Modelling and assessing the effects of road traffic safety measures

Meng Lu[1], **Kees Wevers**[2]

1. Radboud University Nijmegen, The Netherlands. Email <m.lu@fm.ru.nl>
2. NAVTEQ, The Netherlands. Email <kees.wevers@navteq.com>

ABSTRACT

The nature and the effects of improving road traffic safety by infrastructure redesign and Advanced Driver Assistance Systems (ADAS) are different. This makes comparison of such measures difficult, especially because relevant effect data for ADAS are not yet available. To address this issue, a conceptual model is presented for the effects of road traffic safety measures, based on a breakdown in underlying components of road traffic safety (probability and consequence), and five (speed and conflict related) variables that influence these components, and are influenced by traffic safety measures. The model allows estimating relative effects, and together with available data on absolute effects of infrastructure measures, to estimate absolute effects for ADAS based measures. It may in general help to improve insight in the mechanisms between traffic safety measures and their effects. The model is illustrated by a case study concerning rural roads in the Netherlands.

KEYWORDS: ADAS (Advanced Driver Assistance Systems), infrastructure design, traffic safety determinant, effectiveness index

INTRODUCTION

Traffic is the result of the interaction between humans, vehicles and road infrastructure, subject to traffic regulations. In this process the human is a key element, but also the weakest link. Nearly all traffic accidents are due to human error. Measures to counteract traffic accidents can be classified as: 1) legislation and regulation; 2) change of driving behaviour promoted by enforcement, information (government initiated campaigns), education and driving instruction; 3) vehicle related measures, including passive components like car structure, head restraint, seatbelts and airbag, and active components like quality of tyres, electronic stability control (ESC), anti-lock braking (ABS) and so-called Advanced Driver Assistance Systems (ADAS); and 4) physical road infrastructure related measures. The effectiveness of traffic regulations (belonging to class 1) largely depends on the measures in class 2. Especially enforcement and information need continuous efforts to make their effects lasting. This paper focuses on the latter two classes, and especially develops a method for comparative analysis of ADAS and infrastructure design related measures in view of traffic safety goals.

Both infrastructure redesign and ADAS implementation may improve traffic safety by improving the self-explaining and forgiving nature of the road environment. Self-explaining roads have a recognisable road layout dependent on the road category, and thereby induce adequate behaviour, thus making driving safer and avoiding accidents; forgiving roads have structural layout elements that mitigate the consequences of accidents once they happen. However, infrastructure design and ADAS have a totally different nature, and the way of influencing the driving behaviour is also not the same. Moreover, safety assessment of infrastructure measures has relatively more progressed than of ADAS implementation, as ADAS is a relatively new technology with yet limited market penetration. With regard to data availability, the generally used process of studying safety performance (at micro level, e.g. a section of road or an intersection) of the two types of measures is different. The safety impacts of road infrastructure measures are estimated mainly based on historical accident data, statistical models based on regression analysis (e.g. linear, Poisson and negative binomial), before-and-after studies, or expert judgement (e.g. traffic conflict techniques). However, all of these existing approaches leave room for argument (Hydén, 1987; Miaou, & Lump, 1993). The microscopic study of ADAS safety impacts could be carried out by using surrogate conflict measures, e.g. time to collision, gap time, encroachment time, deceleration rate, proportion of stopping distance, post-encroachment time and initially attempted post-encroachment time (Gettman, & Head, 2003). But also these methods create debate, because there is no theoretical and logical causal relationship between the studied parameters and safety impacts, i.e. the change of accident frequency and severity. In current traffic simulation models, assumptions concerning change of behaviour generally have a simple and ambiguous character.

To address the issues of safety assessment in a different way, this paper presents a model for the comparative analysis of traffic safety measures that have a different nature, based on a break-down of the level of traffic safety into components and basic variables, which have no or only limited overlap, and which may be influenced by traffic safety measures. Note however that a determinant may influence another determinant, as discussed later. We provide an in-depth qualitative and quantitative analysis of the functional relationships between traffic safety, and road infrastructure redesign and ADAS respectively. The application of the model is illustrated by means of a road traffic safety assessment in the Netherlands.

TRAFFIC SAFETY FACTORS AND DETERMINANTS

In discussing road traffic safety the focus is actually very much on the opposite concept, traffic unsafety. It is difficult to give a precise definition for both concepts, and to find adequate parameters for their measurement and assessment, as they have a highly subjective and qualitative character. Generally, traffic accident statistics are taken as assessment indicators, in particular parameters like accident frequency, accident severity, number of fatalities, number of injuries and amount of material damage. On a macro level such statistics provide yardsticks for traffic unsafety, and especially for trends thereof. The numbers used are generally based on aggregation of different types of accidents, with often quite different character, that may be related, even within one type, to very different circumstances. In addition it should be emphasized that accident statistics, based on historical data, is not the same as accident probability, which is based on road characteristics and driver behaviour, although in practice one often relies on statistics to say something about probabilities.

