the measurements. Figure 3 gives a picture of the structure for three variables only, where length of vectors again corresponds to the non-error parts of the variables.

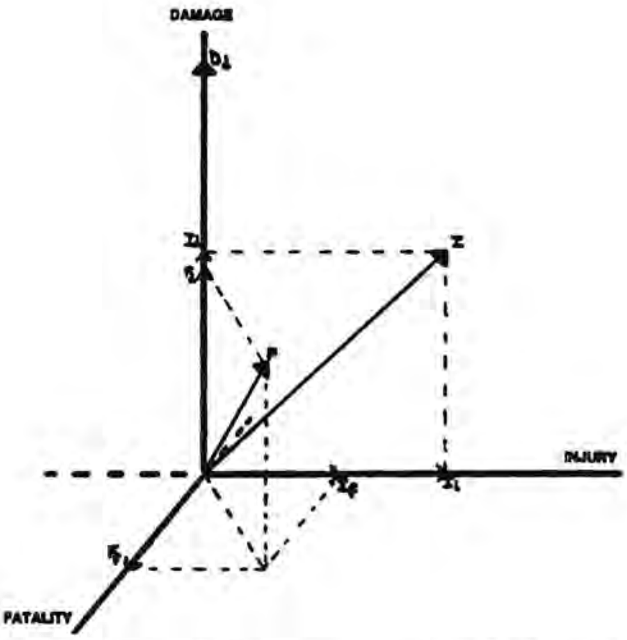

Figure 3 . The additive multi-component model for system safety

Although other representations of structure are conceivable there seems to be no need to do so for the concepts of system safety, since even these simple models presented here are not envisaged by research.
In the theory of adaptive evolution of traffic (see Koornstra, 1990; section 3.4) we hypothesized the validity for the ordered two component model for the analysis of time-series data. In Koornstra (1990) we analyzed the long term development of traffic safety for several countries and found that a weighted sum of time-series of power transformed vehicle kilometers and fatalities forms a good estimate of the time-series for injuries. Since the ordered two-component model assumes that expected variables located between ordered variables are linear combinations of the outer ordered variables, this finding forms evidence for a non-linear version of the ordered two component model. Mc Donald (1967) has presented methods for such a nonlinear factor analysis.

The three models for the structure of the multivariate concept of system safety are summarized in Table 1 by a presentation of the hypothesized component weights or loadings as usual in factor-analytic studies.

	COMMON FACTOR MODEL		ORDERED TWO-COMPONENT MODEL			ADDITIVE MULTI-COMPONENT MODEL					
ORDERED VAR.	Fac-tor	Spec. +err.	Fre-que.	En-ergy	Er-ror	Expo-sure	Con-flict	Mat. dam.	In-jury	Fa-tal	Er-ror
fatality	mid	mid	low	high	high	x	x	x	x	x	high
	high	low				x	x	x	x	0	
						x	x	x	0	0	
						x	x	0	0	0	
exposure	low	high	high	low	low	x	0	0	0	0	low

Table 1 Three models for the structure of system safety

The analysis for these models is given by the application of existing multivariate-analytic methods (Van de Geer, 1971; Morrison, 1967) of cross-product matrices. The mathematical formulation of the three models and the modifications resulting from the analysis of raw cross-product matrices (instead of covariance or correlation matrices) by existing analytical methods are presented in Koornstra (1990) . The additive multi-component model has the problem that more parameters must be estimated the more unreliable the variable is and that these parameters must be solved from a non-overdetermined set of equations. On the other hand, the single factor model does not seem to have much face-validity. Possible non-linear relations between latent components and expected variables may be present. For example speed and reaction-time reducing measures have powered effects on injuries and fatalities and exposure may have a power-transformed relation with vehicle kilometers. These and other complicating model aspects are discussed in Koornstra, (1990).

2. The structure of road-safety measures

The dynamic system approach to road safety, initiated by Asmussen in the early eighties (Asmussen, 1982; Asmussen & Kranenburg, 1985; Kranenburg, 1986), has led to the phase model of the transport and traffic unsafety process. A summary of this phase model is given in the diagram of Figure 4 , taken from Kranenburg (1986).

