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# **Infrastructure Measures versus ADAS for Traffic Safety**

## **- Application of the Grey Relational Analysis Evaluation Method**

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### **ABSTRACT**

Two of the main approaches to improve traffic safety are extensive redesign of the physical road infrastructure and large-scale implementation of Advanced Driver Assistance Systems (ADAS). These strategies are to a large extent substitutes, but also partly complementary. This paper determines strategic road traffic safety scenarios, reviews some of the evaluation methods most commonly used in transportation research, and presents Grey Relational Analysis (GRA). GRA is a normalisation based method. It provides a simple and transparent calculation procedure from which a clear-cut ranking order of strategies derives. The application of GRA to the evaluation problem is addressed, and some preliminary results are reported, especially sensitivity analysis is discussed.

Keywords: road traffic safety, Advanced Driver Assistance Systems (ADAS), road infrastructure redesign, evaluation, normalisation, Grey Relational Analysis (GRA).

### **INTRODUCTION**

In the Netherlands in the early nineties a new concept named *Inherent Safety* originated to improve road traffic safety [Koornstra 1992]. Infrastructure related measures are the most prominent part of this Inherent Safety philosophy and are known as the concept *Duurzaam Veilige Infrastructuur* (DVI, Inherently Safe Infrastructure). It was inspired by the fact that most traffic accidents are caused by human error. To counteract this, the traffic system should be adapted to avoid unintended use of the road infrastructure, encounters at high differences in speed and direction, and uncertainty of the traffic participants. The DVI concept was further developed during the mid nineties and became an integral part of Dutch national traffic policy in 1998. DVI is an extensive and decentralised program, covering several decades and substantial investments to adapt the road network based on the principles of functionality, homogeneity and predictability, and intended to make the road more user-friendly. Main objective is to meet the ambitious Dutch policy targets for 2010: 30% reductions of fatalities and 25% of hospitalisation with respect to the 1998 figures. The DVI principles have been translated to a set of more operational requirements, from which concrete measures can be derived for adapting and upgrading the road network [CROW 1997]. A first modest implementation of DVI measures has taken place in the years 1998-2002. In the mean time doubts have arisen if the required investments will indeed bring the expected benefits.

Implementation of Advanced Driver Assistance Systems (ADAS) provides another way to improve road traffic safety. These systems support or take over vehicle driving tasks by sensing, communication and actuating devices, and are meant to improve the safety, efficiency, and comfort of driving. In previous parts of our research, five candidate ADAS functions were selected which might meet the DVI requirements, and their technical feasibility was analysed. Some state-of-the-art technologies are mature like navigation and speed assistance. Other technologies based on radar, laser, video imaging, communication and/or satellite positioning are promising, but need still considerable improvement in robustness, reliability and cost [Lu 2004].

Although complementary effects of ADAS with respect to infrastructure measures may exist, these applications may be largely considered as potential substitutes for infrastructure redesign. As such ADAS applications might offer an attractive and promising alternative to the high cost and long time scale of DVI measures. Through large-scale introduction of selected ADAS applications, safety effects may be achieved sooner and more cost-effectively, and with less negative effects as compared to DVI measures currently implemented [Lu 2003]. However, possible strategies for this approach are characterised by many uncertainties.

A next step is to build a quantitative evaluation model able to compare items of quite different nature. This paper proposes a first-time application of Grey Relational Analysis for scenario selection in the area of traffic safety. To incorporate more explicit consideration on safety into the decision-making process, a bi-level (macro and micro) decision-making model is required, which is composed by various modules. This paper focuses on a Policy Evaluation Module (PEM) and builds a macro quantitative evaluation model for comparing items of quite different nature.

Nine scenarios are designed and further elaborated for evaluation. These concern DVI only, ADAS only, and a combination of both. Costs and relevant effects (as the input of the model) have been analysed, partly based on in-depth literature study, educated estimation, and the outcome of other modules, i.e. safety performance, traffic analysis, environmental aspects, and implementation condition. The paper proposes the application of Grey Relational Analysis (GRA) for scenario selection in the area of road traffic safety and the sensitivity analysis is addressed.

## **DVI, ADAS AND COMBINED SCENARIOS TO IMPROVE TRAFFIC SAFETY**

This section addresses DVI, ADAS and combined scenarios, and the analysis of the related safety effects, costs, and relevant social, environmental, social and implementation effects.

### **DVI Strategies**

The DVI strategies are based on the results of research by the Dutch Institute for Road Safety Research (SWOV). They include all DVI measures that are currently being implemented and that are analysed in the so-called VVR project [Janssen 2003].

#### *Scenario 1 - DVI, urban*

- local road (inside built-up), in particular plain 30 km/h zones and full DV 30 km/h zones,
- distributor road (inside built-up), in particular bicycle paths or parallel roads, absence of parked vehicles, roundabouts and plateaux.

#### *Scenario 2 - DVI, rural (extra-urban excluding motorways)*

- local road (outside built-up), in particular bicycle lanes, consistent road markings and plateaux.
- distributor road (outside built-up), in particular parallel roads, carriageway dividers that are difficult to drive over, cancellation of (pedestrian) crossings, semi-paved shoulders, obstacle free zones, roundabouts, reduction of crossings and plateaux.
- regional through road (outside built-up), in particular reconstruction of road sections and junctions and shoulder protection.

#### *Scenario 3 - DVI, complete network*

- all of scenarios 1 and 2
- motorway (not studied in the VVR project)

This includes DVI measures for all urban roads, and all extra-urban roads (including rural roads and motorways). For motorways hardly any DVI measure are implemented, which is the main reason why this part of the network is not included in the VRR study.

### **ADAS Scenarios**

The definition of ADAS scenarios is based on previous research [Lu 2003]. Five ADAS functions, which might match DVI requirements, have been selected: 1) navigation with additional functionality, 2) speed assistance, 3) lane keeping assistant, 4) forward (or rear end) collision avoidance, and 5) intersection support. The technical feasibility of these functions has been demonstrated [Lu 2004]. The two basic DVI scenarios focus on urban and rural roads respectively. DVI has a quite different nature than ADAS. Therefore, to ease comparison, two ADAS scenarios are defined that match as good as possible to these two basic DVI scenarios, based on the most feasible applications from a technology maturity and/or economical feasibility (cost and feasibility of large scale implementation) point of view (functions 1, 2 and 3): a scenario for urban roads based on functions 1 and 2 (scenario 4), and a scenario for rural roads based on functions 1, 2 and 3 (scenario 5). In addition, an ADAS scenario is defined that also includes the other two selected functions 4 and 5 (scenario 6). This scenario is chosen to demonstrate the longer-term full potential of ADAS implementation for traffic safety. Due to the current status of the related technologies, large-scale implementation of functions 4 and 5, and therefore any significant realisation of scenario 6, is not to be expected before 2010. Even after 2010 this may only be possible by strong policy measures based on regulation or fiscal incentives. In contrast, the SWOV VVR project focuses on the period 1998-2010. The three ADAS scenarios are described below.

