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Modelling the effects of road traffic safety measures

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Abstract

A model is presented for assessing the effects of traffic safety measures, based on a breakdown of the process in underlying components of traffic safety (risk and consequence), and five (speed and conflict related) variables that influence these components, and are influenced by traffic safety measures. The relationships between measures, variables and components are modelled as coefficients. The focus is on probabilities rather than historical statistics, although in practice statistics may be needed to find values for the coefficients. The model may in general contribute to improve insight in the mechanisms between traffic safety measures and their safety effects. More specifically it allows comparative analysis of different types of measures by defining an effectiveness index, based on the coefficients. This index can be used to estimate absolute effects of advanced driver assistance systems (ADAS) related measures from absolute effects of substitutional (in terms of safety effects) infrastructure measures.

Keywords: Traffic safety factor; Traffic safety determinant; Effectiveness index; Advanced driver assistance systems (ADAS); Infrastructure redesign

1. Introduction

Road 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, see Appendix A); (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 infrastructure measures (all of class 4) and ADAS measures (part of class 3). A model is developed for quantifying the mechanisms between traffic safety measures and their safety effects. Based on this model an approach for comparative analysis of ADAS and infrastructure measures in view of traffic safety goals is proposed.

Both infrastructure redesign and ADAS implementation may improve traffic safety through improving the self-explaining and forgiving nature of the road environment.[1] However, infrastructure design and ADAS have a totally different nature, and thereby different mechanisms of influencing driving behaviour. Moreover, safety assessment of infrastructure measures has relatively more progressed than of ADAS implementation, as ADAS is a relatively new development with yet limited market penetration. As a consequence historical statistical data on the effects of ADAS are hardly available. Due to the differences in data availability, generally different methods are used for studying safety performance at micro-level (e.g. a section of a road or an intersection) of the two types of measures. 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 and Lump, 1993). The microscopic

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[1] Self-explaining roads have a recognisable road layout dependent on the road category, and thereby induce driving behaviour in accordance with the traffic regulations. Forgiving roads have structural layout elements that mitigate the consequences of accidents once they happen.

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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 and Head, 2003). But also these methods have created 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.

This paper presents in Section 2 a model that addresses the issue of traffic safety assessment in a different way. Traffic safety is mainly analysed from a technical perspective, with a focus on probabilities rather than historical statistics. The process between measure and effect is broken down into several steps that together constitute a causal chain. In the model expected traffic safety is determined by the stochastic variables accident risk and accident consequence. These in turn are influenced by five basic technical variables, which have no or only limited overlap: velocity, velocity difference, conflict between different modes, single-vehicle run-off-road, and multi-vehicle conflict. Accident risk also has an influence on accident consequence, which is the ultimate notion for traffic safety. The technical variables are influenced by the functions of measures, due to a change in human behaviour. The model specifies, at a micro-level, the relationships between the different elements of the chain in mathematical terms, and thereby provides a powerful and robust tool for quantitative analysis.

Based on the model presented in Section 2 a method is developed for comparative analysis of traffic safety measures of different nature, which is addressed in Section 3. Section 4 elaborates the functional relationships between infrastructure and ADAS measures, and Section 5 illustrates the application of the method by means of a road traffic safety assessment of a rural road in The Netherlands. Finally, model and method are discussed in Section 6, and a conclusion is provided in Section 7.

2. Model for the effects of traffic safety measures

2.1. *Traffic safety factors and determinants*

In discussing 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 statistical data used are generally based on aggregation of different types of accidents with often quite different character, which may be related, even within one type, to very different circumstances. In addition, it should be emphasised 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 has to rely on statistics to estimate probabilities.

Traffic safety in terms of historical statistics (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): $TS_S = f_s(F,S)$. Traffic safety in terms of probability (TS_P) can be described as the resultant of accident risk (R) and accident consequence (C): $TS_P = f_P(R,C)$. Accident risk and accident consequence are here defined as stochastic variables, while the terms accident frequency and accident severity are defined as the actual outcomes, where obviously frequency is related to risk, and severity to consequence. Note that in some publications these terms are defined in a slightly different way (e.g. IEC, 2000; Kaplan and Garrick, 1981). In the model, the two components (further named factors) risk and consequence, are influenced by technical variables, further named determinants. Five main determinants x_i ($i = 1$–5) as follows:

- x_1 velocity ($\vec{v}$) of an individual vehicle as compared to the legal speed limit or the safe speed limit (see Appendix A), and to logical driving direction (vehicle in this paper means motor vehicle)
- x_2 velocity differences ($\Delta\vec{v}$) of traffic participants, vehicle–vehicle or vehicle–VRU (VRU means vulnerable road user, see Appendix A for a definition)
- x_3 conflict between different modes, especially between vehicles and vulnerable road users (VRUs), in mixed traffic situations
- x_4 single vehicle run-off road by loss of lateral control or by wrong manoeuvring
- x_5 multi-vehicle conflict, i.e. vehicle–vehicle collision situations, including sub-determinants: $x_{5.1}$, run-off lane; $x_{5.2}$, intersection conflict; $x_{5.3}$, rear-end; $x_{5.4}$, head-on; $x_{5.5}$, other conflict (e.g. U-turn related and sideswipe).

The related functions are: $C = g_c(x_1,x_2,x_3,x_4,x_5,R)$ and $R = g_r(x_1,x_2,x_3,x_4,x_5)$. 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; (3) to provide a convenient and transparent framework for comparative analysis.

The diagram of Fig. 1 presents the above concepts in a schematic way. Traffic safety measures (m_k) act, by way of their

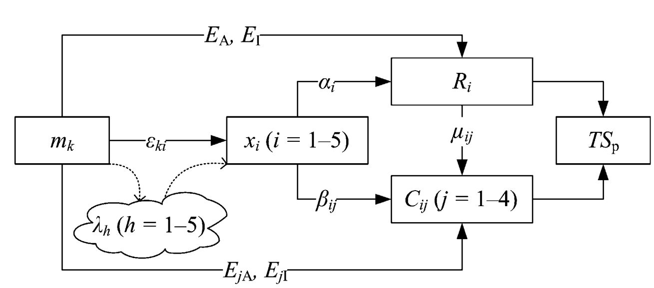

Fig. 1. Causal chain process for the influence of traffic safety measures on traffic safety.

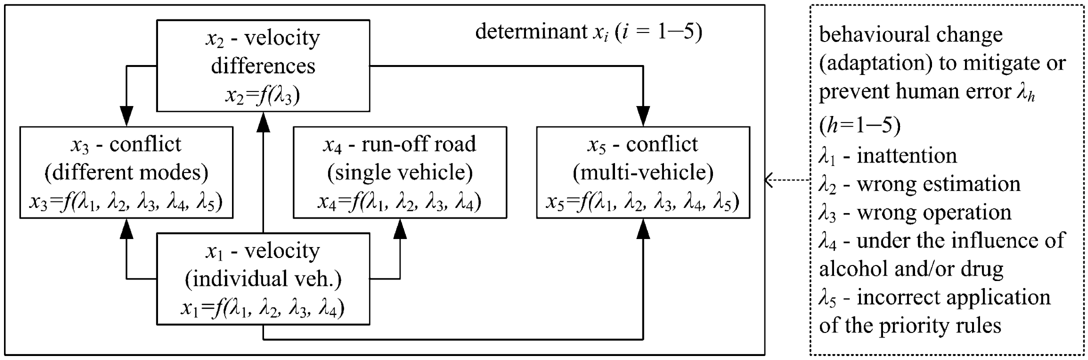

Fig. 2. Traffic safety determinants, their relationships, and related categories of human error.

functions, on the various determinants (x_i) that influence the traffic safety factors (R and C), which in turn determine the level of traffic safety (TS_P).

In addition, the following possible influences of determinants on other determinants are identified, as illustrated in Fig. 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).

The determinants may be influenced by traffic safety measures based on infrastructure redesign or ADAS. The fundamental schema behind the influence of measures on determinants is related to change or adaptation of behaviour (Elvik, 2004). The causal relationships between human behaviour and determinants are summarised as follows (see Fig. 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);
- *disregarding priority rules for crossing and merging traffic* (λ_5), e.g. when a driver does not give priority to traffic coming from the right (in The Netherlands all road traffic coming from the right has priority) is only linked to potential non-single conflicts (x_3 and x_5).

2.2. Relationships and coefficients

We will now elaborate the relationships between the different elements of the causal chain between measure and effect. As explained before, it is assumed that traffic safety is determined by the factors (accident) risk (R) and (accident) consequence (C), and that a certain measure may reduce risk and/or consequence by influencing the determinants that have been defined for these factors: traffic safety measures have a direct influence on determinants, and through these on accident risk R and on accident consequence C (see Fig. 1). The determinants and their influences are taken to be independent, i.e. we ignore any possible (but difficult to determine) coupling between the determinants, which have been chosen from a perspective of minimum overlap.

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 R (via influence on a determinant) (Fig. 1). We further assume as a first approximation that the influence of a measure on a determinant, of a determinant on R and C, and of R on C are all linear. Of course this is a simplification of reality. But reality, i.e. the precise relationships, is generally unknown. Only for the influence of speed on traffic safety research has provided some ideas in terms of precise functional (mathematical) relationships, 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 generally address relatively short intervals of the determinants. Furthermore, for the purpose of this study it in fact is not a very important issue. The first purpose of the model is to provide a better insight in the mechanisms of the causal chain. In its practical application the model is used to define a method for comparative analysis of traffic safety measures of different nature. This method is used to address estimation of the effects of ADAS related measures for which only limited data are available, by comparison with the effects of infrastructure related measures, for which we have more insight, and for which effect estimates are available. It is not the purpose of the proposed model to calculate absolute results from basics. Note that we also assume that the effect of a determinant on consequence through risk can be separated per determinant, i.e. that the total influence on consequence of a certain measure through risk is the sum of the influences through risk per determinant. With all these assumptions, we may then summarise the above statements in the following formulae:

- Relative total effect of measure k on determinant i:

$$\frac{\mathrm{d}x_i}{\mathrm{d}m_k} = \varepsilon_{ki} \tag{1}$$

ε_{ki} denotes *measure effect coefficient*.

- Relative effect of determinant i on accident risk R_i related to determinant i:

$$\frac{\mathrm{d}R_i}{\mathrm{d}x_i} = \alpha_i \tag{2}$$

α_i denotes *risk influence coefficient*.

- Relative direct effect of determinant i on consequence C_{ij} of type j:

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

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

- Relative direct effect of risk R_i on consequence C_{ij} through determinant i:

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

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

- Total effect on consequence of type j for determinant i:

$$\mathrm{d}C_{ij} = \frac{\partial C_{ij}}{\partial x_i}\,\mathrm{d}x_i + \frac{\partial C_{ij}}{\partial R_i}\,\mathrm{d}R_i \tag{5}$$

which results in the overall relative effect of measure k on consequence of type j through determinant i:

$$\frac{\mathrm{d}C_{ij}}{\mathrm{d}m_k} = \varepsilon_{ki}(\beta_{ij} + \mu_{ij}\alpha_i) = \eta_{kij} \tag{6}$$

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

Formula (6), which gives the relative effect of measure k on consequence of type j (j = 1–4, representing four types of consequence: fatality, hospitalisation, slight injury and damage-only) via determinant i (i = 1–5), can be easily derived from formulae (1) to (5).

The total relative effect of measure k on consequence of type j may then be calculated as the *consequence effectiveness index* H_{kj}:

$$H_{kj} = \sum_i \eta_{kij} = \sum_i \varepsilon_{ki}(\beta_{ij} + \mu_{ij}\alpha_i) \tag{7}$$

As an alternative, only risk 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 formulae (1) and (2) the following alternative for formula (6) may be derived:

$$\frac{\mathrm{d}R_i}{\mathrm{d}m_k} = \varepsilon_{ki}\alpha_i = \rho_{ki} \tag{8}$$

The *partial risk effectiveness index* ρ_{ki} expresses the relative effect of measure k on risk through determinant i. The total relative effect of measure k on risk may then be calculated as the *risk effectiveness index* P_k:

$$P_k = \sum_i \rho_{ki} = \sum_i \varepsilon_{ki}\alpha_i \tag{9}$$

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 risk R_i; consequence C_{ij} is ignored, therefore $\beta_{ij} = 0$. Or stated differently, the only consequence that is considered is risk, i.e. consequence is put equal to risk, therefore, $\mu_{ij} = 1$.

3. Method for comparative analysis of measures of different nature

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. This section describes a method for comparative analysis to estimate effects for ADAS applications based on available estimates for the effects of infrastructure measures, using effectiveness indices.

If we know an (estimated) absolute effect for a certain infrastructure-based measure, either on risk 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, i.e. their effectiveness indices, can be estimated. An ADAS measure relates to an ADAS function. Instead of with just one ADAS function, the comparison may also be with two or more ADAS functions that each partially 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:

$$E_{j\mathrm{A}} = \frac{H_{j\mathrm{A}}}{H_{j\mathrm{I}}} E_{j\mathrm{I}} \tag{10}$$

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

$$E_{\mathrm{A}} = \frac{P_{\mathrm{A}}}{P_{\mathrm{I}}} E_{\mathrm{I}} \tag{11}$$

where E denotes absolute effect on risk.

Values for the risk 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. Different from these more objective coefficients, the measure effect coefficient ε_{ki} has a more subjective character. It expresses the relative effect of a measure on a determinant, and replaces the explicit modelling of driver behaviour. Values for ε_{ki} need to be estimated based on expert knowledge. For this it may help to use the four behaviour influence or compulsiveness levels that are generally distinguished for ADAS based on the feedback model that is chosen: information (visual or acoustic), warning (acoustic or haptic), overrideable control (haptic throttle) or non-overrideable control (fuel supply control, gear change and/or braking) (Lu et al., 2005). Although the four compulsiveness levels are clearly derived from ADAS functions, they may be applied to infrastructure measures as well. Value ranges have been estimated for the lower three levels, while the highest level clearly has value 1.00 (maximum effect), as follows:

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

More specific values need to be estimated for each specific case.

Before we can apply the described method to a real comparative analysis of infrastructure redesign and ADAS applications for improving traffic safety, we first need to better understand the nature of infrastructure measures and ADAS, and their functional relationships, and qualify their potential effects on the determinants. This topic is elaborated in the next section.

4. Functional relationships: infrastructure redesign versus ADAS

4.1. Nature of physical infrastructure and ADAS functions

This section addresses some elements of the different nature of infrastructure and ADAS-based measures for improving traffic safety. It should be noted that the described model, and the method for comparative analysis address the microscopic level (a node or a link), and that the issues discussed in this section are especially relevant for a macroscopic model to assess the overall effects for a whole network by using results from the presented microscopic model for traffic safety analysis and relevant macroscopic parameters, including data for non-safety effects of the measures (Lu et al., 2004).

4.1.1. 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 that 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.

4.1.2. 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 be readily adjusted to such changes (e.g. by software or digital map database updates), while also maintenance costs are lower.

4.1.3. Side effects

In contrast to ADAS, physical infrastructure measures in general have non-safety-related negative side effects, in terms of social, economic and environmental aspects. For example, of the road infrastructure measures only the roundabout significantly contributes to making traffic homogeneous, however it requires considerable land space.

4.1.4. Implementation difficulty

The implementation of infrastructure redesign and of ADAS follow completely different scenarios. The former is generally in the domain of the road owner, and thereby very much decentralised to regional or municipal levels, 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 widespread 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.

4.2. Qualitative analysis—compliance of ADAS and road infrastructure design

Table 1 provides an outline of twelve different road traffic safety related requirements for the road environment. These are originally formulated for the road infrastructure, 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 concrete physical infrastructure and ADAS solutions have been identified based on an analysis of their functions (CROW, 1997; Dijkstra, 2003; Lu et al., 2003).

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 risk R, accident consequence C, or both. Influence on R 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

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

No.	Safety requirement	Possible road infrastructure solution(s)	Possible ADAS solution(s)
Functionality—network structure			
1	Create large-size continuous residential areas	Traffic calming[a] 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 and 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 and predictability—route selection			
5	Prevent search behaviour	Presence and locations of signposting; indication of ongoing route at choice moments; street lighting at choice moments	Navigation system (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	Prevent conflicts with oncoming traffic	Protection of oncoming traffic	Lane keeping assistance, intersection support, anti-collision
9	Prevent 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 potential conflict sites	Speed reduction at conflict points	Speed assistance
12	Prevent 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

[a] 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).

functions can or cannot match which infrastructure design measures.

5. Method illustration

Since the early 1990s, 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 by adapting the three aforementioned principles (see Section 4.2). 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 (€ 15 billion for a limited implementation or € 30 billion for a full implementation, partly to be funded from regular local budgets for road maintenance) (Poppe and 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, the potential safety improvement through ADAS applications has not yet been systematically and comprehensively studied due to incomplete and too limited data. This section illustrates the estimation of potential safety improvement through ADAS applications by comparison with road infrastructure measures, for a segment of a rural road in The Netherlands (Leerdam via Amerongen to Elst), using the method for comparative analysis developed in Section 3, based on the model of Section 2.

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 is 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, 2003). These data are used to identify the absolute effects of infrastructure redesign (E_{jI} and E_I).

Values for the coefficients α_i, β_{ij} and μ_{ij} are 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. The SWOV database contains accident data from 1980 to present, and includes details

Table 2
Traffic safety impacts of infrastructure design and ADAS through traffic safety determinants, and per road category

	Risk, *R*					Consequence, *C*					Road category		
	Self-explaining					Forgiving					Motorways	Rural roads	Urban roads
	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	
Dedicated bicycle lanes			x									x	x
Consistent markings and signing				x	x						x	x	x
Semi-paved shoulders				x	x				x	x		x	
Rumble strips				x	x				x	x	x	x	
Roadside slopes and 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
Autonomous and cooperative systems (ADAS)													
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		

such as accident type, road category, speed limit, crash situation, road situation, environment and 77 different accident causes. It should be noted that such type of accident statistics are generally rather inaccurate and incomplete, and full of overlaps. Registration levels for fatalities, hospitalisations and damage-only accidents are about 95%, 60% and 12%, respectively, according to SWOV specification. Based on these data, for each of the provided accident causes, the number of accidents, the number of fatalities and the number of hospitalisations are calculated for which it is the main accident cause. The SWOV figures that are 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 = 1–5). 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 risk influence coefficient α_i, e.g. $\alpha_1 = 0.02$ means that 2% of all accidents is related to vehicle speed;
- 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 ($j = 1$), e.g. $\beta_{21} = 0.009$ means that 0.9% of all fatalities is related to velocity difference between traffic participants;

Table 3
Estimated values of influence coefficients

Determinant, x_i	Risk influence coefficient, α_I	Direct consequence influence coefficient, β_{ij}		Indirect consequence influence coefficient, μ_{ij}	
		$j=1$ (fatality)	$j=2$ (hospitalisation)	$j=1$ (fatality)	$j=2$ (hospitalisation)
x_1	$\alpha_1=0.02$	$\beta_{11}=0.026$	$\beta_{12}=0.208$	$\mu_{11}=0.025$	$\mu_{12}=0.193$
x_2	$\alpha_2=0.03$	$\beta_{21}=0.009$	$\beta_{22}=0.074$	$\mu_{21}=0.012$	$\mu_{22}=0.096$
x_3	$\alpha_3=0.18$	$\beta_{31}=0.009$	$\beta_{32}=0.068$	$\mu_{31}=0.006$	$\mu_{32}=0.088$
x_4	$\alpha_4=0.11$	$\beta_{41}=0.077$	$\beta_{42}=0.592$	$\mu_{41}=0.004$	$\mu_{42}=0.059$
x_5	$\alpha_5=0.62$	$\beta_{51}=0.056$	$\beta_{52}=0.434$	$\mu_{51}=0.005$	$\mu_{52}=0.073$

- 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} ($j=2$), e.g. $\beta_{32}=0.068$ means that 6.8% of all hospitalisations is related to conflict between different modes;
- 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 ($j=1$), e.g. $\mu_{41}=0.004$ means that 0.4% of all accidents related to single vehicle run-off road involve fatalities;
- 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 ($j=2$), e.g. $\mu_{52}=0.073$ means that 7.3% of all accidents related to multi-vehicle conflict involve hospitalisations.

The values for these coefficients (Table 3) are calculated based on accident statistics, to illustrate the presented model. More sophisticated methods to determine these values may be developed in further research.

Table 4 presents the results of the comparative analysis of potential safety improvement (in terms of consequence) in 2010 by the implementation of ADAS ($E_{j\mathrm{A}}$), in contrast to DVI ($E_{j\mathrm{I}}$), 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 are estimated based on subjective judgement of to what extent a measure influences a determinant. Roundabouts are compared with three different ADAS functions. The results for these functions cannot be simply summed up for an integrated system, due to overlaps in functionality. For speed assistance a sophisticated flexible system layout is assumed that differentiates according to road type and traffic safety requirements: (1) mandatory full control on roads and crossings with mixed traffic; (2) mandatory overrideable control (haptic throttle) on single carriageway roads with separation of traffic categories; (3) voluntary warning on dual carriageway roads specifically designed for motor vehicles. For lane keeping assistance the use of magnetic tape (based on magnetic lane markers) is assumed, which can be used in combination with the normal white lane markers, which nowadays are often also applied in the form of tape instead of the traditional painting (Lu et al., 2005). It should be noted that the values for $E_{1\mathrm{I}}$ and $E_{2\mathrm{I}}$ are based directly on SWOV data, while the values of $E_{1\mathrm{A}}$ and $E_{2\mathrm{A}}$ are derived from these values using formula (10). The values of the influence coefficients in Table 3, and of the measure effect coefficients in Table 4 are used to calculate the respective values of the $\mathrm{H}_{j\mathrm{A}}$ and $\mathrm{H}_{j\mathrm{I}}$ in formula (10), by applying formula (7).

The presented values are in the first place meant to illustrate the method presented in Section 3. Certainly better values may be obtained by more elaborate analysis of available data and by use of additional expert knowledge. Nevertheless, the table provides some interesting preliminary results of this quantitative analysis. Several of the DVI measures, i.e. roundabouts, bicycle lane separation, pedestrian crossing cancellation and parallel roads, show higher safety impacts than the related ADAS appli-

Table 4
Estimated values of potential safety improvement through ADAS ($E_{j\mathrm{A}}$, $j=1, 2$) by comparison with road infrastructure ($E_{j\mathrm{I}}$, $j=1, 2$), for a specific rural road in The Netherlands (Leerdam via Amerongen to Elst)

Code	DVI (k)	ε_{ki}	$E_{1\mathrm{I}}$ (%)	$E_{2\mathrm{I}}$ (%)	Code	ADAS (k)	ε_{ki}	$E_{1\mathrm{A}}$ (%)	$E_{2\mathrm{A}}$ (%)
D1	Separate bicycle lane	$\varepsilon_{k3}=0.85$	10.1	6.9	A1	Anti-collision	$\varepsilon_{k3}=0.05$	0.6	0.4
D2	Road category recognisable	$\varepsilon_{k3}=0.05$, $\varepsilon_{k4}=0.05$	0.0	0.0	A2	Navigation	$\varepsilon_{k3}=0.20$, $\varepsilon_{k4}=0.20$	0.0	0.0
D3	Plateau	$\varepsilon_{k1}=0.65$	35.0	25.0	A3	Speed assistance	$\varepsilon_{k1}=0.75$, $\varepsilon_{k2}=0.30$	46.1	33.0
D4	Parallel roads	$\varepsilon_{k3}=0.60$, $\varepsilon_{k5}=0.85$	24.8	17.9	A4	Anti-collision	$\varepsilon_{k3}=0.05$, $\varepsilon_{k5}=0.05$	1.3	1.0
D5	Carriageway separate	$\varepsilon_{k5}=0.70$	9.8	7.2	A5	Lane keeping	$\varepsilon_{k5}=0.85$	12.1	8.5
D6	Pedestrian crossing	$\varepsilon_{k3}=1.00$	5.1	4.2	A6	Anti-collision	$\varepsilon_{k3}=0.05$	2.5	2.1
D7	Semi-shoulder	$\varepsilon_{k4}=0.65$	20.0	14.0	A7	Lane keeping	$\varepsilon_{k4}=0.85$	26.1	18.3
D8	Obstacle free zone	$\varepsilon_{k4}=0.70$	55.1	39.2	A8	Lane keeping	$\varepsilon_{k4}=0.85$	66.8	47.4
D9	Roundabout	$\varepsilon k_1=0.90$, $\varepsilon_{k2}=0.95$, $\varepsilon_{k3}=0.60$, $\varepsilon_{k5}=0.70$	75.0	53.0	A9a	Speed assistance	$\varepsilon_{k1}=0.75$, $\varepsilon_{k2}=0.30$	21.2	14.8
					A9b	Intersection support	$\varepsilon_{k5}=0.60$	33.2	23.5
					A9c	Anti-collision	$\varepsilon_{k3}=0.05$, $\varepsilon_{k5}=0.05$	3.2	2.3
D10	Reducing crossing	$\varepsilon_{k5}=0.75$	80.0	57.0	A10	Intersection support	$\varepsilon_{k5}=0.60$	64.0	45.6
D11	Guard-rail	$\varepsilon_{k4}=0.75$	54.8	38.7	A11	Lane keeping	$\varepsilon_{k4}=0.85$	62.3	44.2

cations. Two of the ADAS measures, speed assistance and lane keeping assistance, show higher safety impacts than any of the related infrastructure measures. As stated before, these results are based on a micro-level analysis, which only addresses safety effects. If the results of this analysis are used as input of a macroscopic model to assess the overall effects of a whole network, other parameters (as discussed in Section 4.1) need to be taken into account as well. Microscopic and macroscopic analysis may lead to different results for comparatively assessing a measure. For instance, for parallel roads (to separate fast and slow traffic) high cost and land use may lead to an unfavourable outcome in the macroscopic model, although the safety effects are considerable in the microscopic model.

6. Discussion

The described microscopic model is based on various assumptions, some of which are certainly simplifying with respect to reality, but inevitable, in absence of more precise insight. It is difficult at this stage to assess the validity and reliability of the model. It provides, however, a practical but founded and transparent method to address the problem of assessment of a traffic safety measure when only incomplete data are available, by enabling comparative analysis of traffic safety measures with different nature. The model may also be a valuable tool for further analysis of the underlying mechanisms of the causal chain between measures and effects (which in the end may help to improve the 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. Uncertainty is also caused by the absence of sufficient and reliable data. Better estimation methods for the various coefficients need to be developed, with more focus on probability, and less on expert judgement and historical data.

The analysis of their functional relationships shows strong links between road infrastructure redesign and ADAS functions. The road traffic safety assessment for a rural road in The Netherlands indicates that ADAS applications 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 et al., 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, stop-and-go and lane change assistance, 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 determinants 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 the yet limited market penetration of ADAS.

7. Conclusion

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 risk and consequence), and five (speed and conflict related) determinants that influence these factors. Risk 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.

Various approaches for the assessment of traffic safety measures exist, but are also much debated. The presented model provides a different view on the causal chain between traffic safety measures and their effects, and may thereby contribute to this debate, as well as to an improved understanding of the actual mechanisms of a process that is difficult to be modelled. The derived method for comparative analysis may already be used in practical applications. Additional research may further detail the model and provide enhanced procedures for estimation of the various coefficients, and thereby improve the method and make it more robust.

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.

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Appendix A. Explanation of terms

A.1. ADAS

Advanced driver assistance systems (ADAS) is a collective name for a whole range of in-vehicle systems based on ICT (Information and Communication Technology) and sensor technology, intended to assist drivers with their driving task, thereby enhancing driving comfort and driver performance, improving driver and traffic safety, and increasing driving efficiency and road network capacity.

The ADAS functions that are included in the case study are listed and explained below. For more details see Lu et al. (2005). Note that in the case study the term "speed assistance" is used for both legal speed limit assistance and curve speed assistance.

Navigation	Vehicle positioning, route calculation and route guidance
Legal speed limit assistance	Assist the driver in keeping within (static or dynamic) legal speed limits
Curve speed assistance	Assist the driver in keeping within an appropriate and safe speed in a curve
Collision avoidance (or: anti-collision)	Assist the driver to avoid imminent forward collisions Two possible modes: warning and warning followed by automatic control if necessary Three possible system layouts: collision warning, collision mitigation and collision control
Intersection support	Two possible system layouts: intersection collision avoidance: avoid collisions at intersections by warning or control, which could be radar and/or vision-based or vehicle positioning and short-range communication based; intersection negotiation: regulate motor vehicle traffic at intersections based on vehicle positioning and short-range communication in all participating vehicles
Lane keeping assistance (or: lane departure avoidance)	Assist the driver to stay in lane (on unintentional lane departure or road departure) Three possible modes: warning (e.g. by rumble strip sound), semi-control of the vehicle (by force feedback on the steering wheel) and full control

A.2. Safe speed limit

The concept of safe speed limit represents a 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 (higher or lower) for: (1) different vehicle types under the same circumstances; (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 risk for an accident to happen, as well as the consequences of an accident when it happens, are at acceptable levels. For actual in-vehicle applications the term "safe speed" is not attractive for liability reasons, and the term "recommended speed" or "safety speed" may be used instead.

A.3. Vulnerable road user (VRU)

A vulnerable road user (VRU) is every person taking part in road traffic that is not driver or passenger of a motor vehicle. The term especially pertains to pedestrians, cyclists and moped drivers, but also to drivers of four wheel mopeds, drivers of invalid carriages, equestrians, leaders of horse or cattle, drivers of horse drawn vehicles, and drivers of hand carts.

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