Traffic safety in statistical terms (TS_S) is the resultant of two components, accident frequency (F) (e.g. total accidents per million vehicle kilometre) and accident severity (S) (e.g. fatality, hospitalisation, slight injury and damage-only): $TS_S = f(F, S)$. Traffic safety in terms of probability (TS_P) can be described as the resultant of accident probability (P) and accident consequence (C): $TS_P = f(P, C)$. Of course frequency is related to probability, and severity to consequence. For the two components (further named factors) probability and consequence, five main variables (further named determinants) x_i (i = 1, 2, 3, 4, 5), and several sub-variables are identified as follows:

x_1 - velocity ($\check{v}$, speed and direction) of individual vehicle as compared to the legal speed limit or the safe speed limit[1], and to logical driving direction

x_2 - velocity differences ($\Delta\check{v}$) of traffic participants, vehicle-vehicle or vehicle-VRU (vulnerable road user), where vehicle is to be understood as a motor vehicle

x_3 - conflict between different modes, especially between motor vehicles and VRUs, in mixed traffic situations

x_4 - single vehicle run-off road by loss of lateral control or by wrong manoeuvring

---

[1] The safe speed limit is theoretical maximum acceptable speed for a certain location under certain circumstances, based on traffic safety considerations, and dependent on various parameters, especially vehicle type, type of road, road layout, road surface, road curvature, traffic density, weather conditions, environment (e.g. urban, rural or motorway) and mix of traffic modes. The safe speed limit is not necessarily the same as the legal speed limit. The legal speed limit is a compromise, and the safe speed limit at a certain location may e.g. be different for 1) different vehicle types under the same circumstances; and for 2) a particular vehicle type under different circumstances. The concept is theoretical in the sense that even at very low speeds accidents are possible in principle. The safe speed limit is such that the probability for an accident to happen, as well as the consequences of an accident when it happens, is at an acceptable level. For actual in-vehicle applications the concept safe speed is not attractive for liability reasons, and the term "recommended speed" or "safety speed" may be used instead.

x_5 - multi-vehicle conflict, i.e. vehicle-vehicle collision situations, with the following sub-variables:

- $x_{5.1}$ - run-off lane
- $x_{5.2}$ - intersection conflict
- $x_{5.3}$ - rear-end
- $x_{5.4}$ - head-on
- $x_{5.5}$ - other, e.g. U-turn related and sideswipe

The guiding principles for identifying these factors and determinants are: 1) to cover all traffic safety related situations; 2) to avoid overlaps (as much as possible) between determinants; and 3) to provide a convenient and transparent framework for comparative analysis. The related functions are:

$P = g_p(x_1, x_2, x_3, x_4, x_5)$

$C = g_c(x_1, x_2, x_3, x_4, x_5, P)$

The diagram of Figure 1 presents the above in a schematic way. Traffic safety measures (m_k) act on the various (sub-determinants and) determinants, which influence the traffic safety factors, which in turn determine the level of traffic safety.

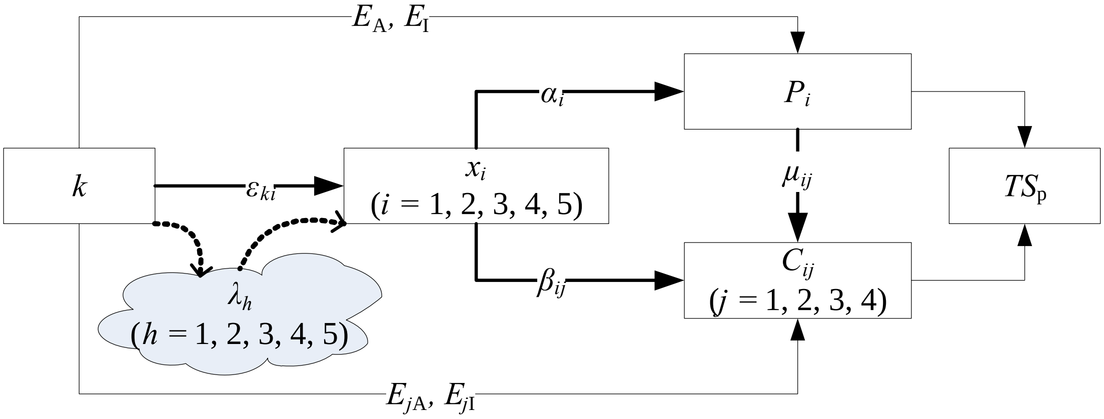

Figure 1: Causal chain process for the influence of traffic safety measures on traffic safety

The following possible influences of determinants on other determinants are identified, as illustrated in Figure 2:

- lower x_1 due to better adherence to legal speed limits (resulting in safer speeds) may reduce speed differences (x_2) and conflict with VRUs (x_3)
- lower x_1 due to less inappropriate speed may reduce single-vehicle run-off-road incidents and collisions (x_4), multi-vehicle conflicts (x_5), and decrease speed differences (x_2)
- lower speed differences (x_2) may reduce multi-vehicle conflicts (x_5) and conflicts with different modes (x_3).

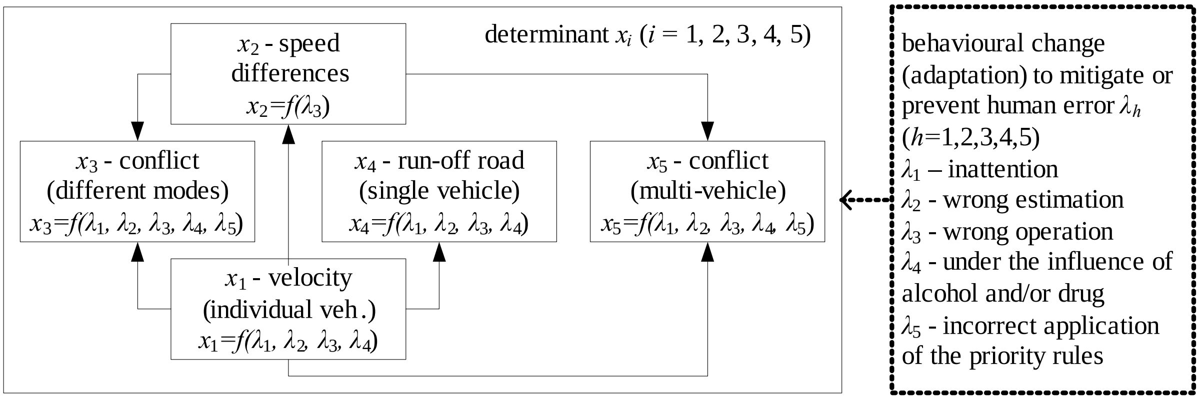

Figure 2: Traffic safety determinants and relationships, related categories of human error