#### *Scenario 4 - ADAS, urban*

- navigation system with additional functionality (NS)
- speed assistance (SA)

The focus of DVI measures for urban roads is for a large part of speed control and for a smaller part on the provision of real-time information. These functions that can be easily by ADAS functions based on the state-of-the-art technology [Lu 2004].

#### *Scenario 5 - ADAS, rural*

- all of scenario 4
- lane keeping assistant (LKA)

The lane keeping system chosen for this analysis is based on installation of magnetic tape in the road (infrastructure component) and a magnetometer on board the vehicle for the relative positioning of the vehicle with respect to the road lay-out. This system is in general considered to be more

mature and more reliable than systems based on vision or satellite/dead reckoning/map based positioning technology [Lu 2004]. The lane keeping system could take control of the vehicle lateral position in sections of road where overtaking is not permitted, and only warn the driver on other parts of the rural road network. The system is mainly applicable for roads with 80 km/h speed limit, not for 60 km/h roads.

#### *Scenario 6 - ADAS, full*

- all of scenario 5
- lane change assistance (LCA)
- forward collision avoidance (FCA) + intersection support (IS)

Further sensitivity analysis will take automotive systems (based on sensor technology) cooperative systems (IVC or V2V communication) and magnetic lane keeping system into account. Because these designs are also relatively easier to be implemented from the current view of technology and policy.

### **Mixed DVI and ADAS Scenarios**

The definitions of mixed DVI and ADAS scenarios are based, for the ADAS part, on the-state-of-the-art technology, and assume substitution of those DVI functions whose performance can be easily or better met by ADAS functions. This is concerned with especially speed control and the self-explaining road concept. Especially realisation of the latter function is difficult to achieve in DVI, but its goals may be met to a large extent by a navigation system with additional functionality. The basic ideas behind the combination are that: 1) even ADAS applications need a good infrastructure design, based on agreed infrastructure design principles, and 2) some DVI functions cannot be matched by ADAS, e.g. roundabouts, separated bicycle routes, vehicle parking separated from the road, and a part of the functionality of roundabouts (the speed reduction function can be met by speed assistance, but the effect of possible encounters not). The related DVI elements then are kept in the scenarios, which for the ADAS part use all the elements of scenarios 4 and 5 respectively. They are partially kept in the scenarios. The third mixed scenario is a combination of scenarios 7 and 8, but extended to the whole road network, including motorways.

#### *Scenario 7 - mixed DVI and ADAS, urban road*

- all of (ADAS) scenario 4 (NS, SA)
- partial DVI on urban roads (roundabouts, separate bicycle lanes, parking places separated from carriageway)

#### *Scenario 8 - mixed DVI and ADAS, rural road*

- all of (ADAS) scenario 5 (NS, SA, LKA)
- partial DVI on rural roads (roundabouts, separate bicycle lanes, parking places separated from carriageway)

#### *Scenario 9 - mixed DVI and ADAS, complete network*

- combination of scenarios 7 and 8.

### **DETERMINATION OF EFFECTS AND COSTS**

The aim of the research is to investigate and compare the contribution of the specified DVI and ADAS scenarios to the improvement of road traffic safety. These scenarios also have impacts on

other factors than mere traffic safety, especially related to social, environmental, and economical aspects, and implementation impediments. A comprehensive evaluation should include these, as well as cost. These factors are taken as main categories of criteria, for each of which one or more sub-criteria or attributes are defined. Criteria, attributes and an operational value description for each attribute are given in Table 1. If an attribute cannot be easily expressed in a measurement unit, a score with scale 1 to 10 is defined for the attribute.

**Table 1** - Criteria, attributes and operational value descriptions

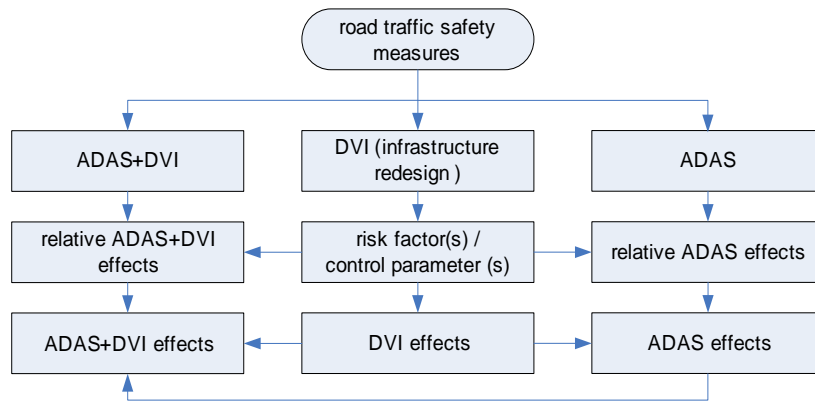
criteria	attributes	operational value description
social aspect	accident frequency	total accident reduction rate (1998-2010)
	accident severity	total fatality reduction rate (1998-2010)
		total hospitalisation reduction rate (1998-2010)
	comfort & convenience	rated from 1 to 10, a higher grade means more comfortable and convenient
emergency services	rated from 1 to 10, a higher grade indicates better for the emergency services	
environmental aspect	reduce emissions	total reduction rate of CO, NOx and HC
	reduce noise	rated from 1 to 10, a higher grade means higher noise reduction
economic aspect	network capacity	rated from 1 to 10, a higher grade indicates higher contribution for the capacity
	land use	rated from 1 to 10, a lower grade means more extra physical space needed for realisation
	reduce fuel consumption	percentage reduction of fuel consumption
	time saving	total travel time reduction rate
implementation difficulty	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 a easier to implement the policy
cost	costs	total NPV in 1million EUR (2000)

The values of the attributes for the nine scenarios are estimated based on review of relevant literature and experts' knowledge. The two safety-related attributes are accident frequency and accident severity. The safety effects of infrastructure measures have been studied by the Dutch Institute for Road safety Research (SWOV) [Janssen 2003]. This study covers the period 1998-2010, and the results allow good estimates of the values of these two attributes for the three DVI scenarios. The safety effects of ADAS are derived from these values by estimating the causal relationships, as depicted in Figure 1.

Instead of finding absolute values for the effects of ADAS scenarios, the relative effects of ADAS compared to DVI are estimated, with the assumption that good estimates for the DVI effects exist. The relative effects are estimated for the different categories of roads that are distinguished in the DVI scenarios, i.e. urban, rural and national (national includes urban and rural, and in addition motorways). This procedure requires an extensive study of both DVI and ADAS measures, of the underlying parameters, and finally an estimation of the causal links.