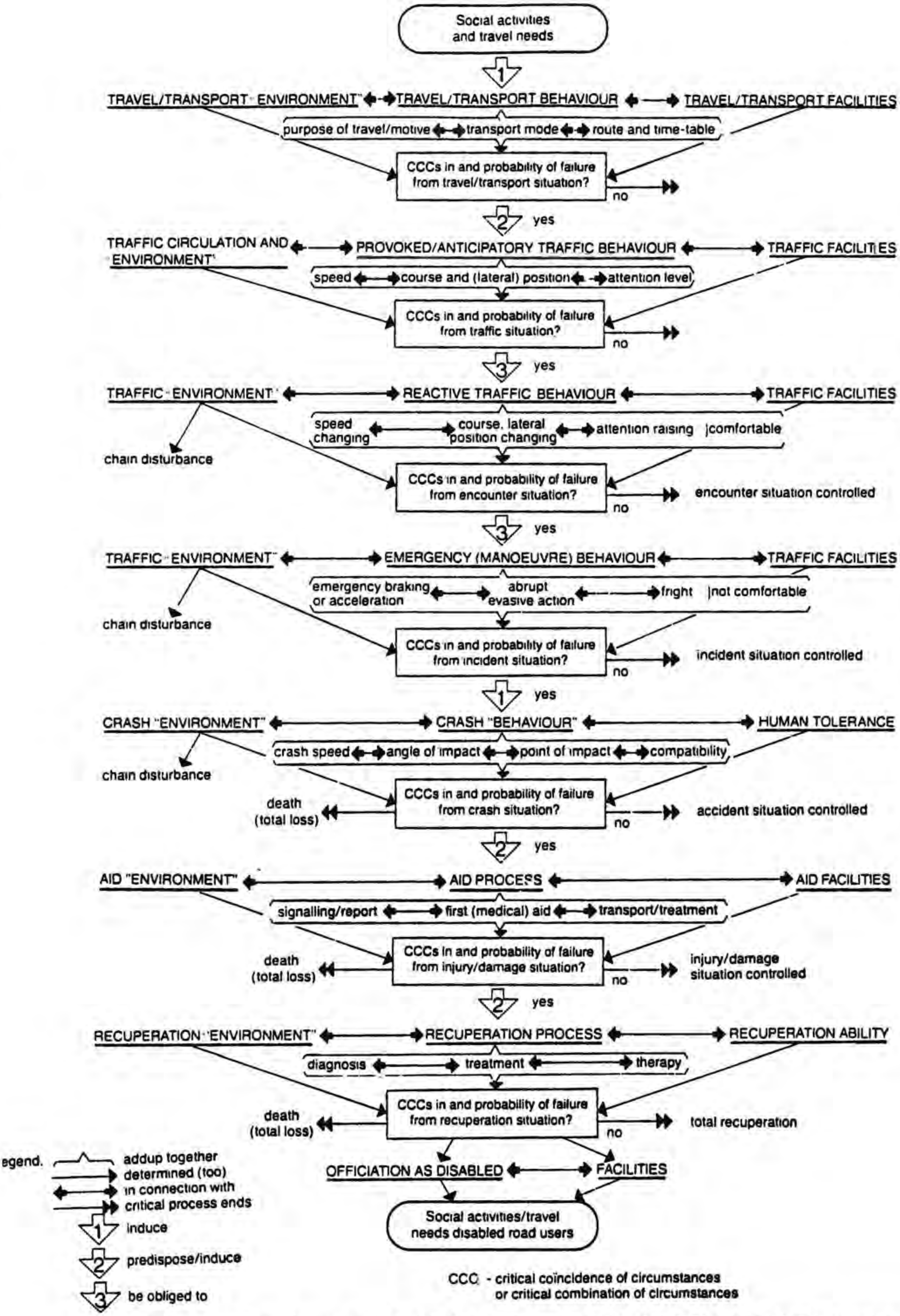

Figure 4 . The phase model of the transport and traffic unsafety process

The variables in the component models are aggregated measurements of events for these phases and the ordering of the variables corresponds to the time-order of the phases. The traffic safety measures can be ordered along the same ordering, since their effects are aimed to enhance the control of the critical coincidence of circumstances in the transition to a particular phase. Thereby the probability of occurrence for a subsequent phase is reduced.

Travel needs are influenced by location of facilities for work, recreation and cultural activities with respect to housing areas as well as by transport reducing innovations in communications and logistics. Such measures aimed at road-mobility reduction influences the growth of vehicle kilometers as a measurement of system generated travel, i.e. the starting point in the phase model.

Measures aimed at changing the given mobility to safer modes of transport influence the amount of exposure and roads and road facilities which segregate flows and types of road traffic reduce the number of encounters with a conflict opportunity, i.e. the transition to the second phase in the phase model.

Measures influencing perception, anticipation, skills and risk acceptance will be aimed at the controllability of the transition to the phases of proactive and reactive traffic behaviour, i.e. the transition to the third and to the fourth phase of the model. These measures also determine the reduction of the number of encounters with a conflict opportunity to the number of actual conflicts or serious incidents.

Measures directed to enhancement of the emergency behaviour of the road user or driver-car unit, such as active car-safety devices and advanced driving courses, belong to the transition to the fifth phase, i.e. the crash phase. Abrupt evasive behaviour tries by braking and steering to resolve the conflict; in case of failure is the remaining collision speed the main varying determinant for the severity of outcome in the next phases. The effects of such measures can be deduced from changes in reduction from the number of conflicts to the number of accidents.

Passive safety measures, such as seat belts and energy absorbing crash zones, influence the factors of the transition from the crash phase to the aid phase. The effectiveness of such measures can be deduced from the reduction of number of accidents to the number of casualties.

The control of the aid phase is determined by measures of accident detection, first aid and medical care. Their effect is partially measured by the reduction of number of casualties to the number of fatalities.

For the additive two-component model this concordance of additive structure of the safety concept and of the safety measures is pictured in Figure 5 .

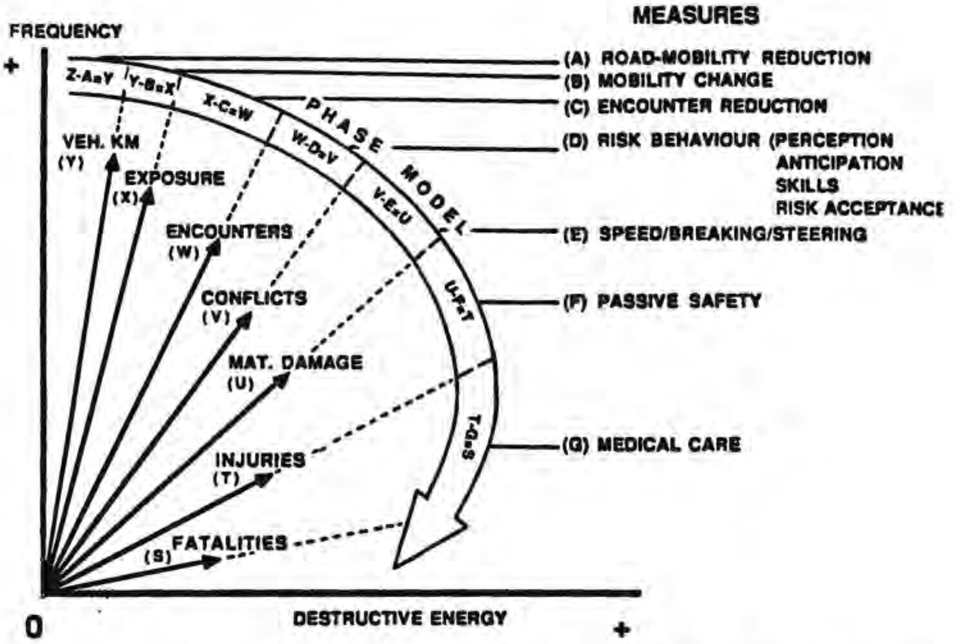

Figure 5 . Additive structure of safety concept and measures

In our component models effects of safety measures on observed variables are thought to originate from the effects on the component values, but possibly the effects of measures may also alter the relation of observed variables to the components. This follows from the fact that every observed variable of measured entities in these models is a weighted combination of the latent component values of the entities and error. Thus the expected changes in the variables are dependent on changes in weights and changes in values for each component.

In the common component model and the ordered two-component model a change in component value has effects on all variables; in the additive multi-component it only effects those variables with non-zero weights. Since measures according to our ordering will not influence the preceding variables, but only the successive variables the additive multi-component model seems to have more theoretical justification, if measures are thought to originate from changes in component values. Effects of safety measures may, also alter the proportionality factor or weights of variables with respect to latent components; for the common factor model and the additive component model this is the only consistent way for the model representation of changes for some successive variables in the ordering without changing the values of preceding variables.