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Modelling and evaluation of the effects of traffic safety measures Comparative analysis of driving assistance systems and road infrastructure

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Abstract: Improvement of road traffic safety is an important policy issue. Various categories of measures are available to effectuate this. The thesis focuses on two categories: road infrastructure and driving assistance systems. A relevant policy question is if certain driving assistance systems may be desirable substitutes for infrastructure measures, in terms of traffic safety effects and other relevant aspects. The objective of this thesis is to develop an analytical method for comparative analysis of the traffic safety effects of these measures with dissimilar nature, as well as to identify an adequate method for policy evaluation, and to design, based on this method, an approach for strategic evaluation of alternative implementation schemes of different measures, which can take into account the results from the comparative analysis method and/or other method(s) concerning traffic safety effects, and other relevant impacts and constraints. For this comparative analysis and evaluation the following research topics are formulated: (1) identification of the functional substitutability relationships between driving assistance systems and infrastructure measures; (2) modelling of the fundamental schema of the influence of a measure on road traffic safety; (3) design of a method for comparative analysis of measures of different character; and (4) elaboration of a systematic analytical framework for linking decision making at the aggregated global level concerning overall effects of alternatives in a network, and decision making focusing at the local level concerning traffic safety effects of one or several measures at an intersection or road section. Through identification of a benchmark, i.e. a comprehensive set of traffic safety principles, and related operational traffic safety requirements, the functional substitutability relationships between these two categories of measures are qualified. In addition, a quantitative causal chain (QCC) model is developed based on a breakdown of the causal chain between measures and traffic safety effects. Based on the QCC model, a method for comparative analysis is derived for assessing safety performance at a local level. Furthermore, the thesis elaborates a systematic analytical framework for policy evaluation, and proposes a normalisation based evaluation method, named grey relational analysis (GRA), to aggregate data at the global level. Application of GRA provides a clear-cut ranking of strategic alternatives for improving traffic safety.

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Preface

This thesis has been completed with the very kind and valuable help and support of a number of people. Especially important was my stay at Lund University in the final stage of my thesis work, where I met friendly and supportive new colleagues. I particularly appreciate the open and truly academic atmosphere, with a sense of equality, at the division of Traffic Engineering of the Department of Technology and Society at the Lund Institute of Technology, as well as the discussions with distinguished experts in the field that were enabled through my stay at Lund.

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Last but certainly not least, a special word of thanks to my husband Kees Wevers for providing substantial support to my PhD research. Without his help and commitment I could not have finished this thesis, as an important part of the start of my new life in The Netherlands.

Meng Lu

Utrecht (The Netherlands) and Lund (Sweden), March 2007

獻給我的父母: 盧潤江 和 胡佩瓊

To my parents: Runjiang Lu and Peiqiong Hu

Acquisition of a PhD title
is an important milestone in an academic career.
However, honesty, openness, fairness, justice and equality
are more important, and essential prerequisites for a good result.

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Notation of variables

Notation related to causal chain

TS_P	traffic safety in terms of probability
R	accident risk
R_y	accident risk R related to determinant y
C	accident consequence
C_{yj}	accident consequence C related to determinant y of type j (e.g. $j = 1,2,3,4$, representing four types of consequence: fatality, hospitalisation, slight injury and property damage-only)
ψ_y	determinant ($y = 1,2,3,4,5$)
ψ_1	velocity of an individual vehicle as compared to the legal speed limit or the safe speed limit, and to the logical driving direction (vehicle in this context means motor vehicle)
ψ_2	velocity differences of road users, vehicle-vehicle or vehicle-VRU (vulnerable road user)
ψ_3	conflict between different traffic modes, especially between vehicle and VRU, in mixed traffic situations, or between vehicle and another object, such as a parked vehicle, an animal (domestic or wild), or a fixed roadside object
ψ_4	single vehicle run-off road
ψ_5	multi-vehicle conflict, e.g. rear-end (i.e. head-rear), head-on (i.e. frontal), head-side, side-side or pile-up
m_q	traffic safety measure q
ε_{qy}	measure effect coefficient: relative total effect of measure q on determinant y
α_y	risk influence coefficient: relative effect of determinant y on accident risk R related to determinant y
β_{yj}	direct consequence influence coefficient: relative direct effect of determinant y on consequence C of type j
μ_{yj}	indirect consequence influence coefficient: relative direct effect of risk related to determinant y on type j consequence
η_{qyj}	partial consequence effectiveness index: overall relative effect of measure q on consequence of type j through determinant y
ρ_{qy}	partial risk effectiveness index: relative effect of measure q on risk through determinant y
H_{qj}	consequence effectiveness index: total relative effect of measure q on consequence of type j
P_q	risk effectiveness index: total relative effect of measure q on risk R

$E_{\mathrm{D}j}$	absolute effect of a measure (or set of measures) based on road infrastructure on consequence of type j
$E_{\mathrm{A}j}$	absolute effect of a measure (or set of measures) based on driving assistance systems on consequence of type j
E_{D}	absolute effect of a measure (or set of measures) based on road infrastructure on risk
E_{A}	absolute effect of a measure (or set of measures) based on driving assistance systems on risk

Notation related to grey system

i	alternative
k	attribute
$x_0(k)$	element of the reference series for attribute k
$x_i(k)$	element of the compared series for attribute k
ζ	identification (or distinguishing) coefficient, $\zeta \in (0,1)$
$\gamma(x_0(k), x_i(k))$	grey relational coefficient of attribute k for alternative i
Γ_{0i}	grey relational grade
w_k	weight for attribute k

Acronyms

ABS	Anti-lock Braking System
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
AHP	Analytic Hierarchy Process
CARE	Community database on Accidents on the Roads in Europe
CBA	Cost-Benefit Analysis
CEA	Cost-Effectiveness Analysis
COOPERS	CO-OPerative SystEms for Intelligent Road Safety
CVIS	Cooperative Vehicle Infrastructure Systems
DV	Duurzaam Veilig (in English literally "sustainably safe"; the actual meaning is "inherently safe")
DVI	Duurzaam Veilige Infrastructuur (in English literally "sustainably safe infrastructure"; the actual meaning is "inherently safe infrastructure")
EC	European Community
eCall	emergency call
ELECTRE	ÉLimination Et Choix Traduisant la RÉalité method (in English: "elimination and choice translating the reality")
ESC	Electronic Stability Control
EU	European Union
FC	Functional Road Class
FM	Frequency Modulation
GAM	Goals-Achievement Matrix
GDF	Geographic Data Files
GNP	Gross National Product
GRA	Grey Relational Analysis
GRS	Grey Relational Space
HMI	Human Machine Interface
ICT	Information & Communication Technology
IN-ARTE	Integration of Navigation and Anti-Collision for Rural Traffic Environment
IP	Integrated Project
ITS	Intelligent Transport Systems
lidar	light detection and ranging
MADM	Multiple Attribute Decision Making
MCA	Multi-Criteria Analysis

MCDA	Multi-Criteria (or Multiple Criteria) Decision Analysis
MCDM	Multi-Criteria Decision Making
NPV	Net Present Value
PBS	Planning Balance Sheet
PROMETHEE	Preference Ranking Organization METHod for Enrichment Evaluations
QCC	Quantitative Causal Chain
radar	radio detection and ranging
RDS	Radio Data System
SAW	Simple Additive Weighting
SWOV	Stichting Wetenschappelijk Onderzoek Verkeersveiligheid (Dutch Institute for Road Safety Research)
TCT	Traffic Conflict Technique
TMC	Traffic Message Channel
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VMS	Variable Message Sign
VRU	Vulnerable Road User

Glossary

accident (road traffic accident) - unexpected and unintentional impact event that results in harm, between a road user and one or more other road user(s), object(s) and/or animal(s), and/or the road side

accident consequence - probability of a certain type of harm due to a road traffic accident per unit of exposure

accident risk - probability of an accident to occur per unit of exposure

causal chain - set of successive cause and effect relationships between elements of a process; the concept is used in road traffic safety to describe the interactions through which a measure influences road traffic safety

collision (road traffic collision) - unexpected and unintentional impact event that results in harm, between a road user and one or more other road user(s) and/or (stationary or moving) object(s)

collision avoidance - in-vehicle system function for detection of obstacles in the most likely path of the vehicle; calculation of the likelihood of a collision with a detected object based on object position and velocity, and vehicle position and speed; and, based on a threshold value for the time to collision, taking control of the vehicle if the driver fails to adequately react to the threat of the imminent impact, by braking or evasive manoeuvring; for evasive manoeuvring complete knowledge of the environment around the vehicle is required, especially of other nearby objects; the function may be combined with collision mitigation and/or collision warning

collision mitigation - in-vehicle system function for detection of obstacles in the most likely path of the vehicle; calculation of the likelihood of a collision with a detected object based on object position and velocity, and vehicle position and speed; and, based on a threshold value for the time to collision, triggering actions to mitigate the consequence of the imminent impact, such as pre-tensioning of seatbelts or timely activation of air bags; the function leaves the driver in complete control of the vehicle; the function may be combined with collision warning

collision warning - in-vehicle system function for detection of obstacles in the most likely path of the vehicle; calculation of the likelihood of a collision with a detected object based on object position and velocity, and vehicle position and speed; and provision of a warning to the driver based on a threshold value for the time to collision; the function leaves the driver in complete control of the vehicle

conflict - potentially unsafe event that requires an evasive action or manoeuvre, such as braking, swerving or accelerating, to avoid a collision; in this thesis, two classes of conflict are distinguished: multi-vehicle rear-end (i.e. head-rear), head-on (i.e. frontal), head-side, side-side and pile-up conflicts; and vehicle-VRU (vulnerable road user) conflicts, such as vehicle with pedestrian and bicyclist

crash (road traffic crash) - violent road traffic accident

driving assistance systems - collective name for a range of in-vehicle systems based on ICT (Information & 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; also called Advanced Driver Assistance Systems (ADAS)

exposure (road traffic exposure) - measure for the amount of involvement in an activity to which a probability of certain types of harm is associated

harm - physical injury or material damage; in the context of this thesis e.g. fatality, hospitalisation, slight injury or property damage-only

intersection collision avoidance - in-vehicle system function for avoiding collisions at intersections by providing warning to the driver or taking temporary control of the vehicle, and based on processing of information about position and movement of other vehicles and VRUs (vulnerable road users), using either radar, lidar and/or computer vision based sensing, or cooperative exchange of vehicle positions and movements using short-range communication, or a combination of these technologies

intersection negotiation - in-vehicle system function for regulating motor vehicle traffic at intersections based on cooperative exchange of vehicle positions and movements using short-range communication, and assuming presence of such systems in all participating vehicles; the function may be extended for use by all road users

road traffic - interaction between humans, vehicles and road infrastructure, subject to legislation and traffic regulations

telematics - provision of information and services, via wireless communications, to and from vehicles and their occupants

vulnerable road user (VRU) - every person taking part in road traffic who is not a driver or a passenger of a motor vehicle; the term especially pertains to pedestrians, bicyclists and moped drivers, but also to drivers of four wheel mopeds, drivers of carriages for disabled persons, equestrians, persons guiding horse or cattle, coachmen and persons using hand carts

List of Publications

I Lu, M., Wevers, K., Bekiaris, E. (2006). Traffic safety principles and physical road infrastructure measures. In Proceedings: *19th ICTCT Workshop* (International Cooperation on Theories and Concepts in Traffic safety), Minsk.

This study was designed by Meng Lu, and accomplished by Meng Lu together with Kees Wevers. Evangelos Bekiaris provided substantial support and valuable comments to the study.

II Lu, M., Wevers, K., Van der Heijden, R. (2005). Technical feasibility of advanced driver assistance systems (ADAS) for road traffic safety. *Transportation Planning and Technology*, vol. 28, no. 3, pp. 167-187.

This study was initiated by Meng Lu and Kees Wevers. It was designed by the Meng Lu and accomplished by Meng Lu together with Kees Wevers.

III Lu, M. (2006). Modelling the effects of road traffic safety measures. *Accident Analysis and Prevention*, vol. 38, no. 3, pp. 507-517.

IV Lu, M., Van der Heijden, R., Wevers, K. (2004). Evaluation of road infrastructure redesign and ADAS applications for traffic safety. *Journal of Grey System*, vol. 7, no. 2, pp. 121-131.

This study was designed by Meng Lu, and accomplished by Meng Lu together with Kees Wevers.

V Lu, M., Wevers, K. (2007). Application of grey relational analysis for evaluating road traffic safety measures: advanced driver assistance systems against infrastructure redesign. *IET Intelligent Transport Systems*, vol. 1, no. 1, pp. 3-14.

This study was designed by Meng Lu, and accomplished by Meng Lu together with Kees Wevers.

1 Introduction

1.1 Road traffic safety measures

Road traffic accidents are perceived as one of the major societal problems in the world. According to an estimate of the World Health Organization, 1.2 million people are killed and as many as 50 million injured in road accidents every year worldwide. Projections indicate that these figures will rise by about 65% over the next 20 years unless there is increased commitment to prevention (Peden et al., 2004). These accidents constitute a substantial cost for society in terms of medical costs, payments for sickness benefits, loss of labour capacity, material damage and increased traffic congestion. In the European Union (EU), in 2000, over 40,000 people died from road accidents and more than 1.7 million people were injured, and the costs of the consequences of road traffic accidents are estimated to be equivalent to 2% of the GNP (Gross National Product) of the EU (EC, 2001).

Road traffic is the interaction between humans, vehicles and road infrastructure, subject to legislation and traffic regulations (see Figure 1.1). In this process the human is a key element, but also the weakest link. In this thesis the view is taken that accidents can be caused by human error, mechanical defects and natural effects, that the latter two causes only provide a marginal contribution, and that, therefore, nearly all traffic accidents involve human error.
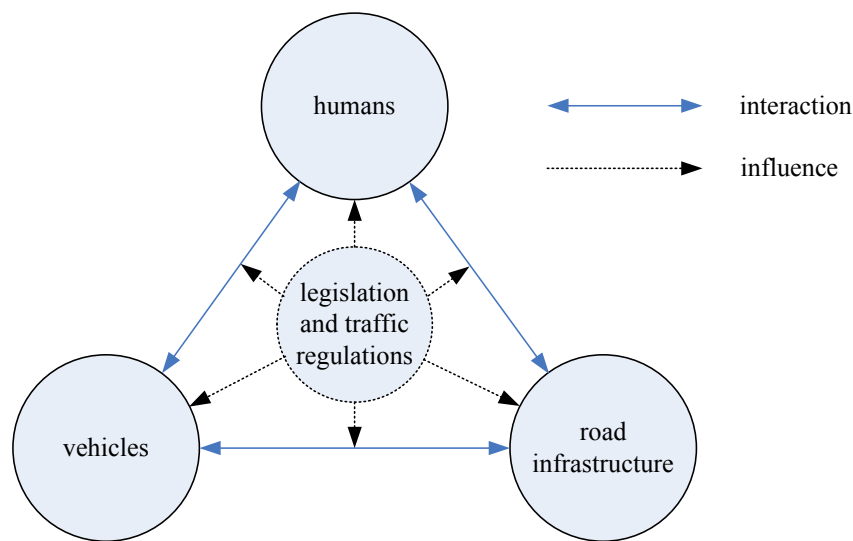
Figure 1.1 - Interaction between humans, vehicles and road infrastructure subject to legislation and regulations

Measures to counteract traffic accidents and to improve traffic safety can be classified as: (1) legislation and traffic regulation; (2) measures directly acting on driving behaviour ; (3) road infrastructure related measures; and (4) vehicle related measures (see Figure 1.2). Although these measures aim at improving traffic safety by preventing or mitigating human error, their effectiveness is uncertain. This especially concerns measures that act through influencing the driver to drive adequately. Actual driver behaviour as a result of a traffic safety measure may be different from what is expected. Current knowledge is still too limited to understand all aspects of human behaviour in this interactive system. Traffic safety measures may sometimes also have adverse effects, despite good intentions (see e.g. (Elvik & Vaa, 2004)).

```
                                        ┌── vehicle requirements
                    legislation and     ├── infrastructure requirements
                    traffic regulations ├── road traffic rules
                                        └── driving license requirements
                                        ┌── traffic surveillance and enforcement
                    measures directly   ├── information
                    acting on driving   ├── education
road traffic        behaviour           └── dynamic traffic management
safety measures
                                        ┌── intersections
                    road infrastructure ├── road sections
                    related measures    └── generic measures (whole network)

                    vehicle related     ┌── passive safety
                    measures            └── active safety
```

Figure 1.2 - Categorisation of road traffic safety measures

Road traffic related legislation and regulations provide a basic framework for the traffic system. The most prominent of these are the traffic regulations, which are primarily intended to reduce the number and severity of road traffic accidents and to make the traffic process in general orderly. But even drivers that have good knowledge of the traffic regulations may make mistakes. And drivers may also sometimes just ignore the regulations. In addition to the traffic regulations, other legislation and regulations are relevant for the traffic system, for instance, the legislation and regulations concerning the requirements for vehicle design.

Drivers are made aware of the traffic regulations by education and by government-initiated information campaigns. Traffic surveillance may be used to maintain a level of awareness of the traffic regulations, and to enforce improved compliance with these. Extensive enforcement may have a substantial effect (see e.g. (Hakkert et al., 2001)), but needs to be continuous to maintain the effect, as it is difficult to influence human behaviour in a sustainable way (see e.g. (Evans, 2004)). According to Evans (1991: p.156) there is "no convincing evidence that driver education, or increased driving skill and knowledge, increase safety". In addition, he states that "increased driving skill and knowledge are not the most important factors associated with avoiding traffic crashes. What is crucial is not how the driver *can* drive (driver performance), but how the driver *does* drive (driver behaviour)" (Evans, 1991: p.158). Driver performance to be interpreted as driver skills or competence.

The physical characteristics of the road network may contribute significantly to supporting drivers to adhere to the traffic regulations, as well as to assist them to avoid errors. Therefore, the design of the road infrastructure should be adapted to prevent unintended use of infrastructure, encounters at high differences in speed and direction, and uncertainty of road users (CROW, 1997). Infrastructure measures based on ICT (Information & Communication Technology) for increasing traffic efficiency (traffic management, e.g. by variable message signs - VMSs), protecting the environment (e.g. speed reduction) and speed limit enforcement (e.g. speed trap and trajectory control) may also contribute to traffic safety.

Vehicle related measures include passive components and active components. Passive components help to mitigate the consequences of accidents. Examples are vehicle structure, head

restraint, seatbelt and airbag. Active components help to avoid accidents in critical situations, and include elements such as quality of tyres, hydraulic braking systems, electronic braking systems (anti-lock braking system - ABS), stability management systems (electronic stability control - ESC) and intelligent transport systems (ITS), and especially its subset of in-vehicle driving assistance systems[1] and telematics[2] applications. In this thesis telematics applications are included in the term driving assistance systems. Measures in this category support the driver with the driving task by providing (whenever necessary) information, warning or (temporary or permanent, and overrideable or non-overrideable) vehicle control, with the purpose of preventing accidents or mitigating the negative effects of accidents.

This thesis focuses on physical road infrastructure measures and driving assistance systems in support of road traffic safety.

1.2 Road traffic safety factors and measures

From a statistics point of view, three basic traffic safety dimensions can be identified: (road traffic) exposure, accident risk and accident consequence (Rumar, 1988; Nilsson, 2004). Exposure can be defined as a measure for the amount of involvement in an activity to which a probability of certain types of harm is associated. For road traffic exposure different units of measure may be used, in relation to a certain period and a certain geographic area: (number of) inhabitants, registered vehicles, vehicle kilometres, road user kilometres, vehicle hours, road user hours, trips or traffic situations. Accident risk can be defined as a ratio expressing a number of accidents (all, or of a certain type) per unit of (a certain type of) exposure, for a certain period and a certain geographic area. Relevant types of accidents are distinguished based on the type (or severity) of harm, e.g. fatal accident (accident involving one or more fatalities, and possibly also one or more injuries), injury accident (accident involving one or more injuries), and property damage-only accident. Concerning injuries, a further distinction can be made between hospitalisations and slight injuries. Injury accidents include fatality accidents. In addition, injury only accidents can be distinguished. Accident consequence can be defined as the number of cases of a certain type of harm per accident, or a number of accidents, of a certain type, for a certain period and a certain geographic area. Multiplication of the three dimensions provides an absolute measure for the level of traffic safety, while multiplication of only accident risk and accident consequence provides a relative measure of traffic safety, per unit of exposure.

In this thesis accident risk is defined as the probability of an accident to occur per unit of exposure; and accident consequence is defined as the probability of a certain type of harm (e.g. fatality, hospitalisation, slight injury or property damage-only) due to a road traffic accident per unit of exposure.

Measures that may influence (and potentially decrease or increase the values of) these safety dimensions are presented in Table 1.1. The table indicates that, compared with accident risk

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[1] Driving assistance systems is a collective name for a range of in-vehicle systems based on ICT 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. Another term is ADAS (Advanced Driver Assistance Systems), in which, however, the word "advanced" has become outdated.

[2] The provision of information and services, via wireless communications, to and from vehicles and their occupants.