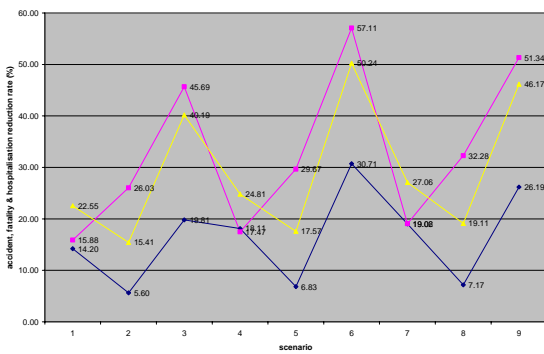
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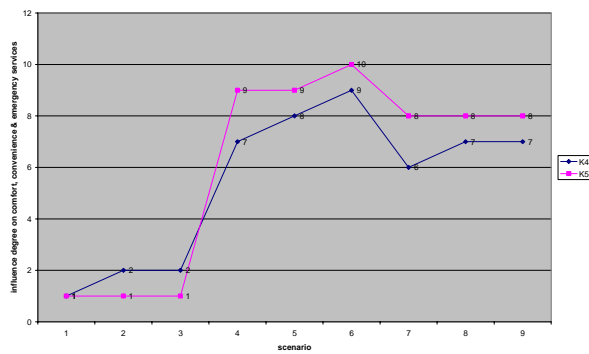


**Figure 1** - Causal relationships for the estimation of safety effects of ADAS

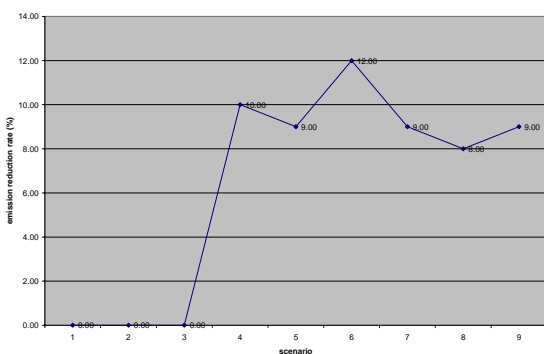
The resulting values for the various attributes for each of the nine scenarios are presented in the Figures 2 to 9 below, and also shown in Table 2.



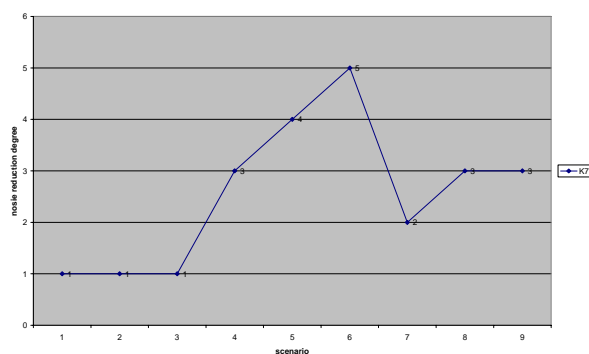
**Figure 2** - Safety aspects  
 K1 accident reduction rate  
 K2 fatality reduction rate  
 K3 hospitalization reduction rate



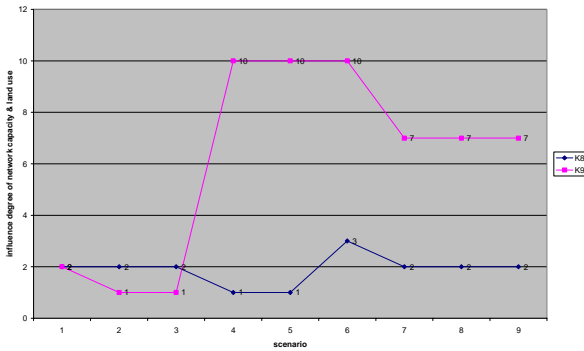
**Figure 3** - Other social aspects  
 K4 comfort & convenience degree  
 K5 emergency services degree



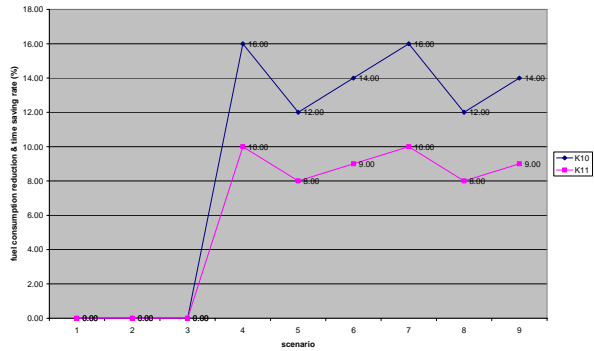
**Figure 4** - Emissions reduction  
 K6 emissions reduction rate



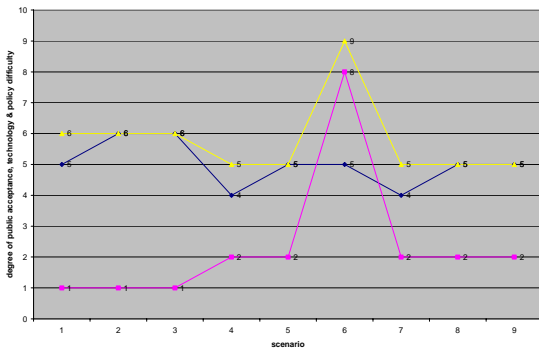
**Figure 5** - Noise reduction  
 K7 noise reduction degree



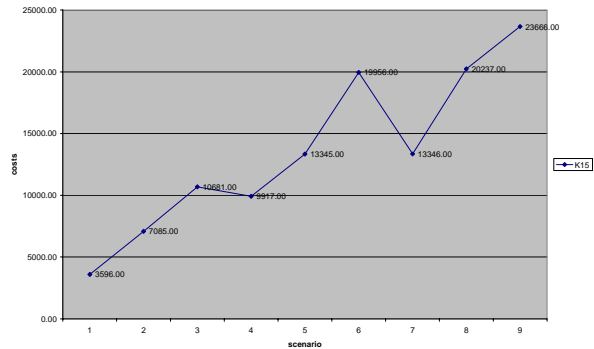
**Figure 6 - Economic aspects (A)**  
 K8 network capacity degree  
 K9 land use degree