The determinants may be influenced by traffic safety measures based on infrastructure redesign or ADAS. The fundamental schema behind this influence is related to change or adaptation of behaviour (Elvik, 2004). The causal relationships between human behaviour and determinants are summarised as follows (Figure 2):

- *inattention* (human error 1, denoted by λ_1), *wrong estimation* of speed of own and/or other vehicle(s), or distance with other moving or fixed vehicle(s), VRU(s) or object(s) (λ_2), *wrong operation*, e.g. no or wrong indication of intended manoeuvre, driving too fast, or driving too close to other vehicle(s) (λ_3), and *driving under the influence of alcohol and/or drug* (λ_4) may cause change of velocity (x_1) and various conflicts (x_3, x_4 and x_5);
- *wrong operation*, i.e. driving too fast (λ_3), may influence speed differences (x_2);
- *incorrect application of priority rules* (λ_5) is only linked to potential non-single conflicts (x_3 and x_5).

The human behaviour could be influenced by various external conditions y_n (n = 1, 2, 3, 4, 5), which are categorized as follows:

y_1 - driver, which could be quantified by, e.g. individual risk perspective, motion, skill, age and gender;

y_2 - vehicle, which could be quantified by, e.g. vehicle type and quality;

y_3 - road infrastructure, which could be quantified by, e.g. category, road width and surface (icy, wet or dry);

y_4 - traffic, which could be measured by, e.g. speed, density and flow; and

y_5 - environment, which could be measured by, e.g. luminosity and vision (rainy, foggy or snowy)

However, we cannot quantify the causal chain process in detail by determine every element (i.e. y_n, λ_h and x_i) directly, due to lack of statistical data and knowledge. To deal with this problem we propose a concept model for quantitative analysis of the effects of road traffic safety measures, which focus is on probabilities rather than on historical statistics, and a derived method for comparative analysis of traffic safety improvement by ADAS and infrastructure measures. Firstly we need to determine and select relevant infrastructure and ADAS measures, that affect one or more determinants, and analyse how and to what extent a certain measure actually reduces the negative impact of determinants on traffic safety.

FUNCTIONAL RELATIONSHIPS: INFRASTRUCTURE DESIGN VERSUS ADAS

Nature of Physical Infrastructure and ADAS Functions

Physical road infrastructure related measures aim to make the infrastructure such that accidents are less likely to happen (self-explaining roads), and that the consequences are less serious once they do actually happen (forgiving roads). ADAS applications also have self-explaining and/or forgiving functionality. They continuously assist drivers with their driving task, and thereby may enhance the comfort and efficiency of driving, as well as driver performance and safety. In this way they may improve the overall level of road traffic safety, and in addition network capacity. However, the nature of road infrastructure and ADAS measures is quite different, which is especially reflected in the following issues:

Penetration

Physical infrastructure only influences speed or conflict at a local, or even sub-local level, i.e. at a specific location with a specific measure. For instance, a speed hump which intends to control the speed has effect only very locally, and the driver may speed up after passing the speed hump. However, the effect extends to every vehicle. On the other hand, the safety effect of ADAS by influencing speed and conflict extends to the whole network, but only for equipped vehicles.

Flexibility and adaptability

Physical infrastructure measures cannot be easily adapted to changes in the environment, e.g. changes in traffic density or road layout. Generally in such cases the measure needs to be removed and/or rebuilt. ADAS on the other hand can easily adapt to such changes, e.g. by software or map updates, while also maintenance costs are lower.

Side-effects

In contrast to ADAS, physical infrastructure measures in general have negative side-effects, in terms of social, economic and environmental aspects. In addition, of the road infrastructure measures only the roundabout significantly contributes to making traffic homogeneous.

Implementation difficulty

The implementation of infrastructure redesign and of ADAS follows completely different scenarios. The former is generally in the domain of the road owner, and thereby very much decentralised to regional or municipal levels, and dependent on the availability of authorities' funding, and related to schemes for road maintenance. The latter, on the other hand, assuming a policy need for wide-spread implementation combined with insufficient basic attractiveness for the user, is primarily dependent on regulation and/or fiscal incentives on a national or even European level.

Compliance of ADAS and Road Infrastructure Design

In this section the match of and the relationship between infrastructure design and ADAS applications for enhancing road traffic safety are highlighted, partly based on (CROW, 1997; Dijkstra, 2003; Lu, Van der Heijden & Wevers, 2003).

Table 1 below provides an outline of (twelve) different road traffic safety related requirements for the road environment, originally formulated for the road infrastructure, and based on three guiding principles related to network structure and layout: 1) functionality, 2) recognisability and predictability, and 3) homogeneity. Fore each of these requirements corresponding more concrete physical infrastructure and ADAS solutions have been identified.

In summary, functional relationships appear to exist between infrastructure redesign and large-scale ADAS implementation. Many of the expected effects of road infrastructure measures show a strong overlap with potential effects of ADAS. Table 2 presents a list of infrastructure measures and ADAS functions that potentially influence the aforementioned five traffic safety determinants on different road categories. The table identifies, in a qualitative way, which of the determinants are influenced by each of the listed measures, and if this influence affects accident probability *P*, accident consequence *C*, or both. Influence on *P* has a self-explaining character, while influence on *C* has a forgiving character. In general infrastructure measures and informative ADAS functions focus on strengthening the self-explaining character of the road, while warning and control based ADAS functions focus more on strengthening the forgiving character. This analysis clearly establishes which ADAS functions can or cannot match which infrastructure design measures.

Table 1: Road traffic safety requirements, and match of road infrastructure redesign and ADAS functions

	#	safety requirement	possible road infrastructure solution(s)	possible ADAS solution(s)
functionality - network structure	1	create / realisation of large-size continuous residential areas	traffic calming* measures, road narrowing and horizontal deflections, plateaux, roundabouts, speed humps, and visibility and visual guidance	speed assistance, anti-collision, intersection support
	2	minimise part of journey on relatively unsafe roads	consistent road markings & signing to reduce the number of category transitions per route, risk per (partial) route and crossroads distances	navigation (digital map and system software adaptation)
	3	make journeys as short as possible	short and direct routes	navigation (smart shortest routes)
	4	let shortest and safest route coincide	(combination of 2 and 3)	navigation (combination of 2 and 3)
recognisability & predictability - route selection	5	avoid search behaviour	presence and locations of signposting; indication of ongoing route at choice moments; street lighting at choice moments	navigation (state of the art)
	6	make road categories recognisable	presence and type of alignment marking, of area access roads, of emergency lanes, of bus and tram stops, and of position of bicycle, moped and other 'slow traffic; obstacle-free; speed limit; colour and nature of road surface	navigation (digital map and system software adaptation)
	7	limited number of standard traffic solutions	reduce the number of structurally different crossroad types, different cross-over provisions and category transitions, and different right-of-way regulations (per route)	speed assistance, navigation
homogeneity - layout of road segments	8	avoid conflicts with oncoming traffic	protection of oncoming traffic	lane keeping assistance, intersection support
	9	avoid conflicts with crossing traffic	protection of crossing and crossing-over traffic; deduce number of possible conflict points	anti-collision, intersection support
	10	separate traffic categories	protection of bicycle, moped, and other 'slow' traffic from motor vehicles	navigation, speed assistance, lane change assistant
	11	reduce speed at sites of potential conflict	speed reduction at conflict points	speed assistance
	12	avoid obstacles along the carriageway	presence and dimensions of profile of free space, obstacle-free zone, and plant-free zone; presence of bus and tram stops, break-down; provisions and parking spaces	lane keeping assistance, anti-collision

*traffic calming - Integrated treatment of areas or stretches of road with various kinds of speed-reducing measures in urban areas. Frequently combined with other measures like road closures, one-way streets and reorganisation of road hierarchy (MASTER Consortium, 1998)

Table 2: Traffic safety impacts of infrastructure design and ADAS

	accident factor	probability (P)					consequence (C)					road category		
	road environment	self-explaining					forgiving					RC1	RC2	RC3
	determinant	x_1	x_2	x_3	x_4	x_5	x_1	x_2	x_3	x_4	x_5			
road infrastructure measures	short and direct trips			x	x	x						x	x	x
	lower legal speed limit	x										x	x	x
	plateaux	x	x				x						x	x
	roundabouts	x	x	x		x	x	x	x		x		x	x
	intersection channelisation	x	x	x		x	x						x	x
	speed bumps	x					x						x	x
	traffic calming measures	x	x	x		x	x	x	x		x			x
	reduction of crossings					x							x	x
	"2+1" carriageway					x							x	
	parallel roads			x		x							x	
	cancel. pedestrian crossings			x									x	
	particular bicycle lanes			x									x	x
	consistent markings & signing				x	x						x	x	x
	semi-paved shoulders				x	x				x	x		x	
	rumble strips				x	x				x	x	x	x	
	roadside slopes & hardware				x								x	
	drainage structures				x								x	
	obstacle free zone									x		x	x	
	roadside safety barriers									x		x	x	
	absence of parked vehicles					x								x
	curve flattening	x			x								x	
	road surface improvement	x										x	x	x
ADAS (autonomous and cooperative systems)	navigation system	x		x	x	x			x	x	x	x	x	x
	lane keeping assistant									x	x	x	x	
	lane change assistant										x	x	x	
	collision warning system								x		x	x	x	x
	collision mitigation system								x		x	x	x	x
	forward collision avoidance								x		x	x	x	x
	adaptive cruise control		x			x						x		
	stop-and-go		x			x						x	x	x
	adaptive light control			x	x	x						x	x	x
	vision enhancement			x	x	x						x	x	x
	driver alertness monitoring								x	x	x	x	x	x
	curve speed assistance	x		x	x	x	x					x	x	x
	legal speed limit assistance	x					x					x	x	x
	dangerous spots warning			x	x	x			x	x	x	x	x	x
	intersection collision avoidance										x		x	x
	intersection negotiation								x		x		x	x
	autonomous driving						x	x		x	x	x		

RC1: flow roads - roads with a through function, intended for the rapid movement of through traffic

RC2: connection roads - roads with a distributor and collector function, intended for the distribution and collection of traffic to and from areas with a residential function (residential areas, neighbourhoods, shopping areas, industrial sites, city centres, etc.)

RC3: local roads - roads with an access function, intended for the direct access to homes, shops and companies, and ensuring the safety of the road (street) as a meeting place

MODEL FOR THE EFFECTS OF TRAFFIC SAFETY MEASURES

A core problem in traffic safety studies is the analysis of the effectiveness of various traffic safety measures. This analysis has progressed more for infrastructure measures than for ADAS measures, because of the availability of data. For ADAS applications some educated guessing is required, for which the following approach is developed.

This section presents a model for the comparative analysis of traffic safety measures that have a different nature, based on a break-down of the level of traffic safety into components and basic variables, which have no or only limited overlap, and which may be influenced by traffic safety measures. In the model that we propose here we assume, as explained before, that traffic safety is determined by the factors (accident) probability (P) and (accident) consequence (C), and that a certain measure will reduce probability and/or consequence by influencing the determinants that have been defined for these factors. We further assume that we can discuss the determinants and their influences independently, i.e. we ignore any possible (but difficult to determine) coupling between the determinants (and which have been chosen from a perspective of minimum overlap). Traffic safety measures have a direct influence on determinants, and through these on accident probability P and on accident consequence C. The effectiveness of a traffic safety measure may be measured in terms of the change in C that it produces. Besides having a direct influence on C (via influence on a determinant), measures also have an indirect influence through the influence on P (via influence on a determinant) (Figure 1). We further assume as a first approximation that the influence of a measure on a determinant, of a determinant on P and C, and of P on C are all linear. Of course this is a simplification of reality. But reality, i.e. the precise relationships, is generally unknown. Actually only for the influence of speed on traffic safety, research has provided some ideas, which however leave room for debate. Even if the influence is a degree four function of the determinant, as has been derived for speed (e.g. Joksch, 1993; Nilsson, 2004), it may be assumed roughly linear for shorter intervals, and the measures will generally address relatively short intervals of the determinants. Furthermore, for the purpose of this study it in fact does not matter that much, as the results are used to find a suitable way to compare the effectiveness of measures, especially to estimate the effects of ADAS related measures for which we do not have a lot of data, by comparison with the effects of infrastructure related measures, for which we have more insight, and for which estimates of effects are available. It is not the purpose of the proposed model to calculate absolute results. Note that we also assume that the effect of a determinant on consequence through probability can be separated per determinant, i.e. that the total influence on consequence of a certain measure through probability is the linear combination of the influences through probability per determinant. With all these assumptions, we may then summarise the above statements in the following formulas:

relative effect of measure *k* on determinant *i*

$$\frac{dx_i}{dm_k} = \varepsilon_{ki} \tag{1}$$

where ε_{ki} denotes *measure effect coefficient*

relative effect of determinant *i* on probability related to determinant *i*

$$\frac{dP_i}{dx_i} = \alpha_i \tag{2}$$

where α_i denotes *probability influence coefficient*

relative direct effect of determinant *i* on consequence of type *j* (*j* = 1, 2, 3, 4, representing four types of consequence: fatality, hospitalisation, slight injury and damage-only)

$$\frac{\partial C_{ij}}{\partial x_i} = \beta_{ij} \tag{3}$$

where β_{ij} denotes *direct consequence influence coefficient*

relative direct effect of probability related to determinant *i* on type *j* consequence

$$\frac{\partial C_{ij}}{\partial P_i} = \mu_{ij} \tag{4}$$

where μ_{ij} denotes *indirect consequence influence coefficient*

total effect on consequence of type *j* for determinant *i*

$$dC_{ij} = \frac{\partial C_{ij}}{\partial x_i} dx_i + \frac{\partial C_{ij}}{\partial P_i} dP_i \tag{5}$$

which results in:

$$\frac{dC_{ij}}{dm_k} = \varepsilon_{ki}(\beta_{ij} + \mu_{ij}\alpha_i) = \eta_{kij} \tag{6}$$

where η_{kij} denotes *partial consequence effectiveness index*

Formula (6), which gives the relative effect of measure *k* on consequence of type *j* via determinant *i*, can be easily derived from the formulas (1) to (5). It contains the following four coefficients and one index (Figure 1):

The overall relative effect of measure *k* on consequence of type *j* may then be calculated as:

$$\mathrm{H}_{kj} = \sum_i \eta_{kij} = \sum_i \varepsilon_{ki}(\beta_{ij} + \mu_{ij}\alpha_i) \qquad (7)$$

As an alternative, only probability may be studied, and not consequence. This applies e.g. in cases where only numbers of accidents are known and no information on consequence is available. The resulting model is simpler, by using only the formulas (1) and (2) the following alternative for formula (6) may be derived:

$$\frac{dP_i}{dm_k} = \varepsilon_{ki}\alpha_i = \rho_{ki} \qquad (8)$$

which denotes the relative effect of measure *k* on probability through determinant *i*. The overall relative effect of measure *k* on probability may then be calculated as:

$$\mathrm{P}_k = \sum_i \rho_{ki} = \sum_i \varepsilon_{ki}\alpha_i \qquad (9)$$

Note that this result is equal to putting in formula (7) all $\beta_{ij} = 0$, and all $\mu_{ij} = 1$. This may be interpreted as follows: the only result of the measure that is considered is probability *P*. Consequence *C* is ignored, therefore $\beta_{ij} = 0$. Or stated differently, the only consequence that is considered is probability, i.e. consequence is put equal to probability, therefore, $\mu_{ij} = 1$.

If we know an (estimated) absolute effect for a certain infrastructure based measure, either on probability or on consequence, the absolute effect of a matching (i.e. compliant) ADAS based measure may be calculated if the relative effects for the infrastructure and ADAS measures can be estimated. Instead of one ADAS based measure this may also relate to two or more ADAS based measures that together comply with the infrastructure measure. The relative effects still need to be estimated, but the presented model with its proposed breakdown in more elementary parts may help to give this process of estimation a better foundation. And although the presented model is based on quite a few assumptions, it provides a useful first approximation for an issue that is difficult to be modelled.

If $E_{j\mathrm{I}}$ is the absolute effect of an infrastructure based measure on consequence of type *j*, $E_{j\mathrm{A}}$ is the absolute effect of an ADAS based measure (or set of measures) on consequence of type *j*, $H_{j\mathrm{I}}$ is the relative effect of an infrastructure based measure on consequence of type *j*, and $H_{j\mathrm{A}}$ is the relative effect of an ADAS based measure on consequence of type *j*, then:

$$E_{j\mathrm{A}} = \frac{\mathrm{H}_{j\mathrm{A}}}{\mathrm{H}_{j\mathrm{I}}} E_{j\mathrm{I}} \qquad (10)$$

Similarly, if only probability is studied, and not consequence, the resulting formula is (mutatis mutandis):

$$E_{\mathrm{A}} = \frac{\mathrm{P}_{\mathrm{A}}}{\mathrm{P}_{\mathrm{I}}} E_{\mathrm{I}} \qquad (11)$$

where *E* denotes absolute effect on probability.

Values for the probability influence coefficient α_i, the direct consequence influence coefficient β_{ij}, and the indirect consequence influence coefficient μ_{ij} may be estimated based on accident statistics. Note again that this is a use of statistical values to estimate probabilities, in the absence of a better method. Values for the measure effect coefficient ε_{ki} may be estimated by distinguishing the following four levels of influence of ADAS and infrastructure implementation on behaviour, each with different expected effect levels:

- information: $0.00 \leq \varepsilon_{ki} \leq 0.60$
- warning: $0.50 \leq \varepsilon_{ki} \leq 0.85$
- overrideable vehicle control: $0.75 \leq \varepsilon_{ki} \leq 0.95$
- non-overrideable vehicle control: $\varepsilon_{ki} = 1.00$

The comparative analysis of ADAS and infrastructure redesign for improving traffic safety by estimating effectiveness indexes, which is based on currently available accident type and causation data for rural roads in the Netherlands.

METHOD ILLUSTRATION

Since the early 1990's, especially in several European countries large-scale programmes for infrastructure redesign have been elaborated. In the Netherlands the road infrastructure redesign programme "Duurzaam Veilige Infrastructuur" (DVI, which actually means "inherently safe infrastructure") was launched in the end of 1997. It aims to make the road network more user-friendly. The objective behind is to meet the ambitious Dutch policy targets for 2010: reductions of 50% for fatalities and 40% for severe injuries with respect to the 1986 figures (Dutch authorities, 1997). This extensive programme covers 30 years and involves high investments (EUR 15 billion for a limited implementation or EUR 30 billion for a full implementation, partly to be funded from regular local budgets for road maintenance) (Poppe, & Muizelaar, 1996). In the mean time the development of ADAS is further progressing, and several applications come closer to possible high volume market introduction. However, data of potential safety improvement through ADAS applications are not available. In this section we illustrate the estimation of potential safety improvement through ADAS applications by comparison with road infrastructure measures using the conceptual model.

In previous research of the SWOV (Dutch Institute for Road Safety Research), potential safety improvement of DVI in 2010 as compared to the situation in 1998 was analysed and predicted, especially regarding fatalities and injuries (on which the Dutch traffic safety policy focuses), taking into account changes of road length and traffic density. The study is based on historical accident data, statistical models using regression analysis, before-and-after studies, expert judgement and educated guessing. (Janssen, 2005) These data are used to identify the absolute effects of infrastructure redesign ($E_{j\mathrm{I}}$ and E_{I}).

Values for the coefficients α_i, β_{ij} and μ_{ij} were estimated partially based on accident type and causation data provided by the SWOV, in a database that is available on the SWOV web site, and in addition based on expert knowledge and educated guessing, as such accident data are generally incomplete and full of overlaps. The SWOV database contains accident data from 1980 to present including details such as accident type, road category, speed limit, crash situation, road situation, environment and 77 different accident causes. Registration levels for fatalities, hospitalisations and damage-only accidents are about 95%, 60% and 12% respectively, according to SWOV specification. Based on these data a table was created that provides for each of the provided accident causes the number of accidents, the number of fatalities and the number of hospitalisations for which it was the main accident cause. The SWOV figures that were used include a correction for underreporting. For each of the accident causes it is then judged if it relates to a certain determinant x_i (i = 1, 2, 3,4, 5). The judgement is based on expert knowledge acquired in discussions with experts from the SWOV and other experts, and from literature study. Then values for the coefficients are calculated as follows:

- the sum of the numbers of accidents related to x_i divided by the total number of accidents provides a value for the probability influence coefficient α_i;
- the sum of the numbers of fatalities related to x_i divided by the total number of fatalities provides a value for the direct consequence influence coefficient β_{i1} for fatalities (j = 1);
- the sum of the numbers of hospitalisations related to x_i divided by the total number of hospitalisations provides a value for the direct consequence influence coefficient for hospitalisations β_{i2} (j = 2);
- the sum of the numbers of fatalities related to x_i divided by the total number of accidents related to x_i provides a value for the indirect consequence influence coefficient μ_{i1} for fatalities (j = 1); and
- the sum of the numbers of hospitalisations related to x_i divided by the total number of accidents related to x_i provides a value for the indirect consequence influence coefficient μ_{i2} for hospitalisations (j = 2).

The resulting values of the influence coefficients for each determinant are listed in Table 3.

Table 3: Estimated values of influence coefficients

determinant	probability influence coefficient	direct consequence influence coefficient		indirect consequence influence coefficient	
		j = 1 (fatality)	j = 2 (hospitalisation)	j = 1 (fatality)	j = 2 (hospitalisation)
x_1	$\alpha_1 = 0.021$	$\beta_{11} = 0.026$	$\beta_{12} = 0.009$	$\mu_{11} = 0.071$	$\mu_{12} = 0.193$
x_2	$\alpha_2 = 0.030$	$\beta_{21} = 0.009$	$\beta_{22} = 0.007$	$\mu_{21} = 0.016$	$\mu_{22} = 0.096$
x_3	$\alpha_3 = 0.176$	$\beta_{31} = 0.009$	$\beta_{32} = 0.038$	$\mu_{31} = 0.003$	$\mu_{32} = 0.088$
x_4	$\alpha_4 = 0.109$	$\beta_{41} = 0.077$	$\beta_{42} = 0.016$	$\mu_{41} = 0.038$	$\mu_{42} = 0.059$
x_5	$\alpha_5 = 0.591$	$\beta_{51} = 0.056$	$\beta_{52} = 0.011$	$\mu_{51} = 0.049$	$\mu_{52} = 0.073$

Table 4: Measure effect coefficients and potential safety improvement by DVI and ADAS on rural roads in the Netherlands (1998-2010)

#	DVI (k)	ε_{ki}	E_{1I} (%)	E_{2I}. (%)	#	ADAS (k)	ε_{ki}	E_{1A} (%)	E_{2A} (%)
D1	separate bicycle lane	ε_{k3} = 0.85	10.1	6.9	A1	anti-collision	ε_{k3} = 0.05	0.6	0.4
D2	road category recognisable	ε_{k3} = 0.05 ε_{k4} = 0.05 ε_{k5} = 0.05	0.1	0.2	A2	navigation	ε_{k3} = 0.20 ε_{k4} = 0.20 ε_{k5} = 0.20	0.4	0.8
D3	plateau	ε_{k1} = 0.65	35.0	25.0	A3	speed assistance	ε_{k1} = 0.75 ε_{k2} = 0.30	46.0	38.1
D4	parallel roads	ε_{k3} = 0.60 ε_{k5} = 0.85	24.8	17.9	A4	anti-collision	ε_{k3} = 0.05 ε_{k5} = 0.05	1.4	0.7
D5	carriageway separate	ε_{k5} = 0.70	9.8	7.2	A5	lane keeping	ε_{k5} = 0.85	11.9	8.7
D6	pedestrian crossing	ε_{k3} =1.00	5.1	4.2	A6	anti-collision	ε_{k3} = 0.05	0.3	0.2
D7	semi-shoulder	ε_{k4} =0.65	20.0	14.0	A7	lane keeping	ε_{k4} =0.85	26.2	18.3
D8	obstacle free zone	ε_{k4} =0.70	55.1	39.2	A8	lane keeping	ε_{k4} =0.85	66.9	47.6
D9	roundabout	ε_{k1} = 0.90 ε_{k2} = 0.95 ε_{k3} = 0.60 ε_{k5} = 0.70	75.0	53.0	A9a	speed assistance	ε_{k1} = 0.75 ε_{k2} = 0.30	17.8	7.4
					A9b	intersect. support	ε_{k5} = 0.60	38.6	17.4
					A9c	anti-collision	ε_{k3} = 0.05 ε_{k5} = 0.05	3.6	2.9
D10	reducing crossing	ε_{k5} = 0.75	80.0	57.0	A10	intersect. support	ε_{k5} = 0.60	64.0	45.6
D11	guard-rail	ε_{k4} = 0.75	54.8	38.7	A11	lane keeping	ε_{k4} =0.85	62.1	43.9

Table 4 presents the result of the comparative analysis of potential safety improvement in 2010 by the implementation of DVI (E_{jI}) and ADAS (E_{jA}) for fatalities (j = 1) and hospitalisations (j = 2) respectively. The table includes values for the measure effect coefficient ε_{ki} for each measure. These values were estimated based on subjective judgement of to what extent a measure influences a determinant. Note that the values for E_{1I} and E_{2I} are based directly on SWOV data, while the values of E_{1A} and E_{2A} are derived from these values using formula (10). The values of the coefficients in Table 3, and of the measure effect coefficients in Table 4 are used to calculate the respective values of the H_{jA} and H_{jI} in formula (10), by applying formula (7).

It should be understood that the presented values are only a first approximation to illustrate the conceptual model. Certainly better values may be obtained by more elaborate analysis of available data and by use of additional expert knowledge.

DISCUSSION

The presented conceptual model is based on various assumptions, some of which are certainly simplifying with respect to reality, but inevitable, in absence of more precise insight. As a model in general is an abstraction of reality, this is allowed, as long as the assumptions are reasonable and based on literature study, educated guessing and common sense. It is difficult at this stage to assess the validity and reliability of the model. The model provides however a practical but founded method to address the problem of assessment of a traffic safety measure when only incomplete data are available. It thereby simplifies the comparative analysis of traffic safety measures with different nature and makes the assessment procedure more transparent and understandable. The model may also be a valuable tool for further analysis, which in the end may help to improve the very model itself. The assumptions and resulting uncertainties especially concern the qualitative and quantitative analysis of the relationships between measures, determinants and factors, and the assumption of linearity of the various coefficients. Of these, the relationship between the traffic safety factors probability and consequence could be further studied, e.g. by using grey system model (Deng, 1989). Uncertainty is also caused by the absence of sufficient and reliable data.

The analysis of the functional relationships shows strong links between road infrastructure redesign and ADAS functions. The road traffic safety assessment for rural roads in the Netherlands indicates that ADAS may be effective for improving road traffic safety, but also that some physical infrastructure measures (e.g. roundabouts, and protection of VRUs by separation of traffic modes) may be more effective than ADAS measures. Because several supporting technologies (sensors and communication) for ADAS still need considerable improvement in robustness and reliability (Lu, Wevers & Van der Heijden, 2005), this may change over time.

Some safety related infrastructure measures cannot or not entirely be matched by ADAS (e.g. roundabouts, separated bicycle routes and vehicle parking separated from the road), while conversely not all of the safety related ADAS functions can be matched by infrastructure measures (e.g. vision enhancement, driver alertness monitoring, adaptive cruise control (ACC), stop-and-go, lane change assistance and collision mitigation systems, which are not included in this research). Concerning the presented model, this implies especially a problem for the non-matched ADAS functions. To evaluate these we could, in principle, estimate, e.g. based on simulation, the changes of accident factors through the change in driving behaviour and related reduction of human error through ADAS. Estimation of the precise influence (and thereby of absolute effects) of ADAS on driving behaviour is however difficult, partly because ADAS applications have limited market penetration or are even not yet on the market.

CONCLUSION

For a structured, comparative evaluation of alternative strategies for road traffic safety, based on ADAS implementation, road infrastructure redesign, and combinations of these, and of their trade-off with a focus on possible substitution, a tool is needed to assess the potential safety effects of measures of quite different nature. Existing approaches for safety assessment are open for debate. In addition, analysis of safety effects of ADAS applications is more difficult than of road infrastructure measures because of incomplete information. It is especially difficult or even impossible to establish absolute values for such effects.

The paper presents a model for quantitative analysis of the effects of road traffic safety measures, based on a breakdown of the causal chain between measures and effects. The focus is on probabilities rather than on historical statistics. Two stochastic components of traffic safety are determined (the factors probability and consequence), and five (speed and conflict related) determinants that influence these factors. Probability also has an impact on consequence. The determinants may in turn be influenced by traffic safety measures. The relationships between the identified elements of the causal chain are modelled by coefficients. The relationships between measures and determinants have a more subjective character, and their coefficients need to be estimated based on expert judgement. The other relationships have a more technical character, and although their coefficients are estimated from accident statistics, more sophisticated estimation methods may be developed that better comply with their stochastic character. In general the proposed breakdown increases the understanding of the whole process, and thereby facilitates the estimation. Based on the model a method is developed for structured comparative analysis of traffic safety measures. The method enables estimating absolute effects for a measure based on the absolute effects of another measure, by estimating the relative effects of both measures. This is particularly helpful for assessing the effects of ADAS based measures, for which few data exist, by using existing data for infrastructure based measures. This method is illustrated with a case study for a part of a rural road in The Netherlands, which provides some interesting, but very preliminary results.

The presented model contributes to the quantitative comparative analysis of safety performance of strategic scenarios based on infrastructure redesign, ADAS, as well as combinations of these. Both the model and the derived method for comparative analysis operate at a micro level, and only address the safety effects of measures. The results can be used in a macroscopic model together with other non-safety related parameters for evaluating the overall effects of traffic safety measures.

ACKNOWLEDGEMENTS

This paper is a result of the EU funded project IN-SAFETY (Infrastructure SAFETY, FP6). It is also a result of a PhD study, part of the research programme BAMADAS (Behavioural Analysis and Modelling of Advanced Driver Assistance Systems), funded by the Dutch National Science Foundation (Connekt/NWO). The authors especially thanks T. Janssen, N. Bos and B. van Kampen (SWOV) for providing information of potential safety improvement by DVI and accident data of the Netherlands.

REFERENCES

CROW. (1997). *Handboek Categorisering wegen op duurzaam veilige basis*. CROW, Ede. - Handbook Categorisation of roads according to the principle of sustainable safety (in Dutch).

Deng, J.L. (1989). Introduction to Grey System Theory. *The Journal of Grey System*, 1 (1), 1-24.

Dijkstra, A. (2003). *Testing the safety level of a road network*. Report No. D-2003-15, Leidschendam, Stichting Wetenschappelijk Onderzoek Verkeersveiligheid (SWOV).

Dutch authorities. (1997). *Convenant Startprogramma Duurzaam Veilig*. Minister van Verkeer en Waterstaat, The Hague. - Agreement Start Programme Sustainably Safe (in Dutch). Policy agreement between the ministry of transport, the provinces, the municipalities and the district water boards in The Netherlands.

Elvik, R. (2004). To what extent can theory account for the findings of road safety evaluation studies? *Accident Analysis and Prevention*, 36 (5), 841-849.

Gettman, D. and Head, L. (2003). *Surrogate safety measures from traffic simulation models: final report*. US DoT, FHWA-RD-03-050, McLean, Virginia.

Hydén, C. (1987). *The development of a method for traffic safety evaluation: The Swedish Traffic Conflicts Technique*. Lund Institute of Technology, Lund.

Janssen, S.T.M.C. (2005). *De Verkeersveiligheidsverkenner gebruikt in de regio: de rekenmethode en de aannamen daarin*. Report R-2005-06, Stichting Wetenschappelijk Onderzoek Verkeersveiligheid (SWOV), Leidschendam. (in Dutch) - The Road Safety Explorer used regionally: the calculation method and its assumptions

Joksch, H.C. (1993). Velocity change and fatality risk in a crash - a rule of thumb. *Accident Analysis and Prevention*, 25 (1), 103-104.

Lu, M., R. van der Heijden and K. Wevers (2003). Traffic safety - from road infrastructure to ITS. In Proceedings *10th World Congress on Intelligent Transport Systems*, TP 2703, Madrid, 17-20 November.

Lu, M., K. Wevers and R. van der Heijden (2005). Technical Feasibility of Advanced Driver Assistance Systems (ADAS) for Road Traffic Safety. *Transportation Planning and Technology*, vol. 28, no. 3. pp. 167-187.

MASTER Consortium (1998). *Management Speeds of Traffic on European Roads (MASTER): Final report*, EU funded project in FP4 RTD Programme, Brussels.

Miaou, S.P. and Lump, H. (1993). Modeling vehicle accidents and highway geometric design relationships. *Accident Analysis and Prevention*, 25 (6), 689-709.

Nilsson, G. (2004). *Traffic safety dimensions and the power model to describe the effect of speed on safety*. Doctoral dissertation, Lund Institute of Technology, Lund, Sweden.

Poppe, F. and Muizelaar, J. (1996). *Financiering van een duurzaam-veilig wegverkeerssysteem*. SWOV Institute for Road Safety Research, Leidschendam. - Financing a sustainably safe road traffic system (in Dutch).