Table 1.1 - Overview of traffic safety measures and their possible influences on the three traffic safety dimensions[3] (adapted based on (Elvik et al., 1989; Ogden, 1996; Hummel, 2001; Elvik & Vaa, 2004; Evans, 2004; Lu, 2006))

road infrastructure related measures	exposure	risk	consequence
promote efficient land use (e.g. compact urban form)	+	○	○
provide efficient networks (e.g. short and direct trips)	+	○	○
promote alternative (non-motorised) modes	+	○	+
lower legal speed limit	○	+	+
roundabouts	○	+	+
intersection channelisation	○	+/–	+/–
elevations (e.g. speed bumps and humps, plateaux)	○	+	+/–
traffic calming measures	○	+	+/–
reduction of crossings	○	+	○
middle wire barrier on "2+1" carriageway	○	+	+/–
service roads	○	+	○
cancellation of pedestrian crossings	○	+	○
dedicated bicycle lanes	○	+/–	+/–
consistent markings and signing	○	+	○
semi-paved shoulders	○	+	+/–
rumble strips	○	+	○
roadside safety structures	○	○	+
absence of parked vehicles	○	+	○
curve flattening	○	+/–	○
road surface improvement	○	+/–	○/–
improved road illumination	○	+	○
road widening	○	+/–	○/–
vehicle related measures	**exposure**	**risk**	**consequence**
improved vehicle structure	○	○	+
restraint systems (e.g. seatbelt)	○	○	+
ABS (anti-lock braking system)	○	+	○
ESC (electronic stability control)	○	+	○
eCall (emergency call)	○	○	+
navigation	+/–	+/–	○
lane keeping assistant	○	+	○
lane change assistant	○	+	○
collision warning	○	+	○
collision mitigation	○	+	+
(forward) collision avoidance	○	+	+
ACC (adaptive cruise control) with stop-and-go	○	+/–	○
adaptive light control	○	+	○
vision enhancement	○	+/–	○
driver alertness monitoring	○	+	○
curve speed assistance	○	+	+
legal speed limit assistance	○	+	+
dangerous spots warning	○	+	○
intersection collision avoidance	○	+	+
intersection negotiation	○	+	+
autonomous driving	○	+	+
measures directly acting on driving behaviour	**exposure**	**risk**	**consequence**
traffic surveillance and enforcement	+/–	+	+/○
information	+/–	+	○
education	○	+	+
traffic management, e.g. road pricing	+/–	+/–	○

+ positive effect   – negative effect   ○ irrelevant relationship
(decrease of factor)   (increase of factor)   (no or limited effect on factor)

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[3] Exposure in this table refers to the unit of measure "vehicle kilometres".

and accident consequence, only a limited number of measures influence exposure. Whether a measure decreases or increases exposure is not unambiguous, as this may depend, to a considerable extent, on the behavioural adaptation of the human and on the time scale. From the statistics perspective, aggregated exposure is generally addressed. However, aggregated exposure over several functional road classes hides the fact that measures have different effects on risk level on different road classes[4]. It ignores the fact that, for instance, reduced exposure on roads of higher functional road class may increase the exposure on roads of lower class. This may have a negative influence on the outcome (e.g. number of fatalities or hospitalisations), due to differences in aggregate risk per road class. This may, therefore, increase aggregate (statistical) accident risk, although it does not necessarily change local accident risk (abstracting, in a first approximation, from factors that may actually influence local accident risk, like higher traffic density or behavioural adaptation).

Another issue is that, except for the navigation system (with TMC - Traffic Message Channel), the measures that may influence exposure generally operate at an overall level (network, or policy and spatial planning), and not at the elementary local level of individual measures (at road sections and intersections). For these reasons, this thesis addresses the two traffic safety dimensions accident risk and consequence.

1.3   Policies for road traffic safety

Road traffic accidents only gradually became an issue of particular interest when the number of accidents progressively increased due to the steadily increasing number of motor vehicles and number of vehicle kilometres driven. Although the road safety records of The Netherlands, Sweden and the United Kingdom (UK) are amongst the best worldwide (see Table 1.2), the accident toll is still considered unacceptably high.

Table 1.2 - Fatality rates in 2000 in several developed countries (adapted after (Koornstra et al., 2002))

country	per 10^9 vehicle-km	per 10^5 inhabitants
UK	7.3	5.9
Sweden	8.4	6.7
The Netherlands	8.5	6.8
EU 15 member states (before 2004)	13.6	11.0
USA	9.5	15.2
Australia	10.1	9.5
Japan	13.4	8.2

Governments of these three countries have been applying a range of successive generations of different strategies for improving road safety since the 1950s. Although road traffic safety has been considerably improved over these years, it is nearly impossible to say to which extent this should be attributed to implementing these successive policies, and how much other autonomous factors have contributed to this effect. In The Netherlands several successive more or less distinct sets of measures of different character may be distinguished, each with

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[4] Functional road class (FC) is an attribute defined in the GDF (Geographic Data Files) standard (ISO, 2004). It provides a classification of roads based on the importance of the role that a particular road performs in the connectivity of the total road network.

an implementation cycle of about ten years (see Figure 1.3). Similar developments took place in Sweden and the UK (Koornstra et al., 2002). The need for such successive sets of measures can be partly explained from the economic law of diminishing marginal returns, which implies decreasing marginal effects of additional investments in a certain measure for improving road traffic safety beyond a certain level of implementation. In such a situation a new approach or a new technology may, however, bring further improvements in a more efficient and economical way (Lu et al., 2003). Another explaining factor is technological development itself, which creates an evolution of requirements for traffic safety measures and of possible solutions.
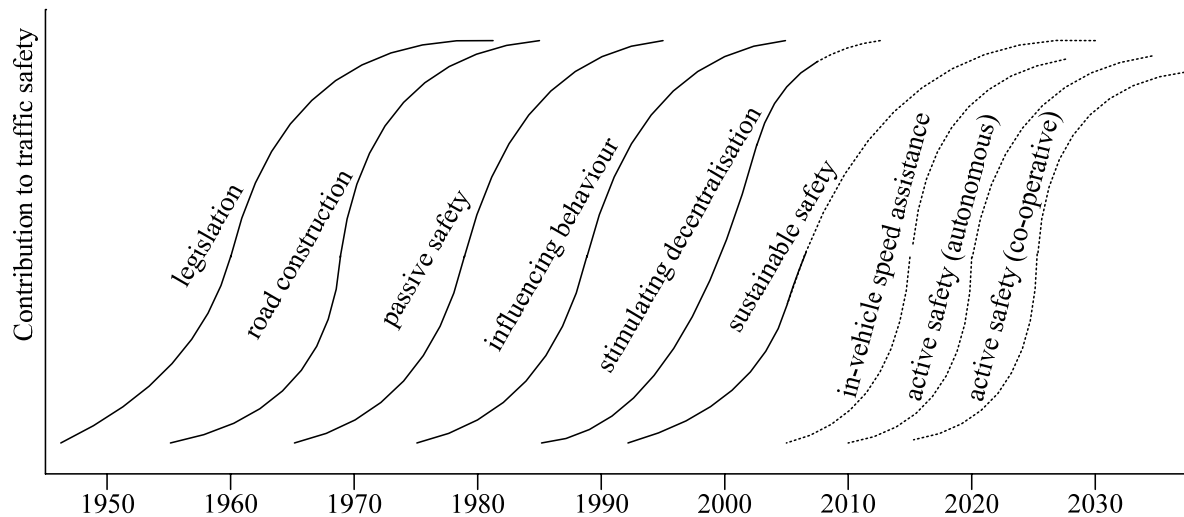
Figure 1.3 - Conceptual view on traffic safety policy development in The Netherlands (adapted after (Koornstra et al., 1992))

During the 1990s, authorities of various countries, notably The Netherlands, Sweden and the UK, have formulated ambitious policy targets with respect to traffic safety, and developed dedicated road safety programmes for reaching these targets. The EU has formulated its own ambitious targets in 2001.

The Netherlands

Since the early 1980s, traffic safety policy in The Netherlands focused on increasing long-term road safety by influencing behaviour, especially by addressing the issues of alcohol and speed, hazardous locations, safety of children and the elderly, and safety devices. Although this policy, which had a mainly reactive and curative character, was effective and overall reductions in road accidents were attained, analysis of accidents in relation to the type of road showed large discrepancies in fatal and serious injury accident rates on different road categories. Also, at the end of the 1980s the decrease in the number of fatalities and injuries slowed down. In reaction, in 1990 the SVV-II (1990) have set as a target for 2010 to reduce fatalities to 750 per year and hospitalisations to 14,000 per year (i.e. reductions of 50% and 40% respectively compared to the 1986 figures). This was followed in 1992 by a new concept for a proactive and preventive strategy combined with a continued and intensified focus on the original issues, constituting a new set of measures comprising four main elements: education, enforcement, infrastructure and ITS. This concept for road traffic safety was named Sustainably Safe (in Dutch "Duurzaam Veilig" - DV) (Koornstra et al., 1992). Road traffic may be considered as a system composed of four main elements: function, design, regulation and

use[5]. Sustainably safe road traffic is in essence a systems approach of traffic safety which requires that these elements are made conformant with one another. Such conformity often does not exist, mainly due to historical reasons, and unintended road use often occurs (CROW, 1997). To increase traffic safety, both the design and the use of the road should be adapted to the following traffic safety principles (Koornstra et al., 1992): (1) prevent unintended use of the road infrastructure; (2) prevent indecisive behaviour of road users; and (3) prevent encounters at high differences in speed and direction. The concept of DV has a strong focus on road infrastructure related measures, which is implemented in a programme for a Sustainably Safe Infrastructure (in Dutch "Duurzaam Veilige Infrastructuur" - DVI). In the framework of DVI the aforementioned three principles were reformulated in 1997 (CROW, 1997) as: (1) functionality of the road network (i.e. clear functional road categories and related intended behaviour of road users); (2) predictable traffic behaviour (i.e. choice of route and necessary manoeuvres always and everywhere understandable and simple for all road users, making traffic behaviour more predictable); and (3) homogeneity of the traffic (i.e. small differences in speed and direction of movement, in mass and in vulnerability between road users, and between road users and obstacles). These principles led to a set of operational requirements (see also Chapter 4).

Sweden

In 1967 Sweden changed from left-side to right-side driving. To enable this drastic transition in a safe way, an intense package of safety measures was implemented, especially focusing on reconstruction of the road network and education, while for a certain period rather low speed limits were set. This eased public acceptance of other mandatory measures in the following fifteen years (such as use of front seat safety belts, use of helmets on motorcycles and mopeds and daylight running lights), and by the mid 1980s road traffic in Sweden was the safest in the world. Annual fatalities reduced from 1200 in 1975 to 700 in 1983. However, in the second half of the 1980s, parallel to a prosperous economy, and thereby expanding traffic, the number of fatalities increased to a level of 900 in 1989. After this, the situation again improved. The 1990 National Traffic Safety Programme set a target of less than 600 fatalities by 2000, which was already reached in 1994. Therefore, the 1994 National Traffic Safety Programme revised this target to less than 400 fatalities by 2000. However, in the period 1994 to 2000 the number of fatalities remained at the same level. In 1997 the government sent a plan to the parliament named "Transport for a sustainable development", which was adopted in June 1998. The plan focused on future societal sustainability of the traffic system, and implied a change in philosophy to improve traffic safety, and a long-term goal for the level of traffic safety to be achieved. It was accepted that the road traffic system cannot be perfect, and that humans will always make mistakes. Therefore, the focus shifted from trying to avoid mistakes to trying to reduce the consequences of mistakes. An important and perhaps the most well-known element of this plan was the Vision Zero: adequate measures should result in zero fatalities and zero serious injuries due to road traffic accidents. For this the design and functionality of the road traffic system should be changed, and both roads and vehicles should be made safer. The plan considered achievement of this goal as a shared responsibility of politicians, public road and other authorities (the owners of the road system), transport service providers, vehicle manufacturers and road users. The plan did, however, not include an operational translation, and no deadline was set for achieving the intended zero levels of fatalities and serious injuries, but it included an interim target, to reduce fatalities by 2007 to 300 (50% of the 1996 level). In 1999

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[5] This definition is slightly different from the definition given on page 1, and especially focuses on the road infrastructure side.

the government presented a short-term plan comprising eleven action points[6]. Of these, two focus on infrastructure measures, and one on driving assistance systems. In 2001 the government presented an infrastructure plan to enable achievement of the 2007 target. (Tingvall, 1997; Vägverket, 1997; Elvik, 1999; Koornstra et al., 2002; Archer, 2005)

UK

The UK has a long tradition of attention for traffic safety, and specific measures were often taken well before they were introduced in other countries. Examples are driving licenses and requirements for vehicle braking systems in 1903, and pedestrian crossings in 1934. In 1987 the government adopted a target to reduce fatalities and serious injuries to two thirds of the average 1981-1985 level, and introduced measures to achieve this goal. Especially the Traffic Calming Act of 1992 (UK Parliament, 1992), "An act to make provision about the carrying out on highways of works affecting the movement of vehicular and other traffic for the purposes of promoting safety and of preserving or improving the environment; and for connected purposes." The name of this act speaks for itself: it is about measures to reduce the amount and the speed of traffic. It especially refers to a range of infrastructure engineering measures focusing on the lower two road categories, distributor and especially local access roads, like speed humps, plateaux, roundabouts and road narrowing, and also includes the creation of *living zones*, a concept that originated in The Netherlands under the name *woonerf*. By 1998 reductions of 39% in fatalities and of 45% in serious casualties were achieved compared to the averages for the period of 1981 to 1985, but surprisingly slight injuries had increased by 16%. In March 2000 the UK government published a new strategy for improving road traffic safety in the document: "Tomorrow's roads - safer for everyone" (DETR, 2000). The strategy had a special focus on reducing the number of children killed or injured in road accidents. The targets comprised reductions by 2010 of 40% of persons and 50% of children killed or seriously injured in roads accidents, and of 10% of the slight injury rate (number of slight injuries per billion vehicle kilometres), as compared to the 1994-1998 averages. The document contains many specific recommendations, and also expresses the intention to review strategy and targets every three years. Proposed measures comprise ten themes (areas of concern and action): safer road use for children, safer drivers (concerning training and testing), safer drivers (concerning drink, drugs and drowsiness), safer infrastructure, safer speeds, safer vehicles, safer motorcycling, safer walking, cycling and horse riding, better enforcement of traffic law, and promotion of safer road use. For each of these themes specific actions are defined, with implementation time horizons, as well as points for special attention. (Koornstra et al., 2002; Ward et al., 2003)

EU

In September 2001 the European Union (EU, then still named European Community - EC) published its white paper "European transport policy for 2010: time to decide" (EC, 2001). This document presents policies for a sustainable future development of the transport system in Europe considering all different modes. It resulted from awareness that the continuously increasing demand for mobility and the corresponding increasing chronic delays in the transport system due to insufficient capacity, with decreasing quality and increasing economic loss,

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[6] The eleven action points include: a focus on the most dangerous roads, safer traffic in built-up areas, emphasis on the responsibilities of road users, safe bicycle traffic, quality assurance in transport work, requirement for use of winter tyres, making better use of Swedish technology, responsibilities of road transport system designers, public responses to traffic violations, the role of voluntary organisations, and alternative forms of financing new roads.

cannot be solved by just building new infrastructure. It was understood that the transport system needs to be optimised to meet both growing demand and sustainable development. A modern transport system must be sustainable from an economic and societal as well as an environmental point of view. One of the issues specifically addressed in the document is road traffic safety. The price paid for mobility in terms of fatalities and injuries is considered far too high. In 2000 these were at levels of more than 40,000 fatalities and more than 1.7 million injuries per year in the EU (the 15 member states of the period before 2004), while the total number of people killed in road traffic accidents amounts to 1.64 million for the period 1970 to 2000. During the beginning of the 1990s, the yearly number of fatalities dropped significantly, but this decrease slowed down during the second half of the 1990s. It is concluded that transport by road is the most dangerous of all transport modes and the most costly in terms of human lives. In the 2001 white paper the target is set to reduce in the period 2000 to 2010 the number of fatalities by half. To achieve this objective, integrated action is needed taking account of human and technical factors. Although the EC has contributed before 1990 to road safety, especially through technical standardisation and by more than 50 directives, made possible by the creation of the internal market[7], only after the Maastricht treaty of 1990 the EC was provided with certain explicit powers in the field of road safety, and with the legal means to introduce related measures. Despite this, even today the implementation of a proper pan-European road traffic safety policy and the related actions is difficult, especially because of the subsidiarity[8] principle. It is recognised that responsibility for taking measures to reach the target will be mainly in the domain of national and local authorities. The EC is expected to be able to contribute through action at two levels: harmonisation of penalties, and promotion of new technologies to improve road traffic safety. New technologies include in-vehicle systems to enhance control and enforcement, the black box to record accident parameters and induce motorists to drive more responsible, and intelligent transport systems and measures, especially in the field of active safety. Specifically mentioned are traffic management and collision avoidance, increased impact resistance of vehicles based on new materials and designs for improved structural integrity, improvement of the quality of tyres, safety standards for the design of car fronts to reduce impact on vulnerable road users (VRUs) in accidents, and methods to induce better compliance with (legal and optimum) speed limits (which will also contribute to reducing congestion and emissions). Except for the need to improve and harmonise road markings and road signs, and for the sentence "Certain technical measures, e.g. involving the safety of the infrastructure, call for major investments that Member States have thus far been dilatory in making.", infrastructure measures are not explicitly mentioned, in contrast with the programmes in the three aforementioned countries. The EC has contributed since the early 1990s significantly to the development of new technologies by its mechanism of EU funded projects[9]. Measures that are mentioned in the 2001 white paper include: (1) a road safety ac-

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[7] Examples are compulsory use of seatbelts, transport of dangerous goods, use of speed limitation devices in lorries, standardised driving licences and roadworthiness testing of all vehicles.

[8] Under the principle of subsidiarity, in areas which do not fall within its exclusive competence the Union shall act only if and insofar as the objectives of the intended action cannot be sufficiently achieved by the Member States, either at central level or at regional and local level, but can rather, by reason of the scale or effects of the proposed action, be better achieved at Union level (Constitution for Europe, 2003: article 9, clause 3).

[9] Examples of related projects in recent years are the IN-ARTE project (Integration of Navigation and Anti-Collision for Rural Traffic Environment; 1998-2001) (Tango & Saroldi, 2001), the Integrated Project (IP) PReVENT (Preventive and Active Safety Applications; 2003-2007) (PReVENT Consortium, 2003), the SpeedAlert project (2004-2005) (Wevers & Lu, 2007), and the more recent IPs in the area of cooperative systems: CVIS (Cooperative Vehicle Infrastructure Systems; focusing on the infrastructure side and traffic efficiency) (CVIS Consortium, 2005) SAFESPOT (Co-operative Systems for Road Safety "Smart Vehicles on Smart Roads"; focusing on the in-vehicle side and traffic safety) (SAFESPOT Consortium, 2005) and COOPERS (CO-OPerative SystEms for Intelligent Road Safety; focussing on the domain of the road operator) (COOPERS Consortium, 2005).

tion plan for 2002-2010 to identify needed measures to achieve the stated objective at European and national levels; (2) improvement of accident prevention and analysis by improved cooperation between member states and introduction of the transnational European road accident database (CARE - Community database on Accidents on the Roads in Europe); (3) harmonisation of current rules and penalties; (4) compilation of a list of locations that are significantly dangerous (based on accident statistics), for improved signposting; and (5) an independent committee of experts for accident investigations. The white paper also states that the Commission might submit regulatory proposals by 2005 should improvements not be significant by that time. In addition, the eSafety Forum was founded in 2003 (eSafety Forum, 2005), as a result of the eSafety Working Group on Road Safety (EC, 2002). In the 2006 review of the 2001 white paper, it is stated that he target of halving the number of deaths in the period 2001 to 2010 remains valid, and will only be met by a joint effort involving governments at all levels, the car and motorway construction industries, infrastructure managers and road users themselves (EC, 2006).

1.4 Motivation and research problem definition

It is apparent from the foregoing that road traffic safety has been an important policy issue since the 1950s, and has received ongoing and increasing attention in the past fifteen years. In addition to continuing efforts focusing on regulation, education and information campaigns, since the early 1990s, especially in several European countries, large-scale programmes for infrastructure redesign have been elaborated. However, full implementation of these programmes covers several decades and requires considerable investment (Poppe & Muizelaar, 1996). In the mean time, the development of driving assistance systems is rapidly progressing, and several types of applications come closer to possible high volume introduction. Considering the implementation difficulty and high cost of the infrastructure redesign programmes, the question may be raised whether certain functions of driving assistance systems could act as substitutes or complements for physical infrastructure measures. If so, the infrastructure related part of traffic safety strategies might need to be reconsidered.

To answer this question, a comparative analysis and an evaluation of the two categories of measures are required, which take into account in the first place their effects on traffic safety, but in addition other relevant effects and various implementation aspects. Such comparative analysis and evaluation are rather complex, as infrastructure measures and driving assistance systems have a quite dissimilar nature, and, in addition, are at a different stage of development. The main differences can be summarised as follows (see also (Lu, 2006)):

1. An infrastructure measure works for every vehicle, but mainly at its specific location, while a driving assistance system (when switched on) works everywhere, but mainly for the vehicle in which it is installed.

2. An infrastructure measure is generally a static piece of infrastructure that acts passively on the vehicle and/or the driver, while a driving assistance device is a dynamic system acting actively on the vehicle and/or the driver by taking decisions based on processed information.

3. Differences in flexibility, adaptability, liability, security, non-safety side effects and implementation impediments (e.g. the implementation of a national policy for improvement of infrastructure design requires support from local authorities; on the other hand, a harmonised and targeted large-scale application of driving assistance systems needs agreement or

even directives at the European level, with national support and possibly legislation and related fiscal and/or other measures).

4. Infrastructure measures are based on proven and mature technology with a high level of robustness, while for many functions of driving assistance systems this is not yet the case.

5. Current penetration levels of the two categories of measures are rather different.

6. Differences in ownership, decision making and financing schemes.

An additional problem is that the availability and reliability of data are often limited, especially for the traffic safety effects of driving assistance systems, but also for some of the other aspects, such as environmental and economic effects, and boundary conditions for implementation.

The need for a systematic comparative analysis of the traffic safety effects of the two categories of measures of dissimilar nature at the local level, and the current absence of an adequate method for such analysis constitute one major part of the motivation for this research. The other part of the motivation derives from the need to identify an adequate method for policy evaluation of various possible implementation alternatives, which takes into account both safety effects of measures and other relevant aspects.

2 Objective, scope and research questions

2.1 Research objective

The first purpose of this thesis is to develop an analytical method for comparative analysis of the traffic safety effects of measures with dissimilar nature: measures based on the implementation of infrastructure redesign, and measures based on the implementation of driving assistance systems. This comparative analysis focuses on safety performance. The thesis concerns an exploratory study to develop an approach for modelling the stated problem, and explicitly not an empirical study.

The second purpose of this thesis is to identify an adequate method for policy evaluation, and to design, based on this method, an approach for strategic evaluation of alternative implementation schemes of different measures, which can take into account the results from the method for comparative analysis and/or other method(s) concerning traffic safety effects, as well as other relevant impacts and constraints.

2.2 Research scope and limitations

To improve road traffic safety, there is a choice from various categories of measures. Two of these categories, road infrastructure and driving assistance systems, are studied and compared in this research.

A prerequisite for enabling the comparative analysis of measures of dissimilar nature that are supposed to have similar functionality in terms of traffic safety effects, is to provide a qualitative analysis of relationships between measures from the two different categories in terms of functional substitutability. For driving assistance systems, which are based on a range of technologies that are in different stages of development, it is important to establish for which technologies and derived systems large-scale implementation is feasible. In addition, a structured overview of infrastructure measures for improving road traffic safety needs to be provided.

To study the traffic safety effects of a measure (or a combination of measures), it is proposed to study the causal chain between a measure and the effect on traffic safety at the elementary local level of a road section or an intersection. Two types of traffic safety factors can be distinguished in modelling the causal chain: engineering factors and behavioural factors (see e.g. (Evans, 1985; Elvik, 2004)), which, however, are strongly related to each other. The approach that is elaborated in this thesis aims to develop a quantitative causal chain (QCC) model for the measure-effect chain, and to derive from this model a method for comparative analysis of safety effects of different measures (with similar functionality). The research for this part is thus carried out with a focus on the engineering perspective (and not directly from the perspective of human behaviour; for this see e.g. (Van Winsum et al., 1999; Lee et al., 2004; Hancock & De Ridder, 2003)). The method should be able to address safety effects of one measure or several measures at the elementary local level. The results can be used as inputs for policy evaluation of strategic alternatives at a higher global level of aggregation, to provide generalised results for, for instance, all roads of a certain road category (collection of roads with similar characteristics and usage) or functional road class within a certain area.

In general, for a strategic evaluation of different implementation policies an evaluation method is used. A multitude of evaluation methods exists, such as cost-benefit analysis, cost-effectiveness analysis and analytical hierarchy process. For each evaluation problem the most adequate method in view of the scope and constraints of the problem needs to be selected. As inputs for the application of an evaluation method, alternatives (or strategic scenarios[10]) and criteria (or attributes) need to be identified and defined. For the current evaluation problem, a scenario could be one or more infrastructure or driving assistance systems based measures, or a combination of measures from the two categories. Criteria include in the first place safety effects, but in addition, also other effects of alternatives, such as societal, environmental and economic effects, and effects related to implementation aspects. The safety effects are actually part of the societal effects, but sometimes mentioned separately, as they are the main reason for implementing traffic safety measures. The evaluation method to be applied needs to be able to cope with the aspect of limitations in data availability, accuracy and reliability. The strategic evaluation should be dynamic to account for the development over time of the penetration levels of different types of measures. Forecasting methods that could be used for estimating such development are, however, not addressed in this research. Also, a detailed analysis of the effects of other relevant aspects than traffic safety is beyond the research scope.

2.3   Research questions

The evaluation of the feasibility of various measures and their potential effects, in order to support decision making (at different levels) with respect to different possible strategic alternatives, is cursed with many uncertainties. Road infrastructure design and driving assistance systems have a completely dissimilar nature. In their implementation they follow completely different scenarios. Furthermore, the conventional methods to study the safety effects of these two categories of measures are different: research into infrastructure measures is mainly based on empirical study and accident statistics or expert knowledge; research into driving assistance systems is generally based on pilot trials, simulator studies and/or simulation modelling, due to yet limited or zero (dependent on the type of function) market penetration. So far, no systematic comparative analysis of the traffic safety effects of the two categories of measures has been carried out. Moreover, a certain measure plays a role to improve traffic safety at a local level, and its effects are not the same for different time periods and every location, since the specific situations (e.g. traffic speed and density, road layout and surface, vehicle type and quality, luminosity and visibility, and driver behaviour) may be different. A method for comparative analysis may especially be useful to overcome the problem of limited data availability for the traffic safety effects of driving assistance systems, by estimating such effects based on comparison with effects for infrastructure measures.

To address both comparative analysis of safety performance and comprehensive evaluation, two levels of study are distinguished in the approach: safety performance at a local level, and policy evaluation at a global level. Safety effects need in the first place to be studied at the elementary level of individual measures acting locally, and then be aggregated at a global level together with inputs concerning other effects. For infrastructure measures, study at the safety performance level means at the level of a road section, e.g. the safety effects of a speed hump or of a separate bicycle lane at that road section; or at the level of an intersection, e.g. the safety effects of a roundabout at that intersection. Study at the policy evaluation level aggregates to a network, e.g. in a country, a province, a municipality, a 30 km/h zone or a par-

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[10] Scenario in this context is synonymous to alternative, and is defined as a possible implementation strategy of a single measure (or function) or multiple measures (or functions).

ticular road. For driving assistance systems, study at the safety performance level relates to the effects of a system function (e.g. navigation, speed assistance or lane keeping) or several (possibly integrated) functions at a road section or an intersection; study at the policy evaluation level relates to one system function or several (possibly integrated) functions in a complete network.

In view of the aforementioned considerations, the following research questions are formulated:

1. What are the relationships in terms of functional substitutability concerning traffic safety effects between infrastructure measures and driving assistance systems?

    As these two categories of measures are of quite dissimilar nature, comparative analysis requires investigation of potential matches in functionality between measures of the two categories, i.e. which driving assistance system (or combination of integrated system functions) is similar in traffic safety functionality to which infrastructure measure (or combination of infrastructure measures).

2. How can the fundamental schema of the influence of a measure on road traffic safety be modelled?

    For developing a method for comparative analysis a theory is required concerning the causal effect chain from traffic safety measure to traffic safety effect. The causal chain can be studied in different ways (see e.g. (Elvik, 2004; Evans, 1985; Asher, 1976; Hall & O'Day, 1971)). For this research, it needs to be defined in a quantitative way based on controllable parameters. In addition, the causal chain model should enable deriving a method for comparative analysis that can be easily applied in practice.

3. What comparative analysis method is appropriate for measures of dissimilar character?

    Such method is needed for the comparative analysis of safety performance, especially for estimating safety effects of driving assistance systems based on existing estimates for safety effects of infrastructure measures. The scope of the intended comparative analysis is different from conventional approaches (e.g. statistical methods, systematic behavioural studies, expert knowledge, simulator studies and simulation). The basis is that for infrastructure measures extensive experience has been acquired, and that data concerning traffic safety effects of such measures are available, while for measures based on driving assistance systems the opposite is true, i.e. limited experience and few data on traffic safety effects.

4. What systematic analytical framework is appropriate for linking the aggregated global level of decision making (taking into account other relevant aspects of alternatives in a network in addition to traffic safety effects) and the local level of decision making (only considering traffic safety effects of one or several measures at an intersection or a road section)?

    A policy evaluation concerns two aspects: (1) aggregation of safety effects of an alternative, i.e. one or more specific traffic safety measures; (2) a comprehensive evaluation of various strategic alternatives taking into account safety effects, as well as effects of other aspects.

In summary, the core elements of this thesis are: (1) to design a method to enable estimating traffic safety effects of traffic safety measures of one category, driving assistance systems, for which few data exist, by comparison with infrastructure measures, for which more data are available, as inputs for the evaluation framework; and (2) to create an evaluation framework for the strategic evaluation of alternative courses of action with respect to the implementation of traffic safety measures, by identifying an adequate evaluation method.

3 Research method

3.1 Introduction

The topic that is addressed by the aforementioned research questions has a certain degree of complexity due to: (1) the disparity between road infrastructure and driving assistance systems, and the way in which they affect traffic safety; and (2) the need for assessment of the effects of measures at local level focusing on a single location, combined with an aggregated evaluation at global level based on scenarios and applied to a network. Within this topic two main issues can be distinguished. The first issue is a (measure by measure) comparative analysis of traffic safety effects of measures from the different categories that are supposed to have comparable functionality, i.e. comparable effects on traffic safety. As such analysis is done on the measure level with a focus on traffic safety, it is referred to as the safety performance level analysis. Due to their dissimilar natures, until now the traffic safety effects of the two categories of measures have generally been studied separately, and by using different methods. However, as functional links between specific measures from the two categories can be established, it becomes possible and feasible to relate and compare such measures and their safety effects. This issue is addressed by logical reasoning and not by empirical testing. Apart form enabling the comparative analysis, the study is also important to take the subject of traffic safety analysis forward. The second issue is an evaluation, at a strategic level, of different implementation alternatives (i.e. sets of one or more measures, from one of the categories or from both categories) under the constraint of limited availability, accuracy and reliability of data, taking into account both the traffic safety effects and all other relevant effects and constraints. As this comparative analysis is done at the global level of strategic implementation, it is referred to as the policy evaluation level analysis.

To be able to answer the research questions, and to deal with the complexity of the topic, a bi-level approach is proposed for decision making concerning strategic alternatives for traffic safety improvement (Lu & Wevers, 2006). It is termed "bi-level" as it addresses both the safety performance of road safety measures at the local level, and policy evaluation at a global level. This approach provides: (1) a fundamental schema for the causal chain by zooming in at the microscopic level; (2) a method for comparative analysis derived from this schema; and (3) a specific method for analysis of the evaluation matrix that zooms out at the macroscopic level and enables a strategic comparison of alternative courses of action. The approach explicitly incorporates road traffic safety considerations.

3.2 Benchmark for assessing functional substitutability of traffic safety measures

To address research question 1, a benchmark needs to be developed to enable comparison, in a qualitative way, of measures based on infrastructure and driving assistance systems respectively. Mainly based on literature review a set of basic principles for road traffic safety is identified and further elaborated, and, in addition, for each of these operational requirements. For each measure of both categories it is established on which requirement(s) it is specifically acting. This enables to match measures from the two categories that have comparable functionality in view of traffic safety. Further quantitative comparative analysis only deals with measures that are functionally related. Road traffic safety principles and operational requirements (that are proposed and used as a benchmark), as well as the functional substitutability relationships between measures, are described in Chapter 4.

3.3   Quantitative causal chain (QCC) model

To address research question 2, a model is developed for quantifying the mechanisms between traffic safety measures and their safety effects (see Chapter 5). The quantitative causal chain (QCC) model is based on a breakdown of the process in underlying factors of traffic safety (i.e. risk and consequence), and determinants (controllable parameters) that influence these factors, and are influenced by traffic safety measures (see Figure 3.1, left part: "safety performance module"). The relationships between measures, determinants and factors are modelled as coefficients. This model may in general contribute to improving insight into the mechanisms between traffic safety measures and their traffic safety effects.

3.4   Comparative method for safety performance assessment

Based on the QCC model, an approach for comparative analysis of driving assistance systems and infrastructure measures in view of traffic safety effects is developed (see Chapter 6), to address research question 3. More specifically, it allows comparative analysis of measures from different categories by defining two effectiveness indices based on the coefficients as defined in the QCC model. These indices can be used to estimate effects of driving assistance systems related measures from effects of substitutional (in terms of safety effects) infrastructure related measures (which are known from other studies). This method enables especially analysis at the local level of a road section or an intersection. The thesis takes the view that effects of a measure in a quantitative sense (e.g. in terms of percentage accident change) cannot always be meaningfully generalised, as they may be very dependent on the local situation and conditions. As these vary, no representative effects of a measure exist that are valid for all cases. This indicates the uncertain outcome of a measure in terms of safety effects.

3.5   Framework for policy evaluation based on grey relational analysis (GRA)

This part concerns research question 4, and investigates and proposes an approach to establish the possible contribution of strategic alternative scenarios, each consisting of a combination of several measures and/or functions, to enhance road traffic safety at the level of a road network or a selected part of it (see Chapter 7). The strategic evaluation method should be able to cope with non-homogeneous inputs (e.g. the effects of a measure dependent on the specific local situation, environment, and way and size of implementation), as well as the inaccuracy of input values.

For this a systematic and comprehensive ex-ante evaluation is required at a global level, using an evaluation method (see Figure 3.1, right part: "policy evaluation module"). Besides safety, such analysis should take into account other effects, such as related to societal, economic and environmental aspects, and implementation impediments. The safety effects of each measure (or function) at each intersection and road section can be assessed by using the developed comparative method based on the QCC model, or other methods; other effects can be estimated based on, for instance, literature study, simulator study, simulation and expert knowledge. The evaluation method aims to aggregate these inputs, and to synthesise the detailed results to a road safety policy decision support outcome. Based on formulated requirements of the evaluation problem vis-à-vis the characteristics of various methods, the grey relational analysis (GRA) method is selected, and its application is further elaborated.
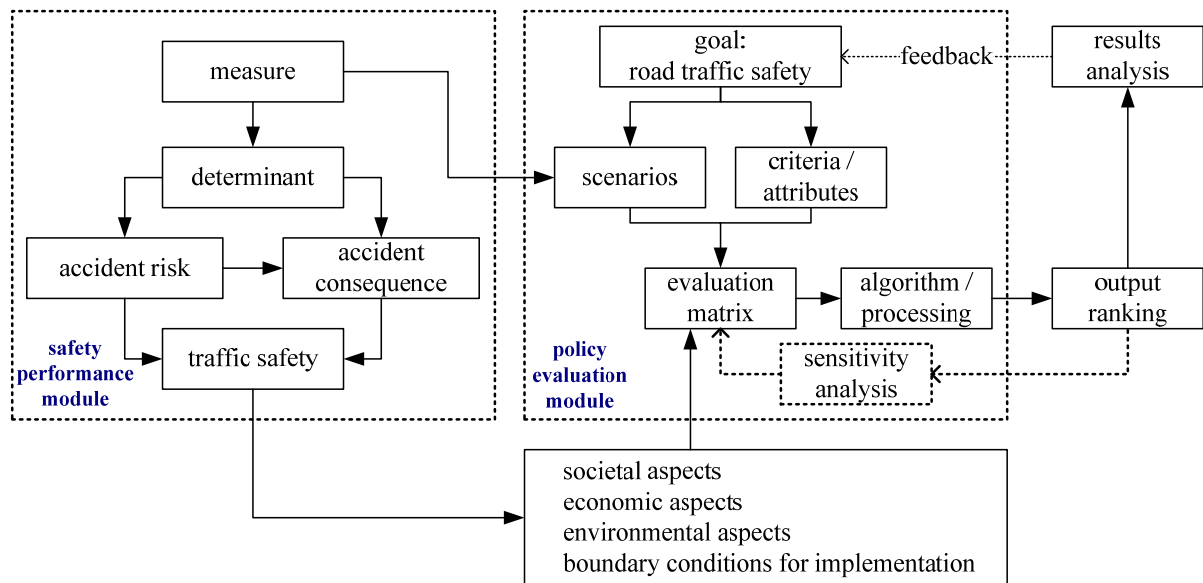
Figure 3.1 - Process for the evaluation of traffic safety measures using the bi-level approach

3.6 Thesis structure

The thesis focuses on two categories of measures for improving road traffic safety: infrastructure related measures (which are systematically reviewed in Paper I) and measures based on driving assistance systems (for which the feasibility of safety functions is explored in Paper II). The chosen approach to qualify the functional substitutability relationships between these two categories of measures of rather dissimilar nature is to identify traffic safety principles and underlying operational traffic safety requirements (see Paper I). In order to establish the fundamental schema of the influence of a measure on road traffic safety, a quantitative causal chain (QCC) model is developed, which is based on a breakdown of the causal chain between measures and traffic safety effects (see Paper III). In addition, a derived method (based on the QCC model) proposes to reflect the differences of safety effects between various measures by identifying (risk and consequence) effectiveness indices (see Paper III). This method for comparative analysis is particularly helpful for assessing the effects of a measure, for which few data exist, by using existing data for another measure. Generally, the results of the estimation of safety effects (safety performance module) only concern the local level (effects of one or several measures or functions at an intersection or road section). The thesis further elaborates a systematic analytical framework to aggregate effects of alternatives in a network (policy evaluation module). For this, it proposes to apply the GRA method for policy evaluation of safety strategies (see Paper IV with an example of an application at national level, and Paper V with an example of an application at local level). The structure of the thesis is outlined in Figure 3.2.

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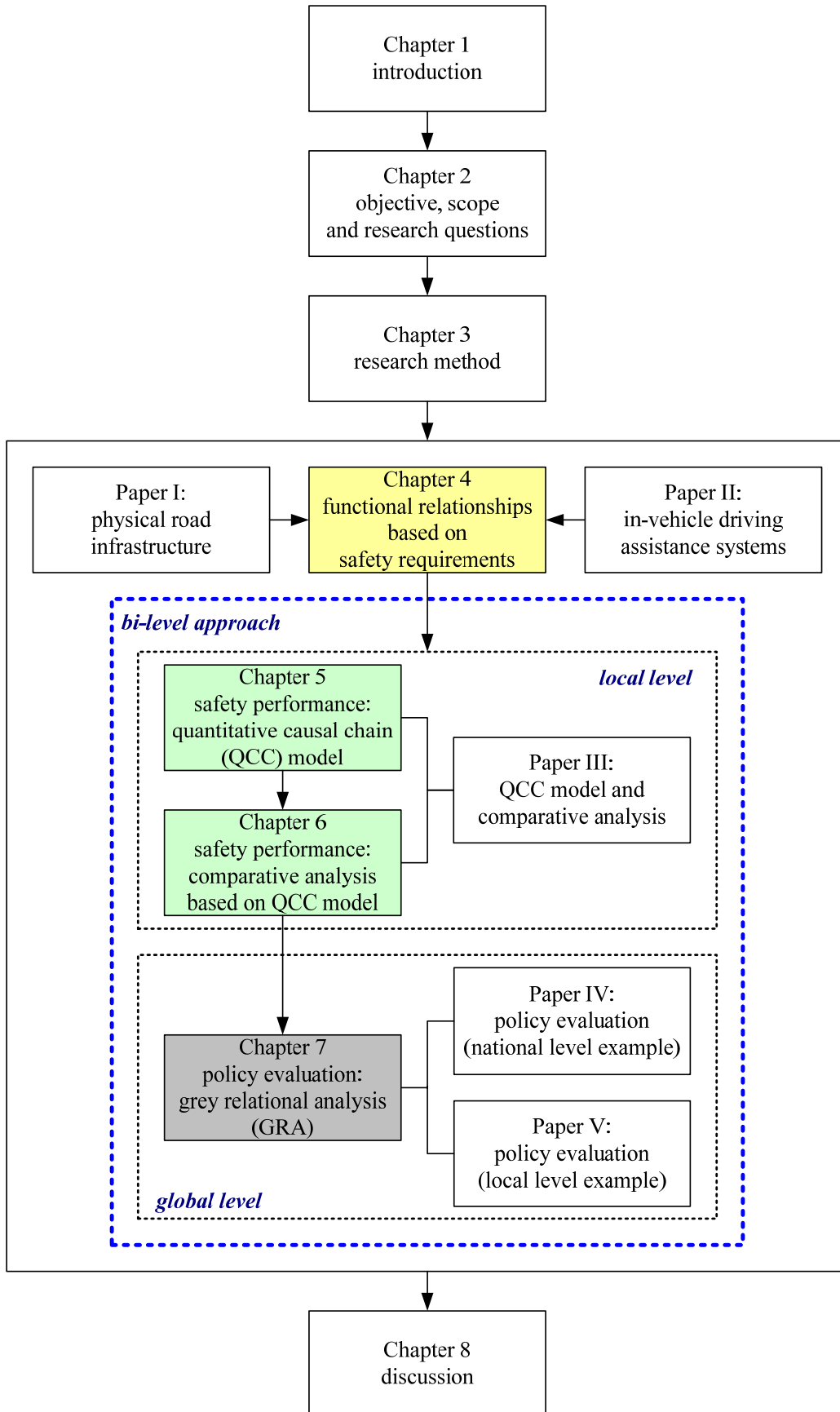
Figure 3.2 - Structure of the thesis

4 Functional match of infrastructure and driving assistance measures

4.1 Functional substitutability

To address the topic of the quantitative comparative analysis and evaluation of two categories of traffic safety related measures, the first step is defining an approach for and performing a qualitative comparative analysis and match of these two categories of measures. The goal of this qualitative analysis is to identify which measures from the two categories are comparable in terms of traffic safety functionality, i.e. in the contribution they provide to improving road traffic safety. For this, the first research question addresses the existence and nature of functional relationships in terms of substitutability between these categories of measures from a traffic safety perspective. It is difficult to precisely define and to quantify the concept of traffic safety. This, and the fact that the two categories of measures have a very dissimilar nature, makes their comparison and match in terms of traffic safety effects complex. Of the differences between the two categories of measures as outlined in Section 1.4, especially the first two relate to functional differences, and are relevant to this analysis.

The traffic safety principles and related operational requirements that were developed in The Netherlands (CROW, 1997), in the framework of the concept Sustainably Safe and with a focus on infrastructure measures, provide a point of reference for developing a more general set of traffic safety principles and operational requirements that cover all relevant infrastructure measures and driving assistance system functions, and enable a comparison and match in terms of traffic safety functionality.

4.2 Traffic safety principles and operational requirements

The principles of road traffic safety have been predominantly studied in relation to infrastructure measures. In The Netherlands, the increased focus from the early 1990s on specific infrastructure measures to improve road traffic safety led to a discussion on the concept of traffic safety, the results of which are a useful starting point for defining traffic safety principles for the purpose of analysing functional substitutability relationships between different measures. This discussion was related to the concept Sustainably Safe launched in 1992 (Koornstra et al., 1992), which entailed an integrated approach to traffic safety with a strong focus on road infrastructure redesign, aiming at drastically reducing the risk of accidents to occur, and the severity of accidents as far as they still occur despite the reduced risk. The three underlying safety principles, concerning preventing unintended use of the road infrastructure, indecisive behaviour of road users, and encounters at high differences in speed, direction and mass, were restated in 1997 as road network functionality, traffic behaviour predictability and traffic homogeneity (CROW, 1997).

To make the concept more operational for implementation of infrastructure redesign, at the same time a set of twelve requirements was defined (CROW, 1997). Substantial research has been carried out on conventional physical infrastructure measures (Lay, 1991; Ogden, 1996; Elvik & Vaa, 2004), the results of which indicate where measures are needed, as well as their expected traffic safety effects. The twelve requirements are a more tangible expression of principles of road design to improve traffic safety, and allow a direct translation into operational measures. Their focus is on functional aspects, and because of this, they also provide an approach to enable the intended comparative analysis. The requirements are well established

and accepted, and officially documented. Clearly these requirements originate from the point of view of road infrastructure design, but they relate in their formulation in a more general sense to the road network and its use for mobility, and thus equally permit interpretation from the point of view of driving assistance systems. However, as the principles and the derived requirements originate from the infrastructure side, not all measures based on driving assistance systems are covered, while, in addition, even some infrastructure measures are not addressed. The twelve requirements focus on prevention and mitigation of the effects of conflicts between vehicle and vehicle, vehicle and other road users, and vehicle and obstacles. Not all possible conflicts in these categories are covered, like for instance, the prevention of collisions with coincidental obstacles on the road. Furthermore, single vehicle situations are completely missing, including single vehicle roll-over and single vehicle run-off road incidents. Also, correction or mitigation of human error by providing a tolerance margin is missing in the original road safety requirements.

Taking the above-mentioned three principles and derived twelve requirements as a basis, an extended more general set of five traffic safety principles is established, as a fundamental benchmark of traffic safety, with no or minimal overlap, and covering the major functional aspects of traffic safety measures based on road infrastructure and driving assistance systems, with a connected extended set of sixteen operational functional requirements. This is done by extending the original set of three traffic safety principles and twelve operational requirements with the traffic safety principle "driving task simplification" (principle 4), with the additional requirements "driver capability enhancement" and "driver workload reduction"; and the traffic safety principle "error forgiveness" (principle 5), with the additional requirements "error correction" and "consequence mitigation". Principle 4 rather specifically relates to the functionality of driving assistance systems functions that have few clear infrastructure alternatives, while principle 5 covers the functionality of a range of driving assistance systems, and at the same time of some infrastructure measures that are not covered in the original set of principles and requirements. The Dutch Institute for Road Safety Research (SWOV - Stichting Wetenschappelijk Onderzoek Verkeersveiligheid) has also recently developed a (slightly different) extended set of Sustainable Safety Principles (Wegman & Aarts, 2006), however, without defining additional operational requirements.

4.3 Functional match of infrastructure measures and driving assistance systems

The identified sixteen operational requirements permit a qualitative analysis of the potential match of infrastructure measures and measures based on driving assistance systems. The result of this is provided in Table 4.1. It lists per operational requirement, for each of the two categories, the measures that exhibit, in one way or another, the indicated functionality. Two distinguished system functions need to be stressed: (enhanced) navigation and speed assistance. Navigation systems, which relate to eight out of sixteen requirements, are a standard option these days in many new vehicle models. The navigation system also provides a platform for the provision of road traffic information, currently mainly provided as TMC messages over RDS (Radio Data System), a data channel in the FM (frequency modulation) sideband. Speed assistance systems relate to seven out of sixteen traffic safety requirements. Other safety related driving assistance system functions that can match infrastructure measures are: anti-collision (including collision warning, collision mitigation and collision avoidance), intersection support (including intersection collision avoidance and intersection negotiation) and lane keeping.

Table 4.1 - Match of road infrastructure measures and driving assistance system functions in relation to road traffic safety principles and requirements (adapted after (CROW, 1997; Dijkstra, 2003; Lu, 2006))

	operational requirement	possible road infrastructure solution(s)	possible driving assistance system solution(s)
safety principle 1: road network functionality			
1	create / realisation of large-size continuous residential areas	traffic calming measures, road narrowing and horizontal deflections, plateaux, roundabouts, speed humps, 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 requirements 2 and 3)	navigation (combination of 2 and 3)
safety principle 2: recognisability and predictability			
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), speed assistance
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
safety principle 3: traffic homogeneity			
8	avoid conflicts with oncoming traffic	middle wire barrier on "2+1" carriageway	lane keeping assistance, intersection support, anti-collision
9	avoid conflicts with crossing traffic	protection of crossing and crossing-over traffic; deduce number of possible conflict points; reduction of crossings; cancel pedestrian crossings	anti-collision, intersection support
10	separate traffic categories	protection of bicycle, moped, and other slow traffic from motor vehicles; parallel roads; particular bicycle lanes	navigation, speed assistance, lane change assistant
11	reduce speed at sites of potential conflict	speed reduction at conflict points, e.g. lower legal speed limit, speed bumps, plateaux	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, vehicle breakdown; provisions and parking spaces	lane keeping assistance, anti-collision, speed assistance
safety principle 4: driving task simplification			
13	driver capability enhancement	road lightning	adaptive light control, vision enhancement
14	driver workload reduction	middle wire barrier on "2+1" carriageway	navigation, ACC, stop-and-go, autonomous driving
safety principle 5: error forgivingness			
15	error correction	edge-line rumble strip, guardrail	lane change assistant, speed assistance, driver alertness monitoring, alco-lock
16	consequence mitigation	roadside energy absorption equipment	telematics, e.g. eCall

Several driving assistance applications (either on the market, or in a stage of early deployment, or under development) can be distinguished, which do not directly match an infrastructure measure, but have a clear potential to improve road traffic safety. These are adaptive cruise control (ACC), adaptive light control, vision enhancement, alco-lock, stop-and-go, lane change assistant, driver alertness monitoring, autonomous driving and telematics. In addition, some infrastructure measures can now be related to a safety principle and a requirement, which were not covered by the original set of twelve requirements.

This qualitative analysis clearly establishes which driving assistance system functions can match which physical infrastructure measures, and in which way. The result helps to further quantify the safety effects of those driving assistance systems based measures that are matched by road infrastructure measures, and to analyse the safety effects of various traffic safety enhancing policy scenarios based on different combinations of measures from both categories.

5 Model for safety performance assessment

5.1 Methods for studying safety performance

5.1.1 Introduction

Both well-designed road infrastructure and driving assistance systems may improve traffic safety. However, measures based on road infrastructure and driving assistance systems have a dissimilar nature, and, thereby, different mechanisms of influencing driving behaviour. Moreover, safety assessment of infrastructure measures has more progressed than of driving assistance system implementation, as the latter constitutes a relatively new development with, for most applications, yet limited market penetration. As a consequence, accident statistics on the effects of driving assistance systems are not usually available. Due to the differences in data availability, generally different methods are used for studying safety performance of measures from the two categories at the local level (i.e. a section of a road or an intersection).

5.1.2 Methods to study safety effects of infrastructure measures

The safety effects of road infrastructure measures are estimated mainly by using before-and-after studies (based on accident statistics), statistical models based on multivariate statistical analysis (e.g. linear, Poisson or negative binomial), in-depth studies and systematic behavioural studies. All of these existing approaches have substantially contributed to the knowledge concerning road traffic safety measures, but at the same time leave room for argument (Hydén, 1987). Because accidents are rare, unexpected and unpredictable events, and because accident conditions are rather complicated, it is, in general, difficult to give an unambiguous explanation for their cause or to give a reliable estimate based on historical data of the probability of a particular type of accident in the future (Oppe, 1993). Approaches based on accident statistics try to establish mathematical relationships between measures and effects. The accident numbers are often rather small which may lead to misinterpretations. Due to biased sampling, the occurred number of accidents is often higher than the average expected number of accidents. Furthermore, accident statistics are, in general, rather incomplete and unreliable. The meta-analysis of before-and-after studies, performed by Elvik & Vaa (2004), demonstrates that the results of such studies may be of limited use in practice due to the high level of uncertainty. Multivariate statistical analysis mainly focuses on the characteristics of a particular road environment, and on a particular type of accident (see e.g. (Kulmala, 1995)). Conventional linear regression models are not able to adequately describe random, discrete, nonnegative, and typically sporadic vehicle accidents, and are, thereby, inadequate for making probabilistic statements about such accidents. The Poisson and negative binomial (NB) regression models are more suitable and often used for this type of statistical analysis. The Poisson model is adequate when the mean and the variance of the accident data are approximately equal, but may overstate or understate the likelihood of vehicle accidents if the accident data are significantly overdispersed relative to the mean (Miaou & Lum, 1993). The NB model is more appropriate when the data are overdispersed (variance of the accident data significantly larger than the mean) (Shankar et al., 1997). Both the Poisson and NB models require the functional form of the model to be known in advance. The NB model can easily and significantly be affected by outliers, cannot handle missing data very well, and cannot deal adequately with multicollinear independent variables (Karlaftis & Golias, 2002). Zero-inflated Poisson (ZIP) modelling and zero-inflated NB (ZINB) modelling are zero-altered variants of these methods that may be useful in certain circumstances (Shankar et al., 1997). ZIP model-

ling may especially be used with overdispersed data, but interpretation of the ZIP model can be difficult (Miaou, 1994). Several issues concerning these methods were recently discussed by Fahrmeir and Echavarría (2006), Ghosh et al. (2006), Lord et al. (2007), and Wang and Alba (2006). Plausible alternative approaches are not based on accident statistics, but also have their limitations. In-depth studies are rather expensive, and therefore rarely used for systematic data collection. Systematic behavioural studies, e.g. traffic conflict techniques (TCT) (Hydén, 1987; Kraay et al., 1986), permit collection of sufficient data in a relatively short time frame (as there are more conflicts than accidents). However, the observation is time-consuming and observers need to be trained (Van den Bossche & Wets, 2003).

5.1.3 Methods to study safety effects of driving assistance systems

The effects of driving assistance systems can be evaluated by field trials, simulator studies and simulation in case of limited or zero market penetration levels. As an example, the study of the safety effects of speed assistance systems is discussed. Since the end of the 1990s large-scale field trials have been carried out in various countries, e.g. Sweden (Biding & Lind 2002; Várhelyi et al., 2004), The Netherlands (Besseling & Van Boxtel 2001), UK (Carsten & Tate 2000), Denmark (Nielsen & Boroch 2001), Finland (Peltola et al., 2004), Belgium (Vlassenroot et al., 2007), France (Sauvagnac & Olivero, 2002) and Australia (Regan et al., 2002). In parallel, speed assistance systems have also been tested by simulator studies (see e.g. (Peltola & Kulmala, 2000)) and simulation models (see e.g. (Ma & Andréasson, 2005)). Simulator studies generally only address a certain system function under certain constraining conditions. Simulation is a powerful tool to identify the main influencing factors, and a system's sensitivity to changes of these factors. Instead of using real world accident data, surrogate safety indicators may be used, for instance, time to collision[11], gap time[12], encroachment time[13], deceleration rate[14], proportion of stopping distance[15], post-encroachment time[16] and initially attempted post-encroachment time[17] (Gettman & Head, 2003). Generally, simulation studies require the estimation of various model parameters, especially including human behaviour. The models are only applicable to specific situations (i.e. a particular road environment, location and system function). The assumptions concerning (adaptation of) behaviour in current traffic flow simulation models generally have a rather simplified and limited character due to a lack of fundamental knowledge (see e.g. (Ma & Andréasson, 2005; Toledo, 2007; Tampère, 2004)). This makes that the outcome of such simulation studies is often questionable and of limited practical value. The main shortcoming of such models is the lack of a logical causal relationship between the studied parameters and the safety effects, i.e. the change of accident risk and consequence.

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[11] time to collision (TTC): expected time for two vehicles to collide if they remain at their present speed and on the same path

[12] gap time (GT): time lapse between completion of encroachment by turning vehicle and the arrival time of crossing vehicle if they continue with same speed and path

[13] encroachment time (ET): time duration during which the turning vehicle infringes upon the right-of-way of through vehicle

[14] deceleration rate (DR): rate at which crossing vehicle must decelerate to avoid collision

[15] proportion of stopping distance (PSD): ratio of distance available to manoeuvre to the distance remaining to the projected location of collision

[16] post-encroachment time (PET): time lapse between end of encroachment of turning vehicle and the time that the through vehicle actually arrives at the potential point of collision

[17] initially attempted post-encroachment time (IAPT): time lapse between commencement of encroachment by turning vehicle plus the expected time for the through vehicle to reach the point of collision and the completion time of encroachment by turning vehicle

In this thesis the estimation of the safety effects of driving assistance systems does not focus on a specific system function in a specific situation and under certain conditions, but concerns all system functions, including those still under development and/or deployment, and aims to cover, as much as possible, various situations and conditions. Therefore, a more general and practical method needs to be developed for enabling estimation of safety effects of driving assistance systems, by comparison with road infrastructure measures. For this a fundamental schema of the influence of a measure on road traffic safety needs to be modelled.

5.2   The causal chain between traffic safety measures and effects

Elaborating earlier research of Evans (1985; 1991), Elvik (2004) proposed a conceptual framework to model the effects of road traffic safety measures based on two causal chains, concerning respectively the engineering and behavioural effects of measures. For exploring the engineering effect of road safety measures nine engineering risk factors are proposed: kinetic energy, friction, visibility, compatibility, complexity, predictability, road user rationality, road user vulnerability and forgivingness. One or more of these factors need to be influenced by a measure to create its intended effects. The behavioural effect, covering behavioural adaptations of road users to road safety measures, is related to the engineering effect, as certain properties of the engineering effect of a road safety measure influence the likelihood that behavioural adaptation will occur. It is modelled in terms of six behavioural factors: ease of noticing measure, antecedent behavioural adaptation, size of engineering effect, affecting probability or consequence, likely size of material damage and prospect of additional utility gain. The nine engineering factors and six behavioural factors are then proposed as a (qualitative) checklist to assess the findings of road safety studies, stating that at the current state of knowledge, a more stringent evaluation of the extent to which theory can explain the findings of road safety evaluation studies is, in most cases, not possible.

The qualitative concept of the causal chain is presented in Figure 5.1. Both engineering and behavioural factors may influence three traffic safety dimensions (exposure, risk and consequence (Rumar, 1988; Nilsson, 2004)).
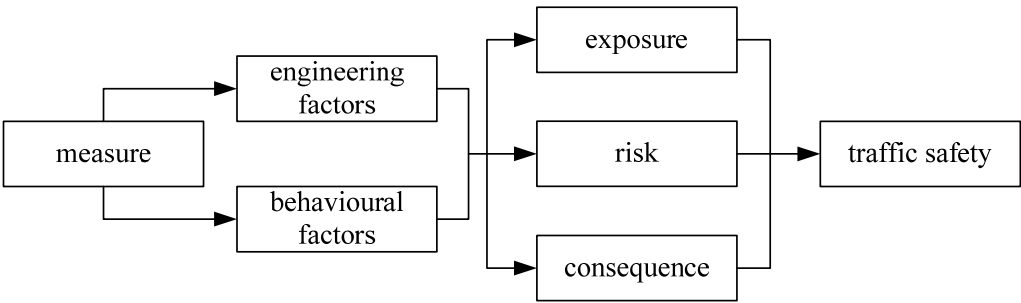
Figure 5.1 - Concept of the causal chain process for the influence of traffic safety measures on traffic safety (adapted after (Elvik, 2004))

5.3   Exploring a quantitative model for the causal chain

Following the work of Evans (1985; 1991) and Elvik (2004), and in line with the research task of this thesis (concerning research question 2), this section presents a quantitative causal chain (QCC) model for assessing the effects of traffic safety measures. As a first step, only the

part of the causal chain that covers engineering factors is taken into account. Exposure is not considered separately in the causal chain, for the reasons mentioned in Section 1.2. The proposed QCC model is based on a breakdown of the process in two underlying factors of traffic safety, i.e. accident risk (R) and accident consequence (C), and five determinants (ψ) that influence these factors, and are influenced by traffic safety measures. Traffic safety measures have a direct influence on determinants, and through these on accident risk R 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 R (via influence on a determinant). The diagram of Figure 5.2 presents the foregoing in a schematic way in a causal chain from traffic safety measure via the determinants and traffic safety factors to traffic safety. The relationships between measures, determinants and traffic safety factors are modelled as coefficients. The determinants and their influences are taken to be independent, i.e. any possible (but difficult to determine) coupling between the determinants, which have been chosen from a perspective of minimum overlap, is ignored. It should be emphasised that accident statistics based on historical data is not the same as accident probability, which is based on parameters such as road and vehicle characteristics, and human behaviour. The focus of the QCC model is on accident probabilities rather than accident statistics, although in practice statistics may be needed to find values for the coefficients, as far as proper methods to derive probabilities from the aforementioned parameters do not yet exist.
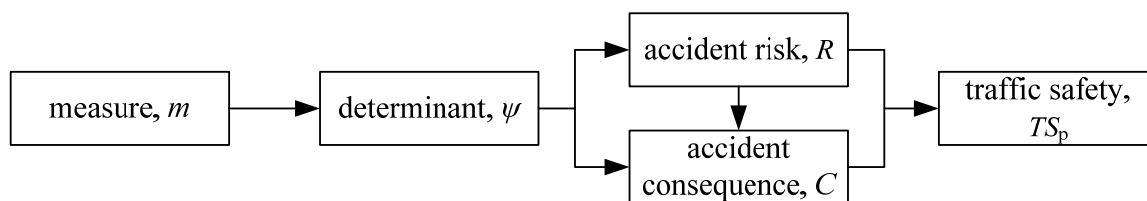
Figure 5.2 - Quantitative causal chain process for the influence of traffic safety measures on traffic safety

5.3.1 Traffic safety factors

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. Traffic safety in terms of historical statistics is the resultant of two components, accident frequency (e.g. total accidents per million vehicle kilometres per year) and accident severity (e.g. proportion of accidents with fatalities, hospitalisations, slight injuries and property damage-only). On a macro level such statistics provide yardsticks for the traffic safety situation, and especially for trends thereof. The statistical data used are usually based on aggregation of different types of accidents with often quite different character, which may be related, even within one type of accident, to very different circumstances.

Traffic safety in terms of probability (TS_p) can be described as the resultant of two factors, accident risk and accident consequence (see Figure 5.2). 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 risk and consequence are defined in a slightly different way (see e.g. (IEC, 2000; Kaplan & Garrick, 1981; Bald, 1991)). In

practice two different definitions of the word risk are used. It is sometimes used as a synonym of probability, and in other cases as the combination of the probability of the occurrence a negative event and its potential impact. Some authors use the term probability instead of risk; others use the term risk to indicate outcome or result (see e.g. (Haight, 1986; Hauer, 1982)). In this thesis risk is used in the meaning of the probability of an accident to occur per unit of exposure. In line with this, the focus of the developed model is on traffic safety in terms of probability.

5.3.2 Traffic safety determinants

In the QCC model, the two factors risk and consequence are influenced by the following five main determinants:

ψ_1 - velocity of an individual vehicle as compared to the legal speed limit or the safe speed limit, and to the logical driving direction (vehicle in this context means motor vehicle)

ψ_2 - velocity differences of road users, vehicle-vehicle or vehicle-VRU

ψ_3 - conflict between different traffic modes, especially between vehicle and VRU, in mixed traffic situations, or between vehicle and another object, such as a parked vehicle, an animal (domestic or wild), or a fixed roadside object;

ψ_4 - single vehicle run-off road or rollover;

ψ_5 - multi-vehicle conflict, e.g. rear-end (i.e. head-rear), head-on (i.e. frontal), head-side, side-side or pile-up

The related functions for accident risk and accident consequence are formulated as follows:

$R = g_r(\psi_1, \psi_2, \psi_3, \psi_4, \psi_5)$

$C = g_c(\psi_1, \psi_2, \psi_3, \psi_4, \psi_5, R)$

The guiding principles for identifying these factors and determinants are: (1) to cover all road traffic safety related situations; (2) to avoid overlaps (as much as possible) between determinants; and (3) to provide a practical and transparent framework for comparative analysis. Although the determinants are selected for minimal or no overlap, influences of some determinants on other determinants do exist. Until now, the transformations from traffic safety measures, via the determinants, to the traffic safety factors has not been explicitly studied in a quantitative and systematic way in one comprehensive model. The proposed modelling of these parameters can be seen as a first step, which may be improved over time.

5.3.3 The quantitative causal chain model

Next, the relationships of the different elements of the causal chain between measure and effect will be elaborated. It is further assumed, 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. 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 (Joksch, 1993; Nilsson, 2004), it may be assumed roughly linear for shorter intervals. 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 into 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 dissimilar nature. This method is used to address estimation of the effects of driving assistance systems related measures for which only limited data are available, by comparison with the effects of road infrastructure related measures, for which more knowledge exists, and for which effect estimates are available. It is not the purpose of the proposed model to calculate the safety effect of a measure from basics. It is also assumed that the effect of a determinant on consequence (either directly or through risk) can be separated per determinant. With these assumptions, the above statements may then be summarised in the following formulae:

- Relative total effect of measure q on determinant y

$$\frac{d\psi_y}{dm_q} = \varepsilon_{qy} \tag{5.1}$$

where ε_{qy} denotes *measure effect coefficient*;

- Relative effect of determinant y on accident risk R_y

$$\frac{dR_y}{d\psi_y} = \alpha_y \tag{5.2}$$

where α_y denotes *risk influence coefficient*;

- Relative direct effect of determinant y on consequence C_{yj} of type j

$$\frac{\partial C_{yj}}{\partial \psi_y} = \beta_{yj} \tag{5.3}$$

where β_{yj} denotes *direct consequence influence coefficient*;

- Relative direct effect of risk related to determinant y on type j consequence

$$\frac{\partial C_{yj}}{\partial R_y} = \mu_{yj} \tag{5.4}$$

where μ_{yj} denotes *indirect consequence influence coefficient*;

- Total effect on consequence of type j for determinant y

$$dC_{yj} = \frac{\partial C_{yj}}{\partial \psi_y} d\psi_y + \frac{\partial C_{yj}}{\partial R_y} dR_y \tag{5.5}$$

which results in the overall relative effect of measure q on consequence of type j through determinant y

$$\frac{dC_{yj}}{dm_q} = \varepsilon_{qy}(\beta_{yj} + \mu_{yj}\alpha_y) = \eta_{qyj} \tag{5.6}$$

where η_{qyj} denotes *partial consequence effectiveness index*.

Formula (5.6), which gives the relative effect of measure q on consequence of type j (e.g. $j = 1,2,3,4$ representing four types of consequence: fatality, hospitalisation, slight injury and property damage-only) via determinant y ($y = 1,2,3,4,5$), can be easily derived from the for-

mulae (5.1) to (5.5)

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

$$H_{qj} = \sum_y \eta_{qyj} = \sum_y \varepsilon_{qy}(\beta_{yj} + \mu_{yj}\alpha_y) \tag{5.7}$$

As an alternative, only risk may be studied, and not consequence. The resulting model is simpler, by using only the formulae (5.1) and (5.2) the following alternative for formula (5.6) may be derived:

$$\frac{dR_y}{dm_q} = \varepsilon_{qy}\alpha_y = \rho_{qy} \tag{5.8}$$

The *partial risk effectiveness index* ρ_{qy} expresses the relative effect of measure q on risk through determinant y. The total relative effect of measure q on risk may then be calculated as the *risk effectiveness index* P_q:

$$P_q = \sum_y \rho_{qy} = \sum_y \varepsilon_{qy}\alpha_y \tag{5.9}$$

Note that this result is equal to putting in formula (5.7) all $\beta_{yj} = 0$, and all $\mu_{yj} = 1$. This may be interpreted as follows: the only result of the measure that is considered is risk R_y. Consequence C_{yj} is ignored, therefore, $\beta_{yj} = 0$. Or stated differently, the only consequence that is considered is risk, i.e. consequence is put equal to risk, therefore, $\mu_{yj} = 1$.

In the model the relationships between measures and determinants relate to human behaviour, and their coefficients need to be estimated based on approaches such as behavioural studies, literature study and expert judgement. The other relationships have a more technical character, and although their coefficients can in practice be 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 process, and thereby facilitates the estimation. The way to identify determinants and factors as presented in this thesis is not a unique approach for studying the causal chain (see e.g. (Elvik, 2004)). The focus of this QCC model is on the coefficients between the measure and determinants, and between determinants and traffic safety factors, instead of on quantifying the determinants and/or factors directly, which is an essential distinction between the QCC model and other related studies.

6 Comparative analysis of traffic safety measures

6.1 Introduction

The QCC model is the basis for a general method for comparative analysis to study the safety performance at the local level. The method does not focus on safety effects of one specific method in a certain situation and under certain conditions, but is generally applicable for studying safety effects of any measure, which has a functional link, in view of traffic safety, with one or more other measures. Qualification of functional substitutability relationships based on a benchmark (defined by five traffic safety principles and sixteen operational traffic safety requirements) is the prerequisite for applying the method for a quantitative comparative analysis, and helps to select comparable measures as a preliminary step. The method for comparative analysis is particularly helpful for assessing the effects of driving assistance based measures, for which few data exist, by using existing data for physical road infrastructure based measures. It enables estimating the absolute value for the effect of a measure (e.g. a measure based on driving assistance systems) from the absolute value for the effect of another measure (e.g. a road infrastructure measure) with comparable effects on traffic safety, by providing an approach for estimating and expressing the relative effects of both measures as effectiveness indices. The term "absolute" is used in this context as opposite to "relative", and not in the mathematical sense.

6.2 Method for comparative analysis based on the QCC model

Based on the quantitative model for the causal chain, and to address the third research question, a method is developed for structured comparative analysis regarding traffic safety effects of various traffic safety measures at local level. If an (estimated) absolute effect for a certain infrastructure based measure, either on risk or on consequence, is known, the absolute effect of a matching (i.e. compliant) driving assistance system based measure may be calculated if the relative effects for the road infrastructure and driving assistance system measures, i.e. their effectiveness indices, can be estimated. A measure based on driving assistance systems relates to an in-vehicle system function. Instead of with just one system function, the comparison may also be with two or more system functions each of which partially complies with the road infrastructure measure, or vice versa. The presented model with its proposed breakdown in more elementary parts intends to give the process of estimation of the relative effects a foundation. And although the presented model is based on several assumptions, it provides a useful first approximation.

If E_{Dj} is the absolute effect of an infrastructure based measure (or set of measures) on consequence of type j, E_{Aj} is the absolute effect of an driving assistance system based measure (or set of measures) on consequence of type j, H_{Dj} is the consequence effectiveness index for an infrastructure based measure on consequence of type j, and H_{Aj} is the consequence effectiveness index of a driving assistance system based measure on consequence of type j, then:

$$E_{Aj} = \frac{H_{Aj}}{H_{Dj}} E_{Dj} \qquad (6.1)$$

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

$$E_{\mathrm{A}} = \frac{P_{\mathrm{A}}}{P_{\mathrm{D}}} E_{\mathrm{D}} \qquad\qquad (6.2)$$

where *E* denotes absolute effect of a measure (or set of measures) on risk.

This derived method tries to compare measures or sets of measures from the different categories (road infrastructure and driving assistance systems) that have similar functionality in terms of the effects on the resultant traffic safety, but may have a different way and/or level of action through the causal chain. It enables to establish a composite effectiveness index for a measure, providing a relative figure for the effect per unit amount of measure, and takes into account that the way and/or level of action of the measure through the causal chain may be different for the two compared measures. The composite effectiveness index H_{qj} or P_q may be seen as the absolute effect per unit implementation of a measure E_{qj} or E_q, taking into account variability based on the local situation and circumstances, such as deriving from environment, traffic situation, driver behaviour, road layout and road geometry. The comparative method then concludes that these relative indices may be used to calculate the effect for an amount of one measure (e.g. from the category of driving assistance systems) based on the known effect for a comparable amount of another measure (e.g. from the category of road infrastructure measures). For example, the assumption is the introduction of a sufficient number of speed humps on a road section to reduce speed versus all vehicles driving through that road section are equipped with a speed assistance system.
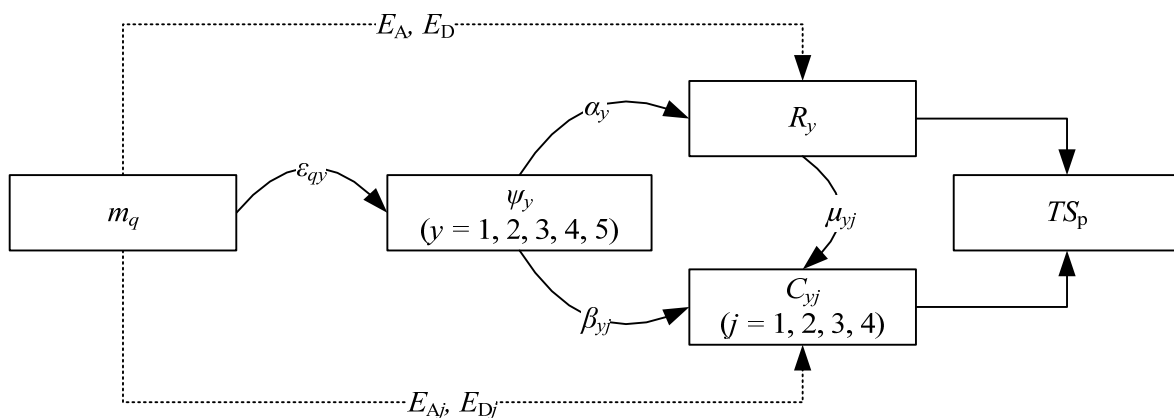
E – effect of measure on accident risk   A – measures based on driving assistance systems
E_j – effect of measure on accident consequence   D – measures based on road infrastructure

Figure 6.1 - Quantitative causal chain, coefficients and overall effects of measures on accident risk and accident consequence

Figure 6.1 illustrates and summarises the causal chain and its relationships in a quantitative way with the related variables and coefficients, as well as overall effects of measures on accident risk and accident consequence, for which effectiveness indices are established. It includes the two indices that are defined based on the coefficients of the model for the causal chain: the risk effectiveness index, which considers in the comparison only accident risk, and the consequence effectiveness index, which considers accident consequence, and thereby also takes into account accident risk. Values for the risk influence coefficient α_y, the direct consequence influence coefficient β_{yj}, and the indirect consequence influence coefficient μ_{yj} may be

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estimated based on accident statistics. It should be emphasised that this is a use of accident statistics to estimate probabilities, in the absence of better methods. Compared to the risk and consequence influence coefficients, the measure effect coefficient ε_{qy} has a different character: it expresses the relative effect of a measure on a determinant, and reflects the explicit modelling of human behaviour.

6.3 Illustration of the method for comparative analysis

To illustrate the developed method based on the QCC model, a hypothetical example is provided. The values for the risk and (direct and indirect) consequence influence coefficients (i.e. α_y, β_{yj} and μ_{yj}, see Figure 6.1) are calculated based on accident statistics. For the measure effect coefficient ε_{qy} illustrative values are provided based on the feedback model of a measure, i.e. information, warning, overrideable control and non-overrideable control. Using the estimation results of the coefficients (α_y, β_{yj}, μ_{yj} and ε_{qy}), and applying the developed comparative analysis method, a specific example is provided concerning the estimation of traffic safety effects of (matching) driving assistance systems compared with a roundabout at an intersection.

6.3.1 Risk and consequence influence coefficient estimation

Values for the coefficients α_y, β_{yj} and μ_{yj} are estimated partially based on accident type and causation data provided by the SWOV, and, in addition, based on expert knowledge. The SWOV database contains accident data from 1980 to present, and includes details, such as accident type, road category, speed limit, crash situation, road situation, environment and seventy-seven 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 property damage-only accidents are about 95%, 60% and 12% respectively according to SWOV specification. The SWOV figures that are used include a correction for underreporting. 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 each of the accident causes it is then judged if it relates to a certain determinant y ($y = 1,2,3,4,5$). The judgement is based on expert knowledge acquired in discussions with researchers of 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 α_y divided by the total number of accidents provides a value for the risk influence coefficient α_y, e.g. $\alpha_1 = 0.021$ means that 2.1% of all accidents is related to vehicle speed (see Table 6.1);

- the sum of the numbers of fatalities related to α_y divided by the total number of fatalities provides a value for the direct consequence influence coefficient β_{y1} for fatalities ($j = 1$), e.g. $\beta_{21} = 0.009$ means that 0.9% of all fatalities is related to velocity differences between road users (see Table 6.1);

- the sum of the numbers of hospitalisations related to α_y divided by the total number of hospitalisations provides a value for the direct consequence influence coefficient for hospitalisations β_{y2} ($j = 2$), e.g. $\beta_{32} = 0.038$ means that 3.8% of all hospitalisations is related to conflicts between different traffic modes (see Table 6.1);

- the sum of the numbers of fatalities related to α_y divided by the total number of accidents related to ψ_y provides a value for the indirect consequence influence coefficient μ_{y1} for fatalities ($j = 1$), e.g. $\mu_{41} = 0.038$ means that 3.8% of all accidents is related to single vehicle run-off road involve fatalities (see Table 6.1); and

- the sum of the numbers of hospitalisations related to α_y divided by the total number of accidents related to ψ_y provides a value for the indirect consequence influence coefficient μ_{y2} for hospitalisations ($j = 2$), e.g. $\mu_{52} = 0.073$ means that 7.3% of all accidents is related to multi-vehicle conflict involve hospitalisations (see Table 6.1).

Table 6.1 - Estimated values of influence coefficients

deter-minant	risk influ-ence coef-ficient	direct consequence influence coefficient		indirect consequence influence coefficient	
		$j = 1$ (fatality)	$j = 2$ (hospitalisation)	$j = 1$ (fatality)	$j = 2$ (hospitalisation)
ψ_1	$\alpha_1 = 0.021$	$\beta_{11} = 0.026$	$\beta_{12} = 0.009$	$\mu_{11} = 0.071$	$\mu_{12} = 0.193$
ψ_2	$\alpha_2 = 0.030$	$\beta_{21} = 0.009$	$\beta_{22} = 0.007$	$\mu_{21} = 0.016$	$\mu_{22} = 0.096$
ψ_3	$\alpha_3 = 0.176$	$\beta_{31} = 0.009$	$\beta_{32} = 0.038$	$\mu_{31} = 0.003$	$\mu_{32} = 0.088$
ψ_4	$\alpha_4 = 0.109$	$\beta_{41} = 0.077$	$\beta_{42} = 0.016$	$\mu_{41} = 0.038$	$\mu_{42} = 0.059$
ψ_5	$\alpha_5 = 0.591$	$\beta_{51} = 0.056$	$\beta_{52} = 0.011$	$\mu_{51} = 0.049$	$\mu_{52} = 0.073$

6.3.2 Value ranges for the measure effect coefficient

As ε_{qy} reflects the explicit modelling of human behaviour, values for this coefficient can be estimated based on methods such as behavioural analysis, literature study and expert knowledge. A specific ε-value needs to be estimated for each specific case. For this it may help to use the four behaviour influence or compulsiveness levels that are generally distinguished in the design of driving assistance systems, 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 and/or braking). Although the four compulsiveness levels are clearly derived from driving assistance system functions, they may be applied to infrastructure measures as well (for an illustration see the next section). As a guideline, illustrative value ranges are provided for the lower three levels, while the highest level clearly has value 1.00 (maximum effect), as follows:

- information: $0.00 \leq \varepsilon_{qy} \leq 0.60$

- warning: $0.50 \leq \varepsilon_{qy} \leq 0.85$

- overrideable control: $0.75 \leq \varepsilon_{qy} \leq 0.95$

- non-overrideable control: $\varepsilon_{qy} = 1.00$

6.3.3 Example of safety effects estimation: driving assistance and roundabout

To illustrate the developed method, the estimation of the safety effects (fatalities and hospitalisations) of integrated driving assistance system functions, based on the safety effects for a roundabout is taken as an example. In previous research of the SWOV, the potential safety improvement in 2010 as compared to the situation in 1998, due to the implementation of DVI, is analysed and predicted, especially regarding fatalities and hospitalisations (on which the Dutch traffic safety policy focuses), taking into account changes of road length and traffic density. The study is mainly based on before-and-after studies (using historical accident data), behavioural studies and educated guess (Janssen, 2003). These data are used to identify the

absolute effects (in percentage) of infrastructure redesign (E_{Dj} and E_D). For a roundabout, the values for fatality reduction $E_{D1} = 75.0\%$, and hospitalisation reduction $E_{D2} = 53.0\%$ are estimated by the SWOV (Janssen, 2003).

Roundabouts can improve traffic safety due to the following reasons (Elvik et al., 1997; cited in Hydén & Várhelyi, 2000: p.12): "(1) they reduce the number of conflict points among traffic flows; (2) road users approaching the roundabout have to give way to those in it; (3) all traffic inside the intersection comes from one direction; (4) roundabouts eliminate left turn in front of meeting traffic, and (5) the lateral displacement reduces the speed." By using traffic safety principles and requirements as a benchmark, three driving assistance system functions can be selected, which have a potential functional match with a roundabout. These potentially substitutional system functions are speed assistance, intersection support and anti-collision functions.

The risk and consequence influence coefficients (presented in Table 6.1) and the measure effect coefficients ε_{qy} are used to calculate the consequence effectiveness indices H_{Aj} and H_{Dj} in formula (6.1), by applying formula (5.7). The ε-values for each measure are estimated as follows (and summarised in Table 6.2):

- The roundabout may influence four determinants: vehicle speed (ψ_1), speed difference (ψ_2), conflict between vehicles and VRUs (ψ_3), and conflict between vehicles (ψ_5). In this case, the ε-values are taken as: $\varepsilon_{q1} = 0.90$, $\varepsilon_{q2} = 0.95$, $\varepsilon_{q3} = 0.60$, and $\varepsilon_{q5} = 0.70$ respectively. Previous research (see e.g. (Hydén & Várhelyi, 2000; Elvik & Vaa, 2004)) shows that roundabouts provide considerable control of vehicle speeds and speed differences between vehicles. In addition, a roundabout reduces conflict points compared with an intersection, and a well designed roundabout may contribute to mitigating conflict between vehicles and VRUs.

- Speed assistance can influence vehicle speed (ψ_1) and speed difference (ψ_2). For speed assistance a sophisticated flexible system layout would be possible that differentiates according to road category and traffic safety requirements: mandatory full control on roads with mixed traffic, mandatory overrideable control (haptic throttle) on single carriageway roads with separation of traffic categories, and voluntary warning on dual carriageway roads specifically designed for motor vehicles. However, control based speed assistance is not currently seen as feasible form a general acceptance point of view. Therefore, in this case the values are taken to be $\varepsilon_{q1} = 0.75$ and $\varepsilon_{q2} = 0.30$, in the warning and information ranges respectively. The influence of information/warning based speed assistance on speed differences between vehicles at this type of intersection is assumed to be not very significant.

- The purpose of intersection support systems is especially to avoid conflict between vehicles (ψ_5), as well as mitigating the consequence. It is assumed that $\varepsilon_{q5} = 0.60$. In view of the current level of development of these systems, especially concerning robustness (including reliability, permanent and fail-safe operation, and few or no false alarms), higher influence on determinant ψ_5 is considered unrealistic.

- The anti-collision function influences two determinants: conflict between vehicles and VRUs (ψ_3) and conflict between vehicles (ψ_5). The ε-values are estimated to be $\varepsilon_{q3} = 0.05$, and $\varepsilon_{q5} = 0.05$. As stated before, considering the current level of development of technologies for positioning and communication, as well as for sensor fusion and HMI (Human Machine Interface) design, the anti-collision function is supposed to have only a limited influence on the related determinants.

Table 6.2 - Example of estimated values of the measure effect coefficient

measure based on road infrastructure	ε-value	measure based on driving assistance systems	ε-value
roundabout	$\varepsilon_{q1} = 0.90$ $\varepsilon_{q2} = 0.95$ $\varepsilon_{q3} = 0.60$ $\varepsilon_{q5} = 0.70$	speed assistance	$\varepsilon_{q1} = 0.75$ $\varepsilon_{q2} = 0.30$
		intersection support	$\varepsilon_{q5} = 0.60$
		anti-collision	$\varepsilon_{q3} = 0.05$ $\varepsilon_{q5} = 0.05$

For the reduction rates of fatalities ($j = 1$) and hospitalisations ($j = 2$) for a roundabout, the values of E_{D1} and E_{D2} are used (based directly on SWOV data), and the method for comparative analysis is applied to estimate the values of E_{A1} and E_{A2}. Firstly, the potential safety improvement (in terms of consequence) for each of three driving assistance system functions is estimated, by comparison with a roundabout; secondly, the safety effects (i.e. reduction rates of fatalities and hospitalisations) by the implementation of integrated system functions compared with a roundabout are estimated.

The results for the potential safety effects for each single driving assistance system function are:

- potential safety improvement by implementation of speed assistance systems, in comparison with the implementation of a roundabout, for fatalities ($j = 1$) and hospitalisations ($j = 2$) respectively

$$E_{A1} = \frac{H_{A1}}{H_{D1}} \times E_{D1} = \frac{\sum\limits_{y=1,2} \varepsilon_{Ay}(\beta_{y1} + \mu_{y1}\alpha_y)}{\sum\limits_{y=1,2,3,5} \varepsilon_{Dy}(\beta_{y1} + \mu_{y1}\alpha_y)} \times E_{D1}$$

$= \{[0.75 \times (0.026 + 0.071 \times 0.021) + 0.30 (0.009 + 0.016 \times 0.030)] / [0.90 \times (0.026 + 0.071 \times 0.021) + 0.95 \times (0.009 + 0.016 \times 0.030) + 0.60 \times (0.009 + 0.003 \times 0.176) + 0.70 \times (0.056 + 0.049 \times 0.591)]\} \times 75.0\%$

$= 17.8\%$

$$E_{A2} = \frac{H_{A2}}{H_{D2}} \times E_{D2} = \frac{\sum\limits_{y=1,2} \varepsilon_{Ay}(\beta_{y2} + \mu_{y2}\alpha_y)}{\sum\limits_{y=1,2,3,5} \varepsilon_{Dy}(\beta_{y2} + \mu_{y2}\alpha_y)} \times E_{D2}$$

$= \{[0.75 \times (0.009 + 0.193 \times 0.021) + 0.30 \times (0.007 + 0.096 \times 0.030)] / [0.90 \times (0.009 + 0.193 \times 0.021) + 0.95 \times (0.007 + 0.096 \times 0.030) + 0.60 \times (0.038 + 0.088 \times 0.176) + 0.70 \times (0.011 + 0.073 \times 0.591)]\} \times 53.0\%$

$= 7.4\%$

- potential safety improvement by implementation of intersection support systems, in comparison with the implementation of a roundabout, for fatalities ($j = 1$) and hospitalisations ($j = 2$) respectively

$$E_{A1} = \frac{H_{A1}}{H_{D1}} \times E_{D1} = \frac{\sum\limits_{y=5} \varepsilon_{Ay}(\beta_{y1} + \mu_{y1}\alpha_y)}{\sum\limits_{y=1,2,3,5} \varepsilon_{Dy}(\beta_{y1} + \mu_{y1}\alpha_y)} \times E_{D1}$$

$= \{[0.60 \times (0.056 + 0.049 \times 0.591)] / [0.90 \times (0.026 + 0.071 \times 0.021) + 0.95 \times (0.009 + 0.016 \times 0.030) + 0.60 \times (0.009 + 0.003 \times 0.176) + 0.70 \times (0.056 + 0.049 \times 0.591)]\} \times 75.0\%$

$= 38.6\%$

$$E_{A2} = \frac{H_{A2}}{H_{D2}} \times E_{D2} = \frac{\sum\limits_{y=5} \varepsilon_{Ay}(\beta_{y2} + \mu_{y2}\alpha_y)}{\sum\limits_{y=1,2,3,5} \varepsilon_{Dy}(\beta_{y2} + \mu_{y2}\alpha_y)} \times E_{D2}$$

= {[0.60 × (0.011 + 0.073 × 0.591)] / [0.90 × (0.009 + 0.193 × 0.021) + 0.95 × (0.007 + 0.096 × 0.030) + 0.60 × (0.038 + 0.088 × 0.176) + 0.70 × (0.011 + 0.073 × 0.591)]} × 53.0%

= 18.9%

- potential safety improvement by implementation of anti-collision systems, in comparison with the implementation of a roundabout, for fatalities ($j = 1$) and hospitalisations ($j = 2$) respectively

$$E_{A1} = \frac{H_{A1}}{H_{D1}} \times E_{D1} = \frac{\sum\limits_{y=3,5} \varepsilon_{Ay}(\beta_{y1} + \mu_{y1}\alpha_y)}{\sum\limits_{y=1,2,3,5} \varepsilon_{Dy}(\beta_{y1} + \mu_{y1}\alpha_y)} \times E_{D1}$$

= {[0.05 × (0.009 + 0.003 × 0.176) + 0.05 × (0.056 + 0.049 × 0.591)] / [0.90 × (0.026 + 0.071 × 0.021) + 0.95 × (0.009 + 0.016 × 0.030) + 0.60 × (0.009 + 0.003 × 0.176) + 0.70 × (0.056 + 0.049 × 0.591)]} ×75.0%

= 3.6%

$$E_{A2} = \frac{H_{A2}}{H_{D2}} \times E_{D2} = \frac{\sum\limits_{y=3,5} \varepsilon_{Ay}(\beta_{y2} + \mu_{y2}\alpha_y)}{\sum\limits_{y=1,2,3,5} \varepsilon_{Dy}(\beta_{y2} + \mu_{y2}\alpha_y)} \times E_{D2}$$

= {[0.05 × (0.038 + 0.088 × 0.176) + 0.05 × (0.011 + 0.073 × 0.591)] / [0.90 × (0.009 + 0.193 × 0.021) + 0.95 × (0.007 + 0.096 × 0.030) + 0.60 × (0.038 + 0.088 × 0.176) + 0.70 × (0.011 + 0.073 × 0.591)]} × 53.0%

= 3.1%

The potential safety effects for implementation of integrated driving assistance systems compared with roundabouts cannot be determined simply by summing up the estimation results of safety effects of these three functions, due to overlaps in functionality. In this case, the value for the integrated system functions is estimated by taking the largest ε-value. For instance, both intersection support and anti-collision concern ε_{q5}. And max {0.60, 0.05} = 0.60, therefore, the value of $\varepsilon_{q5} = 0.60$ for intersection support is adopted as the overall value for the calculation. Then:

- potential safety improvement by implementation of integrated driving assistance systems (i.e. in this case, speed assistance, intersection support and anti-collision systems), in comparison with the implementation of a roundabout, for fatalities ($j = 1$) and hospitalisations ($j = 2$) respectively

$$E_{A1} = \frac{H_{A1}}{H_{D1}} \times E_{D1} = \frac{\sum\limits_{y=1,2,3,5} \varepsilon_{Ay}(\beta_{y1} + \mu_{y1}\alpha_y)}{\sum\limits_{y=1,2,3,5} \varepsilon_{Dy}(\beta_{y1} + \mu_{y1}\alpha_y)} \times E_{D1}$$

= {[0.75 × (0.026 + 0.071 × 0.021) + 0.30 × (0.009 + 0.016 × 0.030) + 0.05 × (0.009 + 0.003 × 0.176) + 0.60 × (0.056 + 0.049 × 0.591)] / [0.90 × (0.026 + 0.071 × 0.021) + 0.95 × (0.009 + 0.016 × 0.030) + 0.60 × (0.009 + 0.003 × 0.176) + 0.70 × (0.056 + 0.049 × 0.591)]} ×75.0%

= 56.8%

$$E_{A2} = \frac{H_{A2}}{H_{D2}} \times E_{D2} = \frac{\sum\limits_{y=1,2,3,5} \varepsilon_{Ay}(\beta_{y2} + \mu_{y2}\alpha_y)}{\sum\limits_{y=1,2,3,5} \varepsilon_{Dy}(\beta_{y2} + \mu_{y2}\alpha_y)} \times E_{D2}$$

= {[0.75 × (0.009 + 0.193 × 0.021) + 0.30 × (0.007 + 0.096 × 0.030) + 0.05 × (0.038 + 0.088 × 0.176) + 0.60 × (0.011 + 0.073 × 0.591)] / [0.90 × (0.009 + 0.193 × 0.021) + 0.95 × (0.007 + 0.096 × 0.030) + 0.60 × (0.038 + 0.088 × 0.176) + 0.70 × (0.011 + 0.073 × 0.591)]} × 53.0%

= 27.9%

It should be stressed that the presented values are in the first place meant to illustrate the method for comparative analysis based on the QCC model. Certainly better values may be obtained by more elaborate analysis of available data, and by use of other methods and additional expert knowledge. Nevertheless, this example provides some interesting preliminary results of the quantitative analysis. The roundabout shows higher safety effects than the related (potentially substitutional) driving assistance system applications. Note that such comparative analysis only addresses safety effects at a local level in a specific case. For comprehensive evaluation of the overall effects for a network, non-safety aspects need to be taken into account as well. Such evaluation is discussed in the next chapter.

7 Framework for policy evaluation

7.1 Introduction

To address research question 4, a systematic analytical framework needs to be elaborated for a comprehensive evaluation of the overall effects of traffic safety measures, which takes into account traffic safety effects, using the results from the comparative method for traffic safety effects at local level, together with non-safety related aspects. For this strategic evaluation of various alternatives an evaluation method needs to be selected.

7.2 Evaluation process

Evaluation methods provide a recipe for analysis and ranking of different available alternatives (or strategic scenarios) for achieving certain goal(s) or objective(s). Generally, first a list of relevant operational attributes (criteria and sub-criteria) of the alternatives is established, creating a (two-dimensional) matrix of alternatives (i) and attributes (k) (see Table 7.1). For each relevant cell of this evaluation matrix a value is established (i.e. the value of one attribute for one alternative). Then some operation is applied to rank the alternatives. Each set of attribute values for one alternative constitutes an alternative vector, and the essence is to transform each alternative vector in a coherent way to an appropriate numerical value, after which the preferable alternative can be determined from the ranking of these values. An evaluation method may also try to pursue more than one objective, creating essentially a cubic array of alternatives, attributes and objectives.

Table 7.1 - Evaluation matrix $i \times k$

alternatives → criteria/attributes ↓	a_1	a_2	...	a_i
c_1 (.)	$c_1 (a_1)$	$c_1 (a_2)$	...	$c_1 (a_i)$
c_2 (.)	$c_2 (a_1)$	$c_2 (a_2)$	...	$c_2 (a_i)$
...	...	...	...	...
c_k (.)	$c_k (a_1)$	$c_k (a_2)$	...	$c_k (a_i)$

7.3 Evaluation methods

There is an abundant number of evaluation methods, each trying to cope in their own specific way with several aspects of the evaluation problem that make it such a notoriously difficult one. These are especially the differences in the nature of the criteria used, and the related issue to aggregate items that are measured in dissimilar units.

7.3.1 Categories of evaluation methods

Two categories of evaluation methods can be distinguished: economics based evaluation and normalisation based evaluation. Each method from both categories in essence provides a procedure to process the evaluation matrix in order to provide a preference ranking of the alternatives. Examples of evaluation methods in the two categories that are commonly in use concern:

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1. Economics based evaluation methods

   Cost-Benefit Analysis (CBA)[18] (Boardman, 1996; Heikkila, 2000; Elvik, 2001; Hakkert & Wesemann, 2004), *Cost-Effectiveness Analysis* (CEA) (Trilling, 1978; Wesemann, 2000), *Planning Balance Sheet* (PBS) (Lichfield, 1956; Lichfield, 1964) and *Goal Achievements Matrix* (GAM) (Hill, 1968; DETR, 1998)

2. Normalisation based evaluation methods[19]

   Analytic Hierarchy Process (AHP) (Saaty, 1980; Saaty 1995), *Simple Additive Weighting* (SAW) (Yoon & Hwang, 1995), *Technique for Order Preference by Similarity to Ideal Solutions* (TOPSIS) (Hwang & Yoon, 1981), *ÉLimination Et Choix Traduisant la RÉalité* (ELECTRE) (Roy, 1968; Chenga et al., 2003), *Preference Ranking Organisation METHod for Enrichment Evaluations* (PROMETHEE) (Brans, 1982, Brans et al., 1986; Brans, 1996; Haralambopoulos & Polatidis, 2003, Al-Rashdan et al., 1999) and *fuzzy multiple criteria decision aid* (Zadeh, 1965; Klir et al., 1997; Chen et al., 1992; Ribeiro et al., 2003; Khan et al., 2002)

Both economics and normalisation based methods have their advantages and limitations, and the results often give a room for arguments. Economics based methods express attribute values as much as possible in a monetary unit. In practice, this often appears to be costly, and sometimes inoperable. But the less stringent this condition is applied (e.g. in CEA, PBS and GAM), the less feasible it becomes to obtain a clear analytical answer. Normalisation based methods try to remove the issue of dissimilar units, but none of them has rigorous theoretical foundations. Each of the normalisation based methods is, in fact, no more than an advanced calculation recipe, and some of these methods are not always able to provide an unambiguous ranking order. The presence of multiple attribute value types that cannot be expressed in monetary units precludes by nature the use of an economics based method.

7.3.2   Requirements for the method to evaluate traffic safety measures

The evaluation case addressed in this thesis concerns two categories of technologies of quite dissimilar character: physical road infrastructure and driving assistance systems. For the traffic safety effects of infrastructure measures data are available; for driving assistance systems such data are not usually available due to limited penetration, but may be estimated in terms of differences with infrastructure effects by using the method for comparative analysis derived from the QCC model, or other methods. Besides traffic safety, a comprehensive evaluation should take into account a range of other aspects, some of which can be expressed in physical measurement units with different levels of certainty, while others can only be valued by, for instance, a scoring approach. From these characteristics three specific requirements derive for the evaluation method to be selected. This method should be able to adequately process and aggregate, in one evaluation matrix: (1) a wide range of attributes with different value types; (2) both attributes expressed in objective physical measurement units, and attributes expressed as subjective scores; and (3) both attributes with accurate and reliable values, and attributes for which all or part of the available data have a high level of uncertainty with respect to accuracy.

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[18] Instead of for comparing and ranking several alternatives, CBA may also be used for assessing just one alternative.

[19] In the literature, normalisation based evaluation is also called multi-criteria analysis (MCA), multi-criteria (or multiple criteria) decision analysis (MCDA), multi-criteria decision making (MCDM) or multiple attribute decision making (MADM) (Figueira et al., 2005).

7.4 Grey system theory and grey relational analysis

7.4.1 Grey system theory and methods

Grey system theory was initiated by J. Deng (1982) in P.R. China. It provides an approach for abstract modelling of systems for which the information is limited, incomplete and characterised by random uncertainty. The term grey stands for poor, incomplete and uncertain, and is especially used in relation to the concept of information. In system control theory, a system for which the relevant information is completely known is sometimes called a white system, while a system for which the relevant information is completely unknown is termed a black system. Any system between these limits then may be called a grey system (Guo, 2005).

Grey system theory gradually developed from requirements for new methods to solve certain problems. The main grey methods within grey system theory are (grey) systems and control, grey modelling (GM) and grey relational analysis (GRA). Grey system and control enriches the domain of systems and control, and provides a valuable complement to conventional methods (Deng, 1982; Zhou & Deng, 1989). Grey system typically deals with systems, objects or concepts having a well-defined external boundary but internal uncertainty or vagueness, while conversely fuzzy mathematics deals with systems, objects or concepts having a well-defined interior but no well-defined external boundary (Liu & Lin, 1998). GM is developed based on requirements for system modelling with limited data, which is a notorious problem for most classical modelling methods. The first order one variable grey model, denoted as GM(1,1) is especially applicable for forecasting (Deng, 1985; Wong & Chen, 2000; Cheng & Chang, 2001; El-Fouly et al., 2006). GRA is a normalisation based evaluation method. It is used for system analysis, as an alternative for traditional statistical methods (Deng, 1984; Lin & Yang, 1999; Hu et al., 2002; Morán et al., 2006). Generally, for addressing problems involving random uncertainty, correlation analysis based on traditional statistical methods requires relatively large sample sizes for a sufficiently reliable analysis of the distribution. GRA, on the other hand, requires a sample of only limited (and from a statistics point of view generally insufficient) size, of discrete sequential (time-series) data to enable reliable modelling and estimation of system behaviour. Furthermore, statistical methods require a probability distribution for the values in the evaluation matrix. In some cases, a probability distribution cannot be determined due to, for instance, limited availability of data. GRA does not require such probability distribution. Presently GRA as well as the other grey system methods are mainly applied in Chinese speaking areas, and hardly known in western countries.

7.4.2 Introduction of the GRA evaluation method

GRA is based on the concept of grey relational space (GRS), one of the elements of grey system theory (Deng, 1989). In the case of an evaluation matrix, each alternative (i) can be taken as one series, which consists of a set of criteria or attributes (k). The sets of values of all the alternatives together constitute a GRS. The fundamental schema of GRS is to integrate two-dimensional Euclidean space (i.e. *distance space*) and set-point topology (i.e. *metric space*). Because the latter cannot be directly and intuitively measured in the distance space, GRA specifies a mathematical way to analyse the correlation between the series that compose a GRS, i.e. to determine the *distance* (i.e. difference) between a *reference series* and each of the *compared series*. The compared series are the series of the set (i.e. the series for each of the alternatives i). The reference series is a vector created from the set of alternatives with for each attribute either the maximum value, the minimum value or the optimum value, depend-

ent on the type of attribute. By applying some further processing, for each series of the original set, a grey relational grade is determined. The grey relational grades provide a ranking of the alternatives.

The characteristics of GRA can be summarised as follows (Deng, 2005): (1) compared to correlation analysis in statistics, only a limited number of data is needed (at least three values in each series); (2) the distribution of the data does not need to be explicitly considered; and (3) the calculation procedure is simple and transparent. GRA is especially able to cope with the uncertainty of data that exists for the evaluation problem that is addressed in this thesis. It does not need to take into account the distribution of the attribute values. GRA only requires relative accuracy of data (see also the algorithm in Section 7.5). In GRA the attributes may be of any relevant type, and the original units may be applied, e.g. physical quantities and scores. GRA enables to aggregate overall effects of alternatives in a network, considering the inaccuracy of the input data, and, thereby, a comprehensive evaluation (including e.g. societal aspects, economic aspects, environmental aspects and implementation impediments) at a global level, and, by this, to provide a clear-cut ranking of alternatives. By implementing the calculation procedure in a computer algorithm (Wen et al., 2006), it is straightforward to evaluate different scenarios, and to perform sensitivity analyses. Based on the foregoing, it can be concluded that the GRA method does fulfil the three stated requirements (see Section 7.3.2). Furthermore, GRA can easily be extended to cover multi-objective evaluation problems. All this does not mean that GRA is a perfect method; it is just a different method with different characteristics, and for other purposes. Like the other presented methods, also GRA is basically no more that a recipe for evaluation, i.e. for processing an evaluation matrix and providing a ranking of the alternatives.

7.5   GRA algorithm

In GRA it is assumed that the input attributes satisfy three conditions for comparability of the set of series (Deng, 1989): (1) for each attribute vector the difference between the maximum and minimum input values is less than an order of magnitude of two; (2) all attributes in an attribute vector are of the same type (maximum value, minimum value or optimum value); and (3) all attributes in an attribute vector have the same measurement scale, and, if in a quantitative scale, have the same unit or no unit. In the GRA literature these conditions are referred to as *scaling* (for the order of magnitude), *polarisation* (for the attribute type), and *non-dimension* (for the measurement scale) (Deng, 1989). If these three conditions are not satisfied, normalisation of the input data prior to GRA processing is required. By applying normalisation (i.e. the data pre-processing), compliance with the three conditions is achieved.

The GRA community has seen quite extensive discussions on normalisation to prove that the original attribute vectors, before normalisation, and the resulting attribute vectors, after normalisation, have the same relative positions in GRS without any distortion. For more detailed discussions on normalisation see (Deng, 1989; Wu & Chen, 1999; Chang, 2000). The most widely used normalisation method is the one developed by Wu and Chen (1999), called the *linear data approach*. It takes into account the type of the attribute (maximum value[20], minimum value[21] or optimum value[22]), and normalises to a scale [0,1]. The respective formulae are:

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[20] Maximum value attribute may also be named benefit attribute or the-larger-the-better attribute.
[21] Minimum value attribute may also be named cost attribute or the-smaller-the-better attribute.
[22] Optimum value attribute may also be named preferred value attribute or objective attribute.

- maximum value:
$$x_i^*(k) = \frac{x_i(k) - \min_k x_i(k)}{\max_k x_i(k) - \min_k x_i(k)} \qquad (7.1a)$$

- minimum value:
$$x_i^*(k) = \frac{\max_k x_i(k) - x_i(k)}{\max_k x_i(k) - \min_k x_i(k)} \qquad (7.1b)$$

- optimum value

$$x_i^*(k) = 1 - \frac{\left| x_i(k) - x_{\mathrm{op}}(k) \right|}{\max\{\max_k x_i(k) - x_{\mathrm{op}}(k), x_{\mathrm{op}}(k) - \min_k x_i(k)\}} \qquad (7.1c)$$

where $\max_k x_i(k)$ is the maximum value of attribute k for alternative i, $\min_k x_i(k)$ is the minimum value of attribute k for alternative i, and $x_{\mathrm{op}}(k)$ is the optimum value of attribute k.

After normalisation the reference series is identified. This is the base vector of reference values with which all series are compared. Which value for a certain attribute defines the value of the reference series depends on the type of the attribute. In general, for a maximum value type attribute the highest value is taken, for a minimum value type attribute the lowest value, and for an optimum value type attribute the predetermined preferred value.

For each alternative vector (or compared series), its difference with the reference vector (or reference series) is calculated:

$$\Delta_{0i}(k) = \left| x_0(k) - x_i(k) \right|, \ k = 1, 2, \ldots, n \qquad (7.2)$$

This creates a new ($i \times k$) matrix of difference vectors. From this matrix, for each alternative i and attribute k, a grey relational coefficient is calculated, which for each element of an alternative vector or compared series is defined as:

$$\gamma(x_0(k), x_i(k)) = \frac{\min_{i,k} \left| x_0(k) - x_i(k) \right| + \zeta \max_{i,k} \left| x_0(k) - x_i(k) \right|}{\left| x_0(k) - x_i(k) \right| + \zeta \max_{i,k} \left| x_0(k) - x_i(k) \right|} \qquad (7.3)$$

where $\gamma(x_0(k), x_i(k))$ denotes the grey relational coefficient of attribute k for alternative i, $x_0(k)$ denotes the element of the reference series for attribute k, $x_i(k)$ denotes the element of the compared series for attribute k, and $\zeta \in (0,1)$ denotes the identification (or distinguishing) coefficient. Formula (7.3) can be worded as follows: for each i, k value in the matrix of difference vectors, the sum of the minimum of all values in the k vector, and the maximum of all values in the k vector multiplied by a distinguishing coefficient, is divided by the sum of the value itself and (again) the maximum of all values in the k vector multiplied by the distinguishing coefficient (Guo, 1985; Deng, 1989; Wen et al., 2006). When the *linear data approach* for normalisation is applied, the value $\zeta = 1$ is taken for the distinguishing coefficient. This avoids the discussion concerning the selection of an appropriate value for this coefficient (Wu & Chen, 1999).

The grey relational grade for the compared series x_i in terms of weight w_k is given as

$$\Gamma_{0i} = \sum_{k=1}^{n} w_k \gamma(x_0(k), x_i(k)) \qquad (7.4)$$

where w_k is the weight of $\gamma(x_0(k), x_i(k))$, and $\sum_{k=1}^{n} w_k = 1$.

The grey relational grades of the set of compared series provide a ranking of the alternatives, where a higher value determines a better alternative. Note that GRA itself does not deal with the issue of applying weights.

7.6   GRA application steps

The process of evaluating the various alternatives (e.g. implementation strategies of driving assistance systems and/or road infrastructure) by the application of GRA may be summarised by the following steps:

1. Identify the relevant alternatives, and criteria or attributes.

2. Give operational definitions for the attributes (see Table 7.2) to enable the specification of values for each alternative.

3. Establish values (for each attribute for each alternative) and create the alternatives (i) versus attributes (k) matrix ($i \times k$) (see Table 7.3, except the right column).

4. Identify the reference series (the ideal alternative), taking into account the type of each attribute (maximum value, minimum value or optimum value) (see Table 7.3, right column).

5. If the three conditions for comparability of the set of series are not satisfied, normalise the original input data as well as the reference series by using formula (7.1a), (7.1b) or (7.1c) dependent on the attribute type (see Table 7.4).

6. Calculate, for each alternative i, the absolute (in a mathematical sense) difference between the reference series and each compared series by using formula (7.2) (see Table 7.5).

7. Calculate the grey relational coefficients $\gamma(x_0(k), x_i(k))$ for each alternative i and attribute k by using formula (7.3) (see Table 7.6, except the bottom line).

8. Calculate the grey relational grade Γ_{0i} for each of the alternatives i by using formula (7.4) (see Table 7.6 bottom line).

9. Rank the alternatives based on the grey relational grades Γ_{0i}. The ranking provides the evaluation result: the larger the value of grey relational grade, the better the alternative.

7.7   Illustration of the application of GRA

Two examples are provided to demonstrate how to apply the GRA evaluation method. The first one concerns a reconsideration of the Dutch national strategy for improving traffic safety (see Paper IV). In this example the (aggregated) values in the evaluation matrix are illustrative. Actual values maybe obtained from research results, or by applying other methods. The second example applies GRA to a road in The Netherlands (see Paper V). This example addresses the case of a local authority who needs to select an alternative for improving traffic safety. Part of the safety effects of each alternative concerning driving assistance systems can be estimated by applying the method for comparative analysis derived from the QCC model that is presented in Chapter 6. It should be emphasised that the process of scenario selection as provided in both examples (for national and local level respectively) is illustrative, and that scenarios are selected based on likelihood. Scenarios are consisting of infrastructure measures only, driving assistance measures only and combinations of measures from the two categories. These scenarios are created based on brainstorm discussion, interview and common logical

Table 7.2 - Example of criteria, attributes and operational value descriptions for a comprehensive evaluation framework

criteria	attributes	operational value description
societal aspects	accident consequence	total fatality reduction rate in a period, as percentage
		total hospitalisation reduction rate in a period, as percentage
		total slight injury reduction rate in a period, as percentage
		total property damage-only reduction rate in a period, as percentage
	accident risk	total traffic accident reduction rate in a period, as percentage
	comfort/convenience	rated from 1 to 10, a higher grade means more comfortable/convenient
	emergency services	rated from 1 to 10, a higher grade indicates less impediment for the services
environment	reduce emissions	total reduction rate of CO, NO_x and C_xH_y, as percentage
	reduce noise	rated from 1 to 10, a higher grade means higher noise reduction
economic aspects	network capacity	rated from 1 to 10, a higher grade means higher contribution to capacity
	land use	rated from 1 to 10, a lower grade indicates more extra physical space needed
	fuel consumption	reduction of fuel consumption, as percentage
	time spent	total travel time reduction rate, as percentage
	costs	total NPV (net present value) of a certain year, for instance in EUR 1 million
implementation	public acceptance	rated from 1 to 10, a higher grade means higher acceptance
	technology difficulty	rated from 1 to 10, a lower grade means fewer technical problems
	policy difficulty	rated from 1 to 10, a lower grade means easier implementation of the policy

Table 7.3 - Evaluation matrix with original input data of each compared series (the alternatives), and the reference series

attribute	alternative (compared series)				reference series
	a_1	a_2	...	a_i	a_0
$k = 1$	$x_1(1)$	$x_2(1)$	...	$x_i(1)$	$x_0(1) = \max_{k=1} x_i(k)$
$k = 2$	$x_1(2)$	$x_2(2)$	...	$x_i(2)$	$x_0(2) = \max_{k=2} x_i(k)$
...	...	...	...	...	...
$k = n$	$x_1(n)$	$x_2(n)$	...	$x_i(n)$	$x_0(n) = \min_{k=n} x_i(k)$

Note: the attributes $k = 1,2$ are taken as maximum value type attributes, and the attribute $k = n$ is taken as a minimum value type attribute, as is reflected in the reference series a_0

Table 7.4 - Normalised data of each compared series and the reference series

attribute	alternative (compared series)				reference series
	a_1	a_2	...	a_i	a_0
$k = 1$	$x_1^*(1) = \dfrac{x_1(1) - \min_{k=1} x_i(1)}{\max_{k=1} x_i(1) - \min_{k=1} x_i(1)}$	$x_2^*(1)$	...	$x_i^*(1)$	$x_0^*(1) = \max_{k=1} x_i^*(k)$
$k = 2$	$x_1^*(2) = \dfrac{x_1(2) - \min_{k=2} x_i(2)}{\max_{k=2} x_i(2) - \min_{k=2} x_i(2)}$	$x_2^*(2)$	...	$x_i^*(2)$	$x_0^*(2) = \max_{k=2} x_i^*(k)$
...	...	...	...	...	...
$k = n$	$x_i^*(n) = \dfrac{\max_{k=n} x_i(n) - x_1(n)}{\max_{k=n} x_i(n) - \min_{k=n} x_i(n)}$	$x_2^*(n)$	...	$x_i^*(n)$	$x_0^*(n) = \min_{k=n} x_i^*(k)$

Note: the attributes $k = 1,2$ are taken as maximum value type attributes, and the attribute $k = n$ is taken as minimum value type attribute, as is reflected in the reference series a_0

Table 7.5 - Difference, for each compared series, between the compared series and the reference series (after normalisation)

attribute	alternative (compared series)			
	a_1	a_2	...	a_i
$k = 1$	$\Delta_{01}(1) = \lvert x_0^*(1) - x_1^*(1) \rvert$	$\Delta_{02}(1)$	...	$\Delta_{0i}(1)$
$k = 2$	$\Delta_{01}(2) = \lvert x_0^*(2) - x_1^*(2) \rvert$	$\Delta_{02}(2)$	...	$\Delta_{0i}(2)$
...	...	...	...	...
$k = n$	$\Delta_{01}(n) = \lvert x_0^*(n) - x_1^*(n) \rvert$	$\Delta_{02}(n)$	...	$\Delta_{0i}(n)$

Table 7.6 - Grey relational coefficient $\gamma(x_0(k), x_i(k))$ of attribute k for alternative i, and ranking based on grey relational grade Γ_{0i} of each alternative i

attribute	alternative (compared series)			
	a_1	a_2	...	a_i
$k = 1$	$\gamma(x_0(1), x_1(1))$	$\gamma(x_0(1), x_2(1))$	...	$\gamma(x_0(1), x_i(1))$
$k = 2$	$\gamma(x_0(2), x_1(2))$	$\gamma(x_0(2), x_2(2))$	...	$\gamma(x_0(2), x_i(2))$
...	...	...	...	...
$k = n$	$\gamma(x_0(n), x_i(n))$	$\gamma(x_0(n), x_2(n))$	...	$\gamma(x_0(n), x_i(n))$
grey relational grade	Γ_{01}	Γ_{02}	...	Γ_{0i}

reasoning, for the illustration of strategic evaluation. Attributes are categorised as societal aspects, economic aspects, environmental aspects and implementation impediments. By applying the GRA algorithm a ranking of alternatives is provided (by computing the grey relational grade for each alternative), and the result enables selection of the preferable strategy. The calculation procedure of GRA (i.e. the aforementioned nine steps), for each of these two examples, is presented in detail in appendices 1 and 2 respectively.

The evaluation result provides the priority ranking of the scenarios. It needs to be noted that the provided illustration and the obtained ranking results only reflect special cases: the obtained rankings are not necessarily representative for roads or the complete road network in The Netherlands. The evaluation approach is equally applicable to other routes or networks (local, regional, national or European), and to scenarios of a different composition. In addition, one should be careful and not take these results as absolute truths. They are the output of an illustrative application of the method. More sophisticated estimation of the input values may lead to a different ranking. The obtained ranking may also be biased by a too optimistic estimation (in the used SWOV figures) of the safety effects of some road infrastructure measures, which are, therefore, not offset by the high costs and other negative factors (e.g. related to comfort and convenience, impediments for emergency services, and effects on land use). The quality of the ranking is essentially dependent on the quality of the input data. The GRA method provides an approach to aggregate data, and to provide a ranking of alternatives. However, to obtain sufficient and reliable input data for the evaluation matrix is and remains a notorious problem, which cannot be solved by the GRA method. The same applies to the determination of weights. A crucial point to keep in mind is that an evaluation method provides a tool for assisting decision making, but that no algorithm can act as a complete substitute for human judgement.

8 Discussion

8.1 Thesis contribution

8.1.1 Scientific contribution

The research provides a contribution to the fundamental knowledge regarding the comparison of various measures of dissimilar nature, road infrastructure and driving assistance systems, with regards to traffic safety effects.

1. A quantitative causal chain (QCC) model is developed to analyse and quantify the mechanisms of the process from traffic safety measures to their traffic safety effects. The QCC model focuses on the transformations from traffic safety measures, via the determinants, to the traffic safety factors, which are specified by coefficients. The model contributes to improving insight into the mechanisms of the causal chain.

2. A method for comparative analysis of measures of dissimilar nature by using effectiveness indices is developed based on the QCC model. It is in principle applicable to any comparative analysis of road traffic safety measures, which are related in terms of functional substitutability.

3. A bi-level approach (consisting of a safety performance module for the local level and a policy evaluation module for the global level) combines the method for comparative analysis at the local level derived from the QCC model with an evaluation method based on grey relational analysis (GRA) for analysis at the global level, and provides a transparent and systematic framework for comparative analysis of different strategies, as a platform for supporting decision making.

8.1.2 Practical relevance

The main relevance of the research can be summarised as follows:

1. On the one hand, a strong political desire exists to accelerate the improvement of road traffic safety; on the other hand, implementation of infrastructure measures is often a time-consuming process due to budget restrictions. If scarce money can be used more effectively by shifting (partly or completely) from physical road infrastructure based strategies to ICT and sensor based strategies, this would entail significant societal advantages. This research helps to make the discussion more transparent, and to suggest ways and provide methods to cope with the related uncertainties.

2. The research highlights the contribution of various types of driving assistance systems to road traffic safety based on comparison with road infrastructure measures.

3. A bi-level approach is proposed, in which two modules are distinguished: safety performance and policy evaluation. Each of the modules can in principle be used on its own. On the one side, the safety performance module provides a comparative method derived from the QCC model, which can help an authority to decide if and where an infrastructure measure should be implemented, by also taking into account the effectiveness of driving assistance system(s). On the other side, the policy evaluation module provides a comprehensive, flexible and easily applicable approach for evaluation.

8.2   Discussion of the research method and further research

This section specifies some relevant topics concerning model and method development, which may serve as inputs for further research.

8.2.1   QCC model and derived method

Model validation in science and technology concerns testing if a model is valid. This may be interpreted as testing if the model, which is an abstract and restricted representation of the reality, correctly or sufficiently represents this reality. This reality generally is a process that produces a certain output from a certain input. For some models experiments can be designed to do the testing. Other models can be tested using existing data. For yet other models validity testing is not straightforward or even impossible. A notorious example is a macro-economic model, which cannot be properly tested. A specific experiment is not possible, and historical data (representing a non-specific one time experiment) may actually have been influenced by the very outcome of the predictions based on the model. The developed QCC model might be tested using historical accident data. The problem, however, is that these accident data are generally rather incomplete and highly inaccurate and unreliable. A core problem in this field is further that accidents are rare events, and that experiments certainly are not possible. For these reasons, and because of yet limited knowledge, it is impossible at this stage to assess the validity of the QCC model by traditional methods. To address this issue, further research is required and, possibly, further development of the model itself. The developed model is a first step in a certain direction to quantify the causal chain.

The described QCC model is based on several assumptions, some of which are certainly simplifying with respect to reality, but inevitable, in absence of more precise insight. It provides, however, a practical but founded and transparent method to address the problem of assessment of a traffic safety measure for which only incomplete data are available, by enabling comparative analysis with a traffic safety measure for which accurate and reliable estimates of the safety effects exist. 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 focus of the QCC model is on the coefficients between measures, determinants and factors, instead of on quantifying the determinants and/or factors directly. This is an distinction between the QCC model (and the derived method for comparative analysis) and other approaches. In addition, the derived method has the purpose to deal with comparative analysis of safety effects of different (types of) measures directly, instead of to estimate safety effects of one specific measure. Better estimation methods for the various coefficients need to be developed, with more focus on probability, and less on expert judgement and historical accident data. For instance, an objective method may be developed for assessing accident probability, which is not based on accident statistics, but on objective road safety audits, or on the use of quantitative static road environment parameters (such as geometry including curvature, road gradient, superelevation, road surface, road width, and road attributes like functional road class and legal speed limit), dynamic traffic parameters (such as speed, density and flow), and dynamic environmental conditions (such as luminosity, vision and weather).

Additional research may further detail the model and provide enhanced procedures for estimation of the various coefficients, and thereby improve the derived method for comparative analysis for use in practical applications. Change or adaptation of behaviour is the fundamental schema behind the influence of measures on determinants. This is a rather complex issue,

since current knowledge and available data are too limited to quantify a general behavioural model (Evans, 1991; 2004). Human driving behaviour may be influenced by various parameters, which can be categorised as driver characteristics (such as individual risk perspective, mood, skill, age and gender), vehicle characteristics (such as vehicle type, vehicle quality and vehicle dynamics), road infrastructure characteristics, traffic conditions and environment conditions. Possible further research could, for instance, be based on behavioural observations (Risser, 1985).

8.2.2 Policy evaluation based on GRA

With respect to the policy evaluation module, the following topics for further study may be identified:

1. More fundamental research of grey system theory and grey relational analysis (GRA)

   The current foundations of grey system theory are not yet sufficiently rigorous in a mathematical sense. Therefore, it may be useful to carry out further fundamental research to see whether an axiomatic foundation for grey system theory can be created. This may help to promote appreciation and adoption outside the Chinese speaking world. The GRA method is an associated fundamental concept that is critical in grey system. Further study on its mathematical foundation may help to strengthen its theoretical basis, and should especially address the following questions, for instance by systematic simulation:

   (a) To which degree can GRA compensate for or tolerate incompleteness and unreliability of data?

   (b) Which GRA data pre-processing (or normalisation) approach is most suitable for which situation(s)?

2. Study, development and application of methods for obtaining values for other attributes than traffic safety in the evaluation matrix

   This concerns especially the following issues:

   (a) Other societal aspects, such as comfort and convenience, and efficiency (e.g. in relation to emergency services)

   For further study standard criteria and a standard procedure for score estimation need to be established, to guide experts in giving reasonable scores.

   (b) Environmental aspects, such as emissions, noise and vibration

   In principle, values for changes in these attributes, expressed in physical measurement units, can be obtained from real world tests or simulation studies.

   (c) Economic aspects, such as network capacity, land use, fuel consumption and total costs

   Some economic effects can be determined in physical measurement units through simulation, e.g. change of network capacity and fuel consumption; for other effects, e.g. change of land use, it is more efficient to use a system based on subjective scores; for systematically studying costs, a database could be established for estimation and prediction of costs, especially for driving assistance systems. Another economic aspect is traffic performance (which is partly related to network capacity), such as total travel time spent. This attribute could also be studied by simulation (based on collected real world data). An example is mitigating shock waves on flow roads using driving assistance systems, which reduces total travel time (Lu et al., 2006).

(d) Implementation conditions, such as public acceptance, and technology and policy implementation impediments

These attributes could to be studied by, for instance, survey or interview.

3. Weighting and sensitivity analysis

In general, the issue of determining values for the weights is in the domain of the operational use of the model, and not of the model development itself. Nevertheless, it may be a topic for further research from the perspective of the model. Weighting may be used for sensitivity analysis, although this actually can be studied directly from the model, for instance, by variation of input values or changes in attribute selection.

8.3 Conclusion and final remark

8.3.1 *Functional substitutability relationships of traffic safety measures*

Five safety related driving assistance system functions (i.e. navigation, speed assistance, anticollision, intersection support and lane keeping) emerged as potential candidates to match infrastructure measures in terms of functional substitutability. The chosen approach to study the functional relationships in terms of substitutability between these two categories of measures of rather dissimilar nature is to identify a comprehensive set of traffic safety principles, and related more operational traffic safety requirements. Driving assistance systems can especially simplify the driving task (safety principle 4) and provide human error forgiveness (safety principle 5); on the contrary, few infrastructure measures can comply with these two principles. Navigation systems and speed assistance systems comply with about half of the traffic safety requirements. In general, the introduction of integrated speed assistance and (enhanced) navigation may reduce the need for and urgency of the various other systems that are being developed.

8.3.2 *Modelling and evaluation of traffic safety measures*

The developed QCC model reflects the fundamental schema of the influence of a measure on road traffic safety. The focus is on modelling the relationships between the identified elements of the causal chain (measures, determinants and factors) by coefficients. The way to identify determinants, as well as to estimate the relevant coefficients in the causal chain is not unique. More sophisticated estimation methods may be developed that better comply with the stochastic character in the chain. In general, the proposed breakdown increases the understanding of the process of the influence of a measure on traffic safety, and thereby facilitates the estimation of safety effects of various measures. The comparative analysis method that is derived from the QCC model addresses the safety effects of measures by effectiveness indices. This method is only applicable for studying safety effects of measures with similar functionality for improving traffic safety. It is particularly helpful for assessing the safety effects of a measure for which few data exist (e.g. a driving assistance system that is under development or in an early stage of deployment), by using existing data for another measure with comparable functionality (e.g. a physical infrastructure measure of which the safety effects have been thoroughly studied). The method based on the QCC model contributes to studying safety performance at a local level.

At a global level, policy evaluation of overall effects of strategic alternatives (which are generally composed of measures) for a network is needed, in which other relevant aspects than safety can be taken into account as well. The thesis proposes the normalisation based evaluation method GRA for comprehensive policy evaluation. GRA provides an easily applicable and transparent procedure to compare various alternatives with the theoretical optimal solution within the values provided by the set of considered alternatives, and to establish a clear-cut ranking order of these alternatives. It requires only relative accuracy of data within an attribute vector, and not absolute accuracy of the specific values. The purpose of GRA is not to provide a perfect method for evaluation, but a practical one. In general, it may be said that no algorithm can act as a complete substitute for human judgement.

The bi-level approach combines the comparative analysis method derived from the QCC model, and the GRA method in one comprehensive approach for assessment of the substitutability of traffic safety measures with comparable functionality.

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Appendix 1 - GRA calculation procedure for the example of Paper IV

This example provides a detailed explanation of the implementation of the nine steps of the procedure (described in Section 7.6) of the application of the GRA method. The example illustrates a policy evaluation of safety strategies at national level for The Netherlands, and is taken from Paper IV. In this case nine alternatives (or strategic scenarios) a_i (i = 1,2,…,9) and fifteen attributes k (k = 1,2,…,15) are taken into account (step 1), and operational value descriptions for the attributes are identified (step 2). Then, an evaluation matrix $i \times k$ is established (step 3). For each cell in this evaluation matrix input data are provided (see Table A1.1, except the last column).

In step 4, each alternative (implementation strategies of driving assistance and/or road infrastructure redesign) is taken as a compared series, and an additional vector, the reference series, is created from the set of compared series, based on the characteristics of the attributes. The largest value of attributes k = 1,2,…,12 (maximum value attributes), and the smallest value of attributes k = 13,14,15 (minimum value attributes) are taken to generate a reference series a_0 (see the last column of Table A1.1).

Table A1.1 - Evaluation matrix with original input data of each compared series (the alternatives), and the reference series (RS)

| attribute | alternatives (compared series) | | | | | | | | | RS |
	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_0
k = 1	14.20	5.60	19.81	16.15	6.22	25.26	16.55	6.38	22.93	25.26
k = 2	15.88	26.03	45.69	16.67	27.85	51.40	17.47	29.15	46.62	51.40
k = 3	22.55	15.41	40.19	23.68	16.49	45.21	24.81	17.26	42.07	45.21
k = 4	1	2	2	7	8	9	6	7	7	9
k = 5	1	1	1	9	9	10	8	8	8	10
k = 6	0.00	0.00	0.00	10.00	9.00	12.00	9.00	8.00	9.00	12.00
k = 7	1	1	1	3	4	5	2	3	3	5
k = 8	2	2	2	1	1	3	2	2	2	3
k = 9	2	1	1	10	10	10	7	7	7	10
k = 10	0.00	0.00	0.00	16.00	12.00	14.00	16.00	12.00	14.00	16.00
k = 11	0.00	0.00	0.00	10.00	8.00	9.00	10.00	8.00	9.00	10.00
k = 12	5	6	6	4	5	5	4	5	5	6
k = 13	1	1	1	2	2	8	2	2	2	1
k = 14	6	6	6	5	5	9	5	5	5	5
k = 15	1632.00	3215.00	4847.00	4500.00	6056.00	15056.00	6056.00	9183.00	10739.00	1632.00

As step 5 of the procedure, the linear data approach is applied, a normalisation method developed by Wu and Chen (1999), for data pre-processing by using formulae (7.1a) and (7.1b). The result is presented in Table A1.2.

In the following step 6, the absolute difference between the reference series and each compared series is calculated by using formula (7.2) for each alternative i. Table A1.3 presents the result.

In step 7, based on formula (7.3) the grey relational coefficient $\gamma (x_0(k), x_i(k))$ of attribute k is calculated for each alternative a_i (i = 1,2,…,9). The result is shown in Table A1.4.

Table A1.2 - Normalised data of each compared series and the reference series (RS)

| attribute | alternatives (compared series) | | | | | | | | | RS |
	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_0
$k = 1$	0.4374	0.0000	0.7228	0.5366	0.0315	1.0000	0.5570	0.0397	0.8815	1.0000
$k = 2$	0.0000	0.2858	0.8392	0.0222	0.3370	1.0000	0.0448	0.3736	0.8654	1.0000
$k = 3$	0.2396	0.0000	0.8315	0.2775	0.0362	1.0000	0.3154	0.0621	0.8946	1.0000
$k = 4$	0.0000	0.1250	0.1250	0.7500	0.8750	1.0000	0.6250	0.7500	0.7500	1.0000
$k = 5$	0.0000	0.0000	0.0000	0.8889	0.8889	1.0000	0.7778	0.7778	0.7778	1.0000
$k = 6$	0.0000	0.0000	0.0000	0.8333	0.7500	1.0000	0.7500	0.6667	0.7500	1.0000
$k = 7$	0.0000	0.0000	0.0000	0.5000	0.7500	1.0000	0.2500	0.5000	0.5000	1.0000
$k = 8$	0.5000	0.5000	0.5000	0.0000	0.0000	1.0000	0.5000	0.5000	0.5000	1.0000
$k = 9$	0.1111	0.0000	0.0000	1.0000	1.0000	1.0000	0.6667	0.6667	0.6667	1.0000
$k = 10$	0.0000	0.0000	0.0000	1.0000	0.7500	0.8750	1.0000	0.7500	0.8750	1.0000
$k = 11$	0.0000	0.0000	0.0000	1.0000	0.8000	0.9000	1.0000	0.8000	0.9000	1.0000
$k = 12$	0.5000	1.0000	1.0000	0.0000	0.5000	0.5000	0.0000	0.5000	0.5000	1.0000
$k = 13$	1.0000	1.0000	1.0000	0.8571	0.8571	0.0000	0.8571	0.8571	0.8571	0.0000
$k = 14$	0.7500	0.7500	0.7500	1.0000	1.0000	0.0000	1.0000	1.0000	1.0000	0.0000
$k = 15$	1.0000	0.8821	0.7605	0.7864	0.6704	0.0000	0.6704	0.4375	0.3216	0.0000

Table A1.3 - Difference, for each compared series, between the compared series and the reference series (after normalisation)

| attribute | alternatives (compared series) | | | | | | | | |
	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
$k = 1$	0.5626	1.0000	0.2772	0.4634	0.9685	0.0000	0.4430	0.9603	0.1185
$k = 2$	1.0000	0.7142	0.1608	0.9778	0.6630	0.0000	0.9552	0.6264	0.1346
$k = 3$	0.7604	1.0000	0.1685	0.7225	0.9638	0.0000	0.6846	0.9379	0.1054
$k = 4$	1.0000	0.8750	0.8750	0.2500	0.1250	0.0000	0.3750	0.2500	0.2500
$k = 5$	1.0000	1.0000	1.0000	0.1111	0.1111	0.0000	0.2222	0.2222	0.2222
$k = 6$	1.0000	1.0000	1.0000	0.1667	0.2500	0.0000	0.2500	0.3333	0.2500
$k = 7$	1.0000	1.0000	1.0000	0.5000	0.2500	0.0000	0.7500	0.5000	0.5000
$k = 8$	0.5000	0.5000	0.5000	1.0000	1.0000	0.0000	0.5000	0.5000	0.5000
$k = 9$	0.8889	1.0000	1.0000	0.0000	0.0000	0.0000	0.3333	0.3333	0.3333
$k = 10$	1.0000	1.0000	1.0000	0.0000	0.2500	0.1250	0.0000	0.2500	0.1250
$k = 11$	1.0000	1.0000	1.0000	0.0000	0.2000	0.1000	0.0000	0.2000	0.1000
$k = 12$	0.5000	0.0000	0.0000	1.0000	0.5000	0.5000	1.0000	0.5000	0.5000
$k = 13$	1.0000	1.0000	1.0000	0.8571	0.8571	0.0000	0.8571	0.8571	0.8571
$k = 14$	0.7500	0.7500	0.7500	1.0000	1.0000	0.0000	1.0000	1.0000	1.0000
$k = 15$	1.0000	0.8821	0.7605	0.7864	0.6704	0.0000	0.6704	0.4375	0.3216

If the weights of the grey relational coefficients $\gamma(x_0(k), x_i(k))$ ($i = 1,2,…,9$) for all attributes ($k = 1,2,…,15$) are equal, then the weight of $\gamma(x_0(k), x_i(k))$ is $w_0 = 1/15$ for each attribute (see Table A1.5). In Paper IV another three additional sets of weights are used for sensitivity analysis, which, for illustration are included in Table A1.5.

Finally, in step 8 the grey relational grade Γ_{0i} for each alternative a_i ($i = 1,2,…,9$) is calculated by using formula (7.4), and in step 9 the ranking of the grey relational grades provides the evaluation result: the larger the value of the grey relational grade, the better the alternative (see Table A1.6).

In Paper IV, a sensitivity analysis is performed by varying the attribute weights (see Table A1.5) and attribute values. Two attribute values are taken into account: costs and safety effects of driving assistance systems, which are estimated at low, medium and high level respectively. The example given in this appendix is based on the values of both costs and safety effects at the medium level. Note that the example in Paper IV is based on the values of costs at the medium level, and of safety effects at the high level. Furthermore, note that in Paper IV, in the GRA evaluation results, the ranking number of scenario S7 should be "6" (instead of "5"), and the ranking number of scenario S8 should be "5" (instead of "6").

Table A1.4 - Grey relational coefficient $\gamma(x_0(k), x_i(k))$ of attribute k for alternative i

attribute	alternatives (compared series)								
	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
$k = 1$	0.3200	0.2500	0.3915	0.3417	0.2540	0.5000	0.3465	0.2551	0.4470
$k = 2$	0.2500	0.2917	0.4308	0.2528	0.3047	0.5114	0.2587	0.3117	0.4495
$k = 3$	0.2840	0.2500	0.4279	0.2903	0.2546	0.5000	0.2968	0.2580	0.4523
$k = 4$	0.2500	0.2667	0.2667	0.4000	0.5000	0.5714	0.4000	0.4444	0.4444
$k = 5$	0.2500	0.2500	0.2500	0.4500	0.4500	0.5000	0.4091	0.4091	0.4091
$k = 6$	0.2500	0.2500	0.2500	0.4286	0.4000	0.5000	0.4000	0.3750	0.4000
$k = 7$	0.2500	0.2500	0.2500	0.3333	0.4000	0.5000	0.2857	0.3333	0.3333
$k = 8$	0.3333	0.3333	0.3333	0.2500	0.2500	0.5000	0.3333	0.3333	0.3333
$k = 9$	0.2647	0.2500	0.2500	0.5000	0.5000	0.5000	0.3750	0.3750	0.3750
$k = 10$	0.2500	0.2500	0.2500	0.5000	0.4000	0.4444	0.5000	0.4000	0.4444
$k = 11$	0.2500	0.2500	0.2500	0.5000	0.4167	0.4545	0.5000	0.4167	0.4545
$k = 12$	0.3333	0.5000	0.5000	0.2500	0.3333	0.3333	0.2500	0.3333	0.3333
$k = 13$	0.2500	0.2500	0.2500	0.2692	0.2692	0.5000	0.2692	0.2692	0.2692
$k = 14$	0.2857	0.2857	0.2857	0.2500	0.2500	0.5000	0.2500	0.2500	0.2500
$k = 15$	0.2500	0.2657	0.2840	0.2799	0.3221	0.5668	0.3221	0.3789	0.4154

Table A1.5 - Weights for the grey relational coefficient $\gamma(x_0(k), x_i(k))$ for each attribute k

k	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
w_0	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15
w_1	0.24	0.24	0.24	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.17
w_2	0.19	0.19	0.19	0.01	0.01	0.01	0.01	0.17	0.01	0.01	0.01	0.01	0.01	0.01	0.16
w_3	0.18	0.18	0.18	0.19	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.17

Table A1.6 - Grey relational grade Γ_{0i} of each alternative i

	alternatives								
	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
$\Gamma_{0i}(w_0)$	0.2714	0.2795	0.3113	0.3531	0.3536	0.4921	0.3464	0.3429	0.3874
rank (w_0)	9	8	7	4	3	1	5	6	2
$\Gamma_{0i}(w_1)$	0.2771	0.2665	0.3797	0.3012	0.2916	0.5121	0.3109	0.3018	0.4348
rank (w_1)	8	9	3	6	7	1	4	5	2
$\Gamma_{0i}(w_2)$	0.2853	0.2776	0.3677	0.2942	0.2878	0.5109	0.3160	0.3101	0.4165
rank (w_2)	8	9	3	6	7	1	4	5	2
$\Gamma_{0i}(w_3)$	0.2709	0.2670	0.3527	0.3202	0.3328	0.5243	0.3288	0.3323	0.4339
rank (w_3)	8	9	3	7	4	1	6	5	2

Appendix 2 - GRA calculation procedure for the example of Paper V

This example provides a detailed explanation of the implementation of the nine steps of the procedure (described in Section 7.6) of the application of the GRA method, for an extra-urban road in The Netherlands, and is taken from Paper V. In this case six alternatives (or strategic scenarios) a_i ($i = 1,2,…,6$) and forty evaluation attributes k ($k = 1,2,…,40$) are selected (step 1), and operational value descriptions for the attributes are identified (step 2). Then, an evaluation matrix $i \times k$ is established (step 3). For each cell in this evaluation matrix input data are provided (see Table A2.1, except the last column).

In step 4, each scenario is taken as a compared series, and an additional vector, the reference series, is created from each compared series, based on the characteristics of the attributes. The largest value of attributes $k = 1,2,…,37$ (maximum value attributes), and the smallest value of attributes $k = 38,39,40$ (minimum value attributes) are taken to generate a reference series a_0 (see the last column of Table A2.1).

In step 5 the linear data approach, a normalisation method developed by Wu and Chen (1999), is applied for data pre-processing, by using the formulae (7.1a) and (7.1b). The result is presented in Table A2.2.

The following step 6 is to calculate the absolute difference between the reference series and each compared series by using formula (7.2) for each alternative i. Table A2.3 presents the result.

In step 7, based on formula (7.3) the grey relational coefficients $\gamma (x_0(k), x_i(k))$ of attribute k for each alternative a_i ($i = 1,2,…,6$) are calculated. The result is shown in Table A2.4 (except the bottom two lines).

In step 8 the grey relational grade Γ_{0i} of each alternative a_i ($i = 1,2,…,6$) is calculated by using formula (7.4). In this case, weights of grey relational coefficient $\gamma (x_0(k), x_i(k))$ ($i = 1,2,…,6$) for all attributes are assumed equal, and no further sensitivity analysis is carried out. And in step 9 the ranking provides the evaluation result: the larger the value of the grey relational grade, the better the alternative (see Table A2.4 two lines at the bottom).

Table A2.1 - Evaluation matrix with original input data of each compared series (the alternatives), and the reference series (RS)

| attribute | alternatives (compared series) | | | | | | RS |
	a_1	a_2	a_3	a_4	a_5	a_6	a_0
$k = 1$	18.34	25.40	33.00	36.30	33.00	36.30	36.30
$k = 2$	25.40	35.20	46.10	47.02	46.10	47.02	47.02
$k = 3$	7.20	8.30	8.50	13.90	8.50	13.90	13.90
$k = 4$	9.80	11.80	12.10	18.50	12.10	18.50	18.50
$k = 5$	17.42	24.13	22.94	28.61	22.94	22.94	28.61
$k = 6$	24.13	33.44	33.38	34.94	33.38	33.38	34.94
$k = 7$	17.90	17.90	0.70	1.15	0.70	17.90	17.90
$k = 8$	24.80	24.80	1.40	1.50	1.40	24.80	24.80
$k = 9$	8.25	11.42	23.96	27.11	23.73	27.11	27.11
$k = 10$	11.43	15.84	33.93	37.08	33.61	37.08	37.08
$k = 11$	7.20	7.92	8.50	10.20	8.50	10.20	10.20
$k = 12$	9.80	10.29	12.10	14.52	12.10	14.52	14.52
$k = 13$	8.25	11.42	23.96	27.11	23.73	27.11	27.11
$k = 14$	11.43	15.84	33.93	37.08	33.61	37.08	37.08
$k = 15$	14.00	14.28	18.30	21.19	18.30	21.19	21.19
$k = 16$	20.00	20.40	26.10	24.10	26.10	24.10	26.10
$k = 17$	53.00	53.00	30.00	30.00	53.00	53.00	53.00
$k = 18$	75.00	75.00	42.00	42.00	75.00	75.00	75.00
$k = 19$	6.20	6.90	1.10	1.21	1.10	6.90	6.90
$k = 20$	9.20	10.20	1.10	1.11	1.10	10.20	10.20
$k = 21$	18.34	25.40	22.60	25.85	22.60	22.60	25.85
$k = 22$	25.40	35.20	32.10	36.38	32.10	32.10	36.38
$k = 23$	6.70	8.30	10.00	13.90	8.90	10.00	13.90
$k = 24$	9.90	11.80	13.30	18.50	11.80	13.30	18.50
$k = 25$	53.00	53.00	30.00	30.00	30.00	53.00	53.00
$k = 26$	75.00	75.00	42.00	42.00	42.00	75.00	75.00
$k = 27$	7.37	9.13	11.20	15.29	9.79	11.20	15.29
$k = 28$	10.89	12.98	14.63	20.35	12.98	14.63	20.35
$k = 29$	2	3	8	9	8	7	9
$k = 30$	2	1	9	10	8	7	10
$k = 31$	0.00	0.00	0.90	1.20	1.00	0.90	1.20
$k = 32$	1	1	4	5	3	4	5
$k = 33$	1	1	4	5	3	4	5
$k = 34$	2	1	10	10	6	5	10
$k = 35$	0.00	0.00	1.20	1.40	1.60	1.20	1.60
$k = 36$	0.00	0.00	0.80	1.05	1.00	0.80	1.05
$k = 37$	4	4	5	6	6	6	6
$k = 38$	1	2	3	8	1	3	1
$k = 39$	1	6	5	9	5	6	1
$k = 40$	0.92	11.42	8.40	28.45	6.28	11.29	0.92

Table A2.2 - Normalised data of each compared series and the reference series (RS)

attribute	alternatives (compared series)						RS
	a_1	a_2	a_3	a_4	a_5	a_6	a_0
$k = 1$	0.0000	0.3931	0.8163	1.0000	0.8163	1.0000	1.0000
$k = 2$	0.0000	0.4533	0.9574	1.0000	0.9574	1.0000	1.0000
$k = 3$	0.0000	0.1642	0.1940	1.0000	0.1940	1.0000	1.0000
$k = 4$	0.0000	0.2299	0.2644	1.0000	0.2644	1.0000	1.0000
$k = 5$	0.0000	0.5996	0.4933	1.0000	0.4933	0.4933	1.0000
$k = 6$	0.0000	0.8612	0.8557	1.0000	0.8557	0.8557	1.0000
$k = 7$	1.0000	1.0000	0.0000	0.0262	0.0000	1.0000	1.0000
$k = 8$	1.0000	1.0000	0.0000	0.0043	0.0000	1.0000	1.0000
$k = 9$	0.0000	0.1681	0.8330	1.0000	0.8208	1.0000	1.0000
$k = 10$	0.0000	0.1719	0.8772	1.0000	0.8647	1.0000	1.0000
$k = 11$	0.0000	0.2400	0.4333	1.0000	0.4333	1.0000	1.0000
$k = 12$	0.0000	0.1038	0.4873	1.0000	0.4873	1.0000	1.0000
$k = 13$	0.0000	0.1681	0.8330	1.0000	0.8208	1.0000	1.0000
$k = 14$	0.0000	0.1719	0.8772	1.0000	0.8647	1.0000	1.0000
$k = 15$	0.0000	0.0389	0.5981	1.0000	0.5981	1.0000	1.0000
$k = 16$	0.0000	0.0656	1.0000	0.6721	1.0000	0.6721	1.0000
$k = 17$	1.0000	1.0000	0.0000	0.0000	1.0000	1.0000	1.0000
$k = 18$	1.0000	1.0000	0.0000	0.0000	1.0000	1.0000	1.0000
$k = 19$	0.8793	1.0000	0.0000	0.0190	0.0000	1.0000	1.0000
$k = 20$	0.8901	1.0000	0.0000	0.0011	0.0000	1.0000	1.0000
$k = 21$	0.0000	0.9401	0.5672	1.0000	0.5672	0.5672	1.0000
$k = 22$	0.0000	0.8925	0.6102	1.0000	0.6102	0.6102	1.0000
$k = 23$	0.0000	0.2222	0.4583	1.0000	0.3056	0.4583	1.0000
$k = 24$	0.0000	0.2209	0.3953	1.0000	0.2209	0.3953	1.0000
$k = 25$	1.0000	1.0000	0.0000	0.0000	0.0000	1.0000	1.0000
$k = 26$	1.0000	1.0000	0.0000	0.0000	0.0000	1.0000	1.0000
$k = 27$	0.0000	0.2222	0.4836	1.0000	0.3056	0.4836	1.0000
$k = 28$	0.0000	0.2209	0.3953	1.0000	0.2209	0.3953	1.0000
$k = 29$	0.0000	0.1429	0.8571	1.0000	0.8571	0.7143	1.0000
$k = 30$	0.1111	0.0000	0.8889	1.0000	0.7778	0.6667	1.0000
$k = 31$	0.0000	0.0000	0.7500	1.0000	0.8333	0.7500	1.0000
$k = 32$	0.0000	0.0000	0.7500	1.0000	0.5000	0.7500	1.0000
$k = 33$	0.0000	0.0000	0.7500	1.0000	0.5000	0.7500	1.0000
$k = 34$	0.1111	0.0000	1.0000	1.0000	0.5556	0.4444	1.0000
$k = 35$	0.0000	0.0000	0.7500	0.8750	1.0000	0.7500	1.0000
$k = 36$	0.0000	0.0000	0.7619	1.0000	0.9524	0.7619	1.0000
$k = 37$	0.0000	0.0000	0.5000	1.0000	1.0000	1.0000	1.0000
$k = 38$	1.0000	0.8571	0.7143	0.0000	1.0000	0.7143	0.0000
$k = 39$	1.0000	0.3750	0.5000	0.0000	0.5000	0.3750	0.0000
$k = 40$	1.0000	0.6186	0.7283	0.0000	0.8053	0.6233	0.0000

Table A2.3 - Difference, for each compared series, between the compared series and the reference series (after normalisation)

attribute	alternatives (compared series)					
	a_1	a_2	a_3	a_4	a_5	a_6
$k = 1$	1.0000	0.6069	0.1837	0.0000	0.1837	0.0000
$k = 2$	1.0000	0.5467	0.0426	0.0000	0.0426	0.0000
$k = 3$	1.0000	0.8358	0.8060	0.0000	0.8060	0.0000
$k = 4$	1.0000	0.7701	0.7356	0.0000	0.7356	0.0000
$k = 5$	1.0000	0.4004	0.5067	0.0000	0.5067	0.5067
$k = 6$	1.0000	0.1388	0.1443	0.0000	0.1443	0.1443
$k = 7$	0.0000	0.0000	1.0000	0.9738	1.0000	0.0000
$k = 8$	0.0000	0.0000	1.0000	0.9957	1.0000	0.0000
$k = 9$	1.0000	0.8319	0.1670	0.0000	0.1792	0.0000
$k = 10$	1.0000	0.8281	0.1228	0.0000	0.1353	0.0000
$k = 11$	1.0000	0.7600	0.5667	0.0000	0.5667	0.0000
$k = 12$	1.0000	0.8962	0.5127	0.0000	0.5127	0.0000
$k = 13$	1.0000	0.8319	0.1670	0.0000	0.1792	0.0000
$k = 14$	1.0000	0.8281	0.1228	0.0000	0.1353	0.0000
$k = 15$	1.0000	0.9611	0.4019	0.0000	0.4019	0.0000
$k = 16$	1.0000	0.9344	0.0000	0.3279	0.0000	0.3279
$k = 17$	0.0000	0.0000	1.0000	1.0000	0.0000	0.0000
$k = 18$	0.0000	0.0000	1.0000	1.0000	0.0000	0.0000
$k = 19$	0.1207	0.0000	1.0000	0.9810	1.0000	0.0000
$k = 20$	0.1099	0.0000	1.0000	0.9989	1.0000	0.0000
$k = 21$	1.0000	0.0599	0.4328	0.0000	0.4328	0.4328
$k = 22$	1.0000	0.1075	0.3898	0.0000	0.3898	0.3898
$k = 23$	1.0000	0.7778	0.5417	0.0000	0.6944	0.5417
$k = 24$	1.0000	0.7791	0.6047	0.0000	0.7791	0.6047
$k = 25$	0.0000	0.0000	1.0000	1.0000	1.0000	0.0000
$k = 26$	0.0000	0.0000	1.0000	1.0000	1.0000	0.0000
$k = 27$	1.0000	0.7778	0.5164	0.0000	0.6944	0.5164
$k = 28$	1.0000	0.7791	0.6047	0.0000	0.7791	0.6047
$k = 29$	1.0000	0.8571	0.1429	0.0000	0.1429	0.2857
$k = 30$	0.8889	1.0000	0.1111	0.0000	0.2222	0.3333
$k = 31$	1.0000	1.0000	0.2500	0.0000	0.1667	0.2500
$k = 32$	1.0000	1.0000	0.2500	0.0000	0.5000	0.2500
$k = 33$	1.0000	1.0000	0.2500	0.0000	0.5000	0.2500
$k = 34$	0.8889	1.0000	0.0000	0.0000	0.4444	0.5556
$k = 35$	1.0000	1.0000	0.2500	0.1250	0.0000	0.2500
$k = 36$	1.0000	1.0000	0.2381	0.0000	0.0476	0.2381
$k = 37$	1.0000	1.0000	0.5000	0.0000	0.0000	0.0000
$k = 38$	1.0000	0.8571	0.7143	0.0000	1.0000	0.7143
$k = 39$	1.0000	0.3750	0.5000	0.0000	0.5000	0.3750
$k = 40$	1.0000	0.6186	0.7283	0.0000	0.8053	0.6233

Table A2.4 - Grey relational coefficient $\gamma(x_0(k), x_i(k))$ of attribute k for alternative i, and ranking based on grey relational grade Γ_{0i} of each alternative i

attribute	alternatives (compared series)					
	a_1	a_2	a_3	a_4	a_5	a_6
$k = 1$	0.5000	0.5000	0.7313	1.0000	0.8448	1.0000
$k = 2$	0.5000	0.5000	0.9216	1.0000	0.9592	1.0000
$k = 3$	0.5000	0.5000	0.5000	1.0000	0.5537	1.0000
$k = 4$	0.5000	0.5000	0.5000	1.0000	0.5762	1.0000
$k = 5$	0.5000	0.5586	0.5244	1.0000	0.9956	0.9956
$k = 6$	0.5000	0.7828	0.8443	1.0000	1.0000	1.0000
$k = 7$	1.0000	1.0000	0.5000	0.5066	0.5000	1.0000
$k = 8$	1.0000	1.0000	0.5000	0.5011	0.5000	1.0000
$k = 9$	0.5000	0.5000	0.7496	1.0000	0.8480	1.0000
$k = 10$	0.5000	0.5000	0.8028	1.0000	0.8808	1.0000
$k = 11$	0.5000	0.5000	0.5000	1.0000	0.6383	1.0000
$k = 12$	0.5000	0.5000	0.5000	1.0000	0.6611	1.0000
$k = 13$	0.5000	0.5000	0.7496	1.0000	0.8480	1.0000
$k = 14$	0.5000	0.5000	0.8028	1.0000	0.8808	1.0000
$k = 15$	0.5000	0.5000	0.5544	1.0000	0.7133	1.0000
$k = 16$	0.5000	0.5000	1.0000	0.7531	1.0000	1.0000
$k = 17$	1.0000	1.0000	0.5000	0.5000	1.0000	1.0000
$k = 18$	1.0000	1.0000	0.5000	0.5000	1.0000	1.0000
$k = 19$	0.8923	1.0000	0.5000	0.5048	0.5000	1.0000
$k = 20$	0.9010	1.0000	0.5000	0.5003	0.5000	1.0000
$k = 21$	0.5000	0.8930	0.6736	1.0000	1.0000	1.0000
$k = 22$	0.5000	0.8231	0.6786	1.0000	1.0000	1.0000
$k = 23$	0.5000	0.5000	0.5618	1.0000	0.8852	0.9730
$k = 24$	0.5000	0.5000	0.5630	1.0000	0.8431	0.9348
$k = 25$	1.0000	1.0000	0.5000	0.5000	0.5000	1.0000
$k = 26$	1.0000	1.0000	0.5000	0.5000	0.5000	1.0000
$k = 27$	0.5000	0.5000	0.5735	1.0000	0.8852	0.9892
$k = 28$	0.5000	0.5000	0.5630	1.0000	0.8431	0.9348
$k = 29$	0.5000	0.5000	0.7778	1.0000	1.0000	1.0000
$k = 30$	0.5294	0.5000	0.8265	1.0000	1.0000	1.0000
$k = 31$	0.5000	0.5000	0.6667	1.0000	1.0000	1.0000
$k = 32$	0.5000	0.5000	0.6667	1.0000	0.8333	1.0000
$k = 33$	0.5000	0.5000	0.6667	1.0000	0.8333	1.0000
$k = 34$	0.5294	0.5000	1.0000	1.0000	1.0000	0.9643
$k = 35$	0.5000	0.5000	0.6667	0.8421	1.0000	1.0000
$k = 36$	0.5000	0.5000	0.6774	1.0000	1.0000	1.0000
$k = 37$	0.5000	0.5000	0.5000	1.0000	1.0000	1.0000
$k = 38$	0.5000	0.5385	0.5833	1.0000	0.7500	0.8750
$k = 39$	0.5000	0.5714	0.5333	1.0000	0.9167	1.0000
$k = 40$	0.5000	0.5656	0.5251	1.0000	0.8309	0.9240
Γ_{0i}	0.5963	0.6308	0.6346	0.8902	0.8255	0.9898
rank	6	5	4	2	3	1