**Figure 7 - Economic aspects (B)**  
 K10 fuel consumption  
 K11 time saving



**Figure 8 - Implementation difficulty**  
 K12 public acceptance  
 K13 technology difficulty  
 K14 policy difficulty



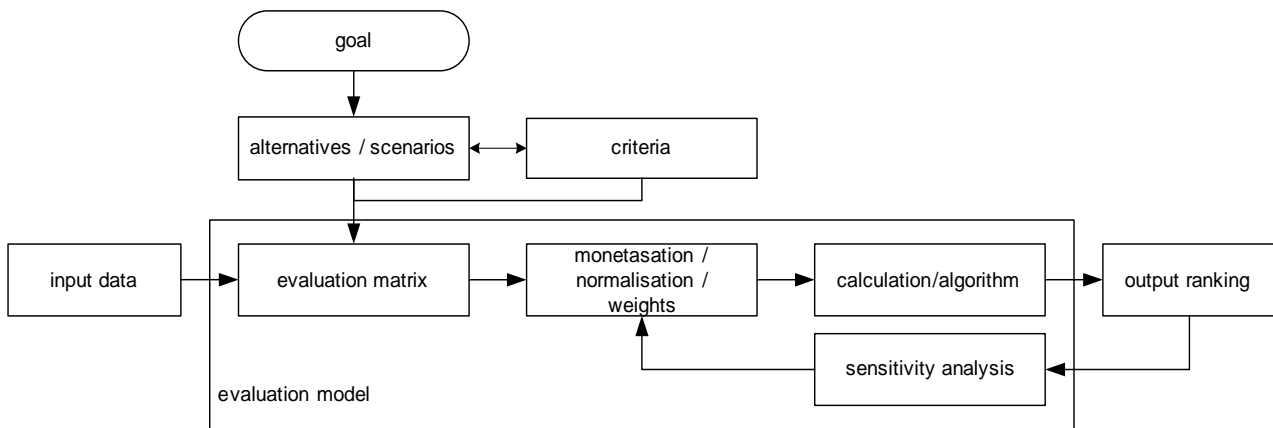
**Figure 9 - Costs**  
 K15 costs

For further elaboration and comparison of these scenarios, and to evaluate which are the best options for decision support on alternative investment strategies, an adequate evaluation is needed. The following section provides an overview of relevant evaluation methods.

## EVALUATION METHODS

In general an evaluation method (also called decision support method) provides a recipe for analysis and ranking of different available alternatives for achieving a certain goal or objective. A list of relevant attributes of the alternatives is established, creating a matrix of alternatives and attributes. For each relevant cell of this matrix, a value is established (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 all alternative vectors in a coherent way to appropriate scalar values, after which the best or optimal alternative can be determined (the alternative with the highest resulting value). Alternatively the relative ranking of the alternatives based on the resulting values may be used for allocation purposes. A major problem in evaluation is that it is generally impossible to express the relevant attributes in the same unit, which make the calculation of an overall result per alternative difficult or even not feasible. The evaluation process is depicted in Figure 10. Attributes may be expressed in cardinal or ordinal units, measurement units or scores. An evaluation method may also try to pursue more than one objective, creating essentially a cubic array of alternatives, attributes and objectives, which makes only sense if certain attributes will obtain different values and/or weights for different objectives.





**Figure 10** - Evaluation process

Two major categories of evaluation methods may be distinguished.

*Economics based methods* express attribute values as much as possible in a monetary unit as an objective weight measure. The most well-known method in this category is Cost-Benefit Analysis (CBA) which uses a monetary unit for all attributes. Cost-Effectiveness Analysis (CEA) is a more flexible variant of CBA, which expresses costs in a monetary unit, but benefits in other real units, as it is often difficult to express these in a monetary unit. Other variants of CBA are Cost-Utility Analysis (CUA), environmental impact reviews, profitability assessment and fiscal impact analysis. Planning Balance Sheet (PBS) and Goals-Achievement Matrix (GAM) are extended monetary methods that express part of the attributes in monetary terms, and other attributes in non-monetary real units or as objective weights. CBA and its derivatives require use of NPVs (net present values) for monetary units, but are often applied in less strict sense by using budget values. By allowing more than one and incomparable units, each of the CBA derivatives limit the result of the analysis to gaining a better qualitative insight. See appendix 1 for a concise description of some of these methods.

*Normalisation based methods* originated in an attempt to overcome the fact that it is difficult and often impossible to express multiple attributes of different nature in one common unit (monetary or other), and because of the lack of adequate techniques to process a set of attributes which are expressed in a range of different units. These methods completely abstain from putting efforts in valuing benefits and costs, or defining better methods to do this. Instead, they apply a normalisation to the attribute vectors. This transformation to dimensionless values enables to compare attributes of different character. In addition, in most cases (but at choice) a set of subjective weights is applied to the attribute categories. Based some specific further processing, each method provides ranking order, which is however not always clear-cut for every method. These methods are generally referred to as Multi-Criteria Analysis (MCA) methods. Some well-known methods in this category are Analytical Hierarchy Process (AHP), Simple Additive Weighting (SAW), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), ELimination Et Choix Traduisant la Réalité method (ELECTRE, elimination and choice translating the reality), Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE), and fuzzy evaluation. See appendix 1 for a concise description of these methods.

Each method in both categories has its advantages and limitations. No method is able to provide fully satisfying results, and there is often room for arguments. All methods try to provide a ranking of alternatives, by calculating a resulting number per alternative. The economics based methods ex-

press attribute values as much as possible in a monetary unit. This appears to be very difficult in practice, but the less stringent this condition is applied, the more difficult it becomes to obtain a clear analytical answer. The normalisation based methods try to remove the issue of incomparable units, but none of them is founded on a fundamental theory. Each of these methods is in fact no more than an advanced calculation recipe, and not every method is always able to provide an unambiguous order.

As an alternative to the above mentioned methods, in this study, Grey Relational Analysis (GRA) is introduced, a normalisation based evaluation and ranking method that originated and is still mainly used in China. Section 4 introduces the method, and provides some arguments why this method deserves some more attention, and a place in the list of normalisation based methods. Section 5 explains the recipe of GRA by applying the method to the problem formulated in section 2.

## GREY RELATIONAL ANALYSIS AND APPLICATION

### Introduction

Grey system theory was developed in 1982 by J.L. Deng in China [Deng 1982], and aims, in general, to describe and analyse abstract systems, which are based on logical reasoning. The term grey stands for poor, incomplete and uncertain, and is especially used in relation to the concept of information. To substantiate the structural characteristics of a system, information concerning the system needs to be processed. Grey system theory tries to deal with situations where such information is incomplete or unreliable. Grey Relational Analysis (GRA) is a derived evaluation model which is based on the concept of grey relational space (GRS), one of the elements of grey system theory. Presently, GRA is mainly applied in mainland China and Taiwan [Wang 1985, Ma 1988, Sun 1999, Lin 1999, Lin 2001], and hardly known in western countries, although sometimes attempts are made for wider dissemination [Lin & Liu 2004].

### GRA Evaluation Method

In GRA, the attributes may be of any relevant category, and the original units may be applied. Like in other normalisation based methods, a matrix of  $i$  alternatives and  $k$  attributes is created, and the attribute vectors need to be expressed in dimensionless (hence comparable) units and similar scales. Different approaches for normalisation may be used.

The GRA community has seen quite extensive discussions on normalisation, the so-called data pre-processing, to prove that the original and the resulting attribute vectors have a linear relationship, without any distortion [Deng 1998, Wu & Chen 1999, Chang 2000]. See Appendix 2 for some details of the different normalisation approaches used in GRA. In this paper the normalisation method of Wu & Cheng [1999] is adopted. The main reason for this is the fact that "this normalisation method solves the difficulties of providing a value for the distinguishing factor to determine the grey relational coefficients (see formula (5)), and of providing subjective weights to determine the grey relational grades.

The method of [Wu & Chen 1999] takes into account the type of the attribute (benefit, costs or optimisation), and normalises to a scale [0,1]. For benefit type attributes the formula is:

$$x_i^*(k) = \frac{x_i(k) - \min_k x_i(k)}{\max_k x_i(k) - \min_k x_i(k)} \quad (1)$$

where  $\max_k x_i(k)$  is the maximum value of attribute  $k$  for alternative  $i$ , and  $\min_k x_i(k)$  is the minimum value of attribute  $k$  for alternative  $i$ . For cost type attributes the formula is:

$$x_i^*(k) = \frac{\max_k x_i(k) - x_i(k)}{\max_k x_i(k) - \min_k x_i(k)} \quad (2)$$

and for optimisation attributes, and attributes with a clearly defined targeted value:

$$x_i^*(k) = 1 - \frac{|x_i(k) - x_{ob}(k)|}{\max\{\max_k x_i(k) - x_{ob}(k), x_{ob}(k) - \min_k x_i(k)\}} \quad (3)$$

where  $x_{ob}(k)$  denotes the targeted (objective) value of attribute  $k$ , which can be determined, e.g. by a certain policy goal.

Then the so-called reference series (or vector of best values) is identified. Which value for a certain attribute defines the value of the reference series depends on the type of the attribute. In general for a benefit type attribute the highest value is taken, for a cost type attribute the lowest value, and for the 'targeted value' category the predetermined preferred or optimal value.

For each alternative vector (in GRA also called a compared series, because each alternative vector is compared with the reference series) the difference of the reference vector and the alternative vector is calculated:

$$\Delta_{0i}(k) = |x_0(k) - x_i(k)|, \quad k = 1, 2, 3, \dots, n \quad (4)$$

Such difference for alternative  $i$  and attribute  $k$  is called the grey relational coefficient for that attribute at point  $k$ . The grey relational coefficient for each element of an alternative vector or compared series is defined as:

$$\gamma(x_0(k), x_i(k)) = \frac{\min_{i,k} |x_0(k) - x_i(k)| + \zeta \max_{i,k} |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \zeta \max_{i,k} |x_0(k) - x_i(k)|} \quad (5)$$

where  $\gamma(x_0(k), x_i(k))$  denotes grey relational coefficient of attribute  $k$  for alternative  $i$ ,  $x_0(k)$  denotes the element of the referential series for attribute  $k$ ,  $x_i(k)$  denotes the element of the compared series for attribute  $k$ , and  $\zeta \in (0,1)$  denotes the so-called identification or distinguishing coefficient [Guo 1985, Deng 1989]. A larger value of this coefficient increases the differences between the values of the coefficients in each attribute vector, and therefore the differences of the values within the ranking vector. This coefficient and its value has been the subject of extensive discussion. It has been argued that its value can be set equal to 1 if the normalisation of [Wu & Chen 1999] is used.

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

$$\Gamma_{0i} = \sum_{k=1}^n w_k \gamma_{0i}(k) \quad (6)$$

where  $w_k$  is the  $k$ -th weight of  $\gamma_{0i} = \gamma(x_0(k), x_i(k))$ .

The grey relational grade of a compared series provides a measure of how good this series is compared with the reference series, which is based on the best values for each attribute over all alternatives. In a first approximation (or if they are not relevant) the weights may be put all equal to  $w_k = 1/n$ , and variation of the weights may be used for sensitivity analysis. The set of grey relational grades for the different alternatives provides the ranking vector for these alternatives.

An alternative procedure is to first sum the grey relational coefficients for each alternative, and apply the weights already in the calculation of the grey relational coefficient, by replacing the first term of the denominator of formula (5):

$$\sum_{k=1}^n w_k |x_0(k) - x_i(k)| \quad (7)$$

Then the grey relational grade for the series is calculated. The resulting ranking order is the same.

### Discussion of GRA

The normalisation based GRA evaluation method provides a simple and transparent calculation procedure to compare various alternatives with the theoretical optimal solution within the values provided by the set of all considered alternatives, and to establish a clear-cut ranking order of these alternatives. Attribute values can be used in their original values, and a normalisation is generally applied to these values.

The most general normalisation procedures applied in normalisation based methods are linear normalisation and vector normalisation, but other procedures are applied as well, as e.g. in AHP and PROMETHEE. A discussion of why a particular normalisation procedure is used, as well as its influence on the data series and their interrelationships, is generally omitted. However, the choice of a particular normalisation procedure may in fact have an influence on the obtained ranking. In contrast, in the GRA literature there is abundant discussion about why a particular part of the method is used, as well as about the influence of the applied normalisation (the so-called data pre-processing) on the data series and their interrelationships. GRA applies a method of linear normalisation which is slightly more sophisticated than what is normally called linear normalisation. It is proven [Chang 2000] that this procedure does not affect the interrelationships between the data series, and therefore provides a robust result.

In GRA it is argued [Deng 1989] that no normalisation needs to be applied (implying that the values are directly comparable) if the original input attributes satisfy three conditions: 1) the difference between the maximum and minimum input values (taken over all attributes) is less than an order of magnitude of two; 2) all attributes are of the same type (benefit, cost, or maximum value); and 3) all attributes have the same measurement scale, and if it is a quantitative scale, have the same unit. In the GRA literature these conditions are (in not so clear terminology) referred to as *scaling* (for the order of magnitude), *polarisation* (for the attribute type), and *non-dimension* (for the measurement scale). However, a clear proof of this argument has not been given. In the problem case to which GRA is applied in this paper, the input data have different measurement scales, which imply that the alternatives cannot be directly compared without normalisation.

Except GRA, all other normalisation based methods apply weighting of the attributes together with normalisation in the beginning of the procedure. A weight is a subjective judgement about the importance of an attribute as compared to other attributes. This subjective step is accepted, because an

objective solution is not possible. GRA does not necessarily use weighting, although it may be applied as a last step.

Sensitivity analysis is a core aspect of economics based methods, and is done by variation of the input values and the internal return rate. Normalisation based methods on the other hand generally abstain from sensitivity analysis. In GRA a sensitivity analysis of the results may be performed by adding or removing attributes, and, when there is considerable uncertainty about the accuracy of certain input values, by variation of these. This paper proposes to also use weights as a last step in the GRA procedure as one of the parameters for such sensitivity analysis.

Of the other methods discussed in this paper, GRA is most close to TOPSIS, which however also applies weights at an early stage, and provides three ranking measures that may give conflicting rankings. Like in TOPSIS, GRA also calculates a kind of "separation measure" from the best possible or "positive-ideal" solution within the set. There is however an essential difference between the analyses applied in GRA and TOPSIS. In the latter method the separation measure considers only a (the square root of a) summation of (the squares of) the differences per attribute. This is comparable to the first part in the denominator in formula (5). GRA on the other hand takes also into account the characteristics of the whole series, which is expressed by the numerator and the second part of the denominator of formula (5).

The GRA method requires only relative accuracy of attribute values within each attribute vector, and not absolute accuracy, which provides an essential difference of this method with the economics based methods, and some of the normalisation based methods like ELECTRE and TOPSIS. This is an advantage for the problem case of this paper, as attribute values for the ADAS scenarios are difficult to obtain, and will be estimated relative to the DVI scenarios. Another advantage of GRA is that it allows also negative values for attributes [Chang 2000], while other normalisation methods generally have a problem to cope with negative values. This may be of use for the referenced application, for which some of the attributes may indeed exhibit negative values, like emission reduction, noise reduction, network capacity, land use, fuel consumption and time saving.

In the current model the groups who gain and pay are mixed, and these may be separated by extending GRA with elements of the evaluation framework provided by the PBS and GAM approaches. As the proposed procedure of GRA is very robust, the method may also be easily extended to cover multi-objective evaluation problems. [Jiang 1993, Wu & Wen 1999]

In general, GRA includes some of the positive aspects of both economics and normalisation based methods, and besides this has its own unique characteristics for evaluation. Nevertheless, also GRA is not a perfect method. GRA is presented in the context of the following statement of Morris Hill: "If it does not sufficiently inform the decision-makers and the public so that they can use the information provided in order to arrive at a more rational decision, evaluation is an academic exercise. For this purpose, evaluation will have to be more contexts responsive." [Hill 1985]

## **APPLICATION OF GRA**

### **GRA Application in Nine Steps**

In this section, the GRA method is applied to the problem that was defined in section 2. The process of evaluating the various ADAS and DVI implementation strategies by the application of GRA may be summarised by the following steps:

1. Establish the relevant alternatives, and criteria and attributes (sub-criteria). Alternatives are the scenarios of ADAS, DVI, and some appropriate combinations, criteria include social, environmental, economic and implementation aspects (benefits and costs; Table 1).
2. Give operational definitions for the criteria and attributes to enable the specification of values for each alternative (Table 1).
3. Establish values and create the attributes ( $k$ ) versus alternatives ( $i$ ) matrix ( $k \times i$ ) (Table 2).
4. Identify the reference series (the ideal alternative), taking into account the (benefit or cost) character of each attribute (Table 2).
5. Normalise the input data by using the formulas (1), (2) and (3).
6. Calculate the absolute difference the between reference and each compared series by using formula (4) for each alternative  $i$ .
7. Calculate  $\gamma(x_0(k), x_i(k))$  for each difference series, and the grey relational grades  $\Gamma_{oi}$  by formulae (5) and (6) (Table 2).
8. Rank the alternative scenarios based on the grey relational grades (Table 2). The ranking provides the evaluation result.
9. Do sensitivity analysis and explain the evaluation result (Table 3).

Part of the output form is presented in Table 2 and Table 3.

**Table 2** - Outline of output form for GRA results

$k$	scenarios → attributes ↓	DVI			ADAS			ADAS & DVI		
		S1 urban	S 2 rural	S3 nation	S4 urban	S5 rural	S6 nation	S7 urban	S8 rural	S9 nation
1	accident red %	14.20	5.60	19.81	16.15	6.22	25.26	16.55	6.38	22.93
2	fatality reduction %	15.88	26.03	45.69	17.47	29.67	57.11	19.06	32.28	51.34
3	hospital. reduction.%	22.55	15.41	40.19	24.81	17.57	50.24	27.06	19.11	46.17
4	comfort & convenient	1	2	2	7	8	9	6	7	7
5	emergency	1	1	1	9	9	10	8	8	8
6	emission reduction%	0.00	0.00	0.00	1.00	0.90	1.20	0.90	0.80	0.90
7	reduce noise	1	1	1	3	4	5	2	3	3
8	network capacity	2	2	2	1	1	3	2	2	2
9	land use	2	1	1	10	10	10	7	7	7
10	fuel consumption %	0.00	0.00	0.00	1.60	1.20	1.40	1.60	1.20	1.40
11	total time spend %	0.00	0.00	0.00	1.00	0.80	0.90	1.00	0.80	0.90
12	pub acceptance	5	6	6	4	5	5	4	5	5
13	tech difficulty	1	1	1	2	2	8	2	2	2
14	policy difficulty	6	6	6	5	5	9	5	5	5
15	costs (mil. EUR)	1632	3215	4847	4500	6056	15056	6056	9183	10739
	$\Gamma_{oi}$	0.2714	0.2795	0.3113	0.3531	0.3536	0.4921	0.3464	0.3429	0.3874
	rank	9	8	7	4	3	1	5	6	2

The result of ranking shows the following priority sequence of the nine scenarios from high to low, denoted in the special GRA notation:

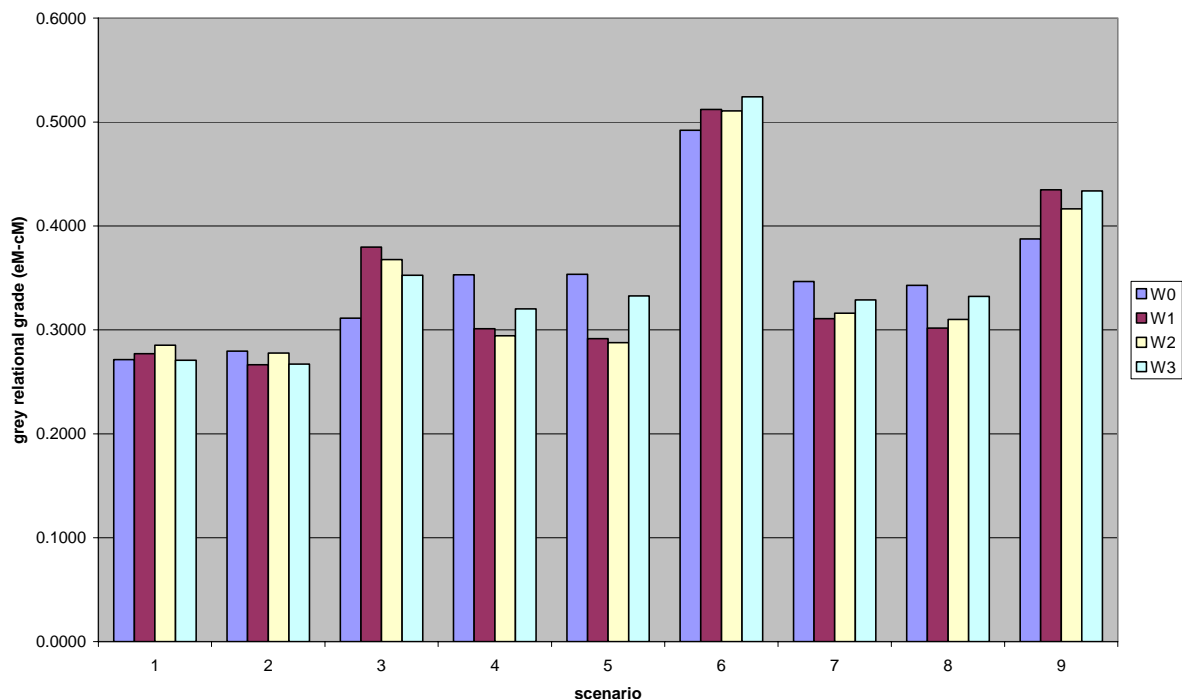
$$S6 \succ S5 \succ S9 \succ S5 \succ S4 \succ S7 \succ S8 \succ S3 \succ S2 \succ S1.$$

### Sensitivity Analysis

A sensitivity analysis has been performed by varying two parameters, attribute weights and attribute values. No addition or removal of attributes has been tested.

A strategy for sensitivity analysis based on weights has been developed. The weight vector cannot be obtained by modelling, but may be obtained from experts views, or e.g. by applying AHP or other normalisation based methods. The preliminary result (see Table 2 and Figure 11) assumes that the weights for each attribute are equal (W0). Based on unequal weights, two groups of weights for attributes 1 to 15 are determined by experts:

k	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
W1	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
W2	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
W3	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



**Figure 11** - Sensitivity analysis by weighting

- W0 weights for each attribute are equal
- W1 safety oriented weights
- W2 safety and economy oriented weights
- W3 safety, comfort and convenient oriented weights

Another sensitivity analysis is by varying ADAS costs estimation, and safety effects of ADAS estimation at low (L), medium (M) and high (H) level respectively, denoted as:

$C_{ADAS}$  - costs of full ADAS (S6)

$E_{ADAS}$  - safety effects (accident frequency, fatality and hospitalisation) of ADAS applications compared with DVI implementations (S4, S5, S6)

Table 3 provides a summary of the evaluation results produced by the application of GRA to the stated problem, including the sensitivity analysis.

**Table 3** - GRA evaluation results

C <sub>ADAS</sub>	weights	E <sub>ADAS</sub>																										
		L						M						H														
L	w0	1	8	7	4	3	1	5	6	2	5	8	7	4	3	1	6	5	2	5	8	7	4	3	1	6	5	2
	w1	1	9	3	6	7	2	4	5	1	8	5	3	6	7	1	5	4	2	8	5	3	7	6	1	5	4	2
	w2	1	9	3	6	8	1	5	4	2	8	5	3	6	7	1	5	4	2	8	5	3	7	6	1	5	4	2
	w3	1	9	3	7	5	1	6	4	2	8	5	3	7	5	1	6	4	2	5	8	6	7	4	1	5	3	2
M	w0	1	8	7	3	4	1	5	6	2	5	8	7	4	3	1	5	6	2	5	8	7	4	3	1	5	6	2
	w1	1	9	3	5	7	1	4	6	2	8	5	3	6	7	1	4	5	2	8	5	3	6	7	1	4	5	2
	w2	1	9	3	6	8	1	4	5	2	8	5	3	6	7	1	4	5	2	8	5	3	6	7	1	4	5	2
	w3	1	9	3	7	4	1	5	6	2	8	5	3	7	4	1	5	6	2	8	5	5	7	4	1	6	3	2
H	w0	1	8	7	3	4	1	5	6	2	5	8	7	3	4	1	5	6	2	5	8	7	4	3	1	5	6	2
	w1	1	9	3	5	7	1	4	6	2	8	5	3	5	7	1	4	6	2	8	5	3	5	7	1	4	6	2
	w2	1	9	3	6	8	1	4	5	2	8	5	3	6	7	1	4	5	2	8	5	3	6	7	1	4	5	2
	w3	1	9	3	6	4	1	5	7	2	8	5	3	7	4	1	5	6	2	8	5	4	7	3	1	6	5	2
scenario no.		2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	
road categ.	1	r	r	u	r	r	u	r	r	u	r	r	u	r	r	u	r	r	u	r	r	u	r	r	u	r	r	
scenario type		DVI	ADAS	comb.		DVI	ADAS	comb.		DVI	ADAS	comb.		DVI	ADAS	comb.												

**DISCUSSION OF RESULTS**

The measures of DVI perform better on urban roads (S1) than on rural roads (S2) for weights scenarios w1 (safety oriented), w2 (safety and economy oriented), and w3 (safety, comfort and convenience oriented), denoted as  $S1 \succ S2$ . Only when the weights for all attributes are take as equal (weights scenario w0), a reversed conclusion can be drawn, denoted as  $S2 \succ S1$ . ADAS applications perform better on the rural or urban roads depend on various weights. In the cases of w0 and w3, ADAS measures perform better on rural roads than on urban roads, denoted as  $S5 \succ S4$ ; in the other cases (w1 and w2)  $S4 \succ S5$ . The combined ADAS/DVI scenario for urban roads (S7) in general performs better than the one for rural roads (S8), denoted as  $S7 \succ S8$ .

On urban roads the combined ADAS/DVI scenario (S7), in general, performs better than the ADAS scenario (S4), and the latter is better than the DVI scenario (S1), denoted as  $S7 \succ S4 \succ S1$ , except for equal weights scenario (w0). In this case, the priority sequence changes to  $S4 \succ S7 \succ S1$ , which implies that the pure ADAS strategy is better than the combination strategy.

On rural roads, the ADAS scenario (S5) performs better than the combined of ADAS/DVI scenario (S8), and the later is better than the DVI scenario (S2), denoted as  $S5 \succ S8 \succ S2$ , for the weights scenarios w0 (all weights equal), and for part of w3 (safety, comfort and convenience oriented, i.e. EL-CM, EM-CM and EM-CH). The priority sequence changes to  $S8 \succ S5 \succ S2$  for all cases of the weight scenarios w1, w2 and part of w3.

In a similar way, conclusions can be drawn with respect to the scenarios for the complete network (S3, S6, S9). Both the ADAS scenario (S6) and the combined ADAS/DVI scenario (S9) perform better than the DVI scenario (S3). In most cases, except when  $E_{ADAS}$  is low,  $C_{ADAS}$  is low and the weights scenario is w1, the full ADAS scenario is the best possible strategy, denoted as  $S6 \succ S9 \succ S3$ .



## CONCLUSIONS

In this paper a comparison is made between the effects on traffic safety of infrastructure related measures according to the Dutch DVI programme, and of the implementation of ADAS applications. Both for DVI and for ADAS an urban, a rural and a national scenario is designed. In addition three combined scenarios were defined. These nine scenarios were analysed with Grey Relational Analysis (GRA).

GRA is a normalisation based evaluation method that is mainly used in the Chinese-speaking areas. The paper explains the essentials of GRA. The GRA evaluation method provides a simple and transparent calculation procedure to compare various alternatives with the theoretical optimal solution within the values provided by the set of all considered alternatives, and to establish a clear-cut ranking order of these alternatives. By applying GRA, much less efforts are put for determining the accurate value of each attributes. In GRA, abundant discussion is on data pre-processing (normalisation) for proving that this procedure does not affect the interrelationships between the data series, and therefore provides a robust result. The linear normalisation applied in GRA is slightly more sophisticated than in other normalisation based methods. Another distinguished advantage of GRA is that the input data (original values for attributes) of a series can be (mixed) positive and negative value. The GRA evaluation model can be easily extended to cover multi-objective evaluation problems. However, GRA, as well as other normalisation-based methods does not based on a fundamental theory or the theory itself is still not completely “white”. As other evaluation methods GRA is no more than an advanced calculation recipe, and is not always able to provide an unambiguous order. There are considerable uncertainties in the evaluation process. To deal with this problem, this paper proposes sensitivity analysis by adding or removing attributes, by variation of certain input values and weights of the attributes. We argue to use weights as a last step in the GRA procedure for sensitivity analysis in order to keep the original evaluation results objective, and make the evaluation process logical and transparent.

The result clearly indicates that for improving traffic safety, the ADAS scenarios (S4, S5, S6) and the combined ADAS/DVI scenarios (S7, S8, S9) are better than the DVI scenarios (S1, S2, S3), taking into account all criteria (costs as well as the social, economic, environmental and implementation effects). In general, ADAS measures perform better than DVI measures to enhance road traffic safety. However, implementation of such scenario is not feasible before 2010, in the first place because of technology issues, but also because of policy issues. Therefore, the best recommendation at a national level would be to implement scenario S9 (the combination of ADAS and DVI).

A crucial point to keep in mind is that ADAS applications need a good infrastructure design, based on agreed infrastructure design principles. An evaluation method provides a tool for assisting decision making, but no algorithm can act as a complete substitute for human judgement.

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## APPENDIX 1 - Overview of Prevailing Evaluation Methods

The following two tables provide summary overviews of the most common and popular economics based and normalisation based evaluation methods respectively.

### Summary overview of some common economics based methods

<b>CBA</b> origin	Cost-Benefit Analysis 1844 (France); first serious applications stimulated by US Flood Control Act of 1936
approach	(1) express all benefits and costs in monetary terms; (2) calculate benefit-cost ratio for each alternative; (3) rank
characteristics	efficiency is defined in terms of maximisation of general welfare, and evaluated based on Pareto criterion (welfare is increased when a change makes at least one person better off and no-one worse off)
comments	fundamental theory based exact approach; cannot deliver this exactness in practical reality due to various severe limitations; requires high accuracy of the monetised input
<b>CEA</b> objective	Cost-Effectiveness Analysis to overcome some of the difficulties of CBA
approach	(1) express benefits in relevant non-monetary unit; (2) calculate effectiveness-cost ratio per alternative
comments	clear-cut ranking order generally not possible when two or more effects are included
<b>PBS</b> founder/year	Planning Balance Sheet N. Lichfield, 1956
objectives	to overcome some of the difficulties of CBA; to enable community to choose plan that will maximise the achievement of community welfare goals
approach	(1) separate impacts of each alternative for different groups (avoid double counting); (2) express costs and benefits in monetary unit if possible, or otherwise in any physical unit, score, or even in descriptive terms; (3) no calculation of rank order, but use of matrix to support understanding of impacts for different groups
comments	only high level goal addressed, while impacts only have meaning in relation to a well-defined objective; resource allocation cannot be resolved in case of conflicting goals or interests
<b>GAM</b> founder/year	Goal Achievements Matrix M. Hill, 1968
objectives	to overcome some of the difficulties of CBA; to view costs and benefits always in terms of achievement of operational rather than abstract goals
approach	(1) establish applicable unit of measurement for each identifiable goal, in quantitative, or otherwise in qualitative terms; (2) per alternative (course of action) create a matrix of goals versus affected groups or sectors; (3) benefits increase and costs decrease the state of achievement of a goal (compensatory character, trade-offs are possible), and may be summed up if expressed in the same unit; (4) per goal identify the relative weights of the groups, and identify the relative weights of each of the goals with respect to the other goals;
comments	if all objectives could be expressed in the same unit, the result would resemble a weighted variant of CBA (but not necessarily in monetary terms); comparison of goals expressed in different units remains a problem; it is assumed that weights can be established objectively, which is often not the case in reality; the method does not accommodate for interdependence of objectives; while the method is quite capable to express complexity of decision problems, it is also itself complex and thereby costly, and does not easily give a clear evaluation result

### Summary overview of some common economics based methods

<b>AHP</b> founder/year	Analytic Hierarchy Process T.L. Saaty, 1980
characteristics	use of a special approach for normalisation
approach	(1) per attribute establish the relative importance (weight) of each alternative by pairwise comparison, using a fixed scale of scores ranging from 1 to 9 and their

comments	<p>reciprocals; (2) from the scores calculate a weight vector for each of the attributes, expressing the weight per attribute of the different alternatives (so-called eigenvector calculation, for which different approaches are in use); (3) use same method (scoring and weight vector calculation) to establish weight vector for the attributes; (4) multiply attribute weight and alternative weight for that particular attribute, and sum the results per alternative, providing an overall priority score for each of the alternative, which can be used for ranking</p> <p>an advantage is the clear hierarchical structuring of the decision problem, and of the criteria, clarifying their relative importance; a limitation is the use of the artificial 9 points scale; the method is cursed with the so-called rank reversal problem (ranking of alternatives may sometimes be reversed when an extra alternative is added to the existing set)</p>
<b>SAW</b> approach	<p>Simple Additive Weighting</p> <p>(1) express attributes (any category) in their original units; (2) establish attribute weights by (subjective) expert judgement; (3) normalise each attribute vector (e.g. by linear normalisation); (4) multiply each alternative vector by the attribute weight vector; (5) the sums of the resulting values per alternative vector provide a ranking of the alternatives</p>
comments	the method is indeed simple and straightforward
<b>TOPSIS</b> founder/year approach	<p>Technique for Order Preference by Similarity to Ideal Solutions</p> <p>Hwang and Yoon, 1981</p> <p>(1) express attributes (any category) in their original units; (2) establish attribute weights by subjective judgement; (3) normalise attribute vectors by vector normalisation, and multiply by weight vector; (4) establish vectors of positive ideal values (highest value for benefit, lowest for cost attribute) and negative ideal values (reverse); (5) calculate for each alternative a positive (<math>S^+</math>) and a negative (<math>S^-</math>) ideal separation measure as square root of the sum of the squares of the difference of each attribute value with the value in the positive and negative ideal values vectors respectively; both the <math>S^+</math> and the <math>S^-</math> values provide rankings of the alternatives, which may be different; (6) a derived measure called similarity is calculated as <math>C = S^- / (S^+ + S^-)</math> and provides yet another ranking, which may again be different</p>
comments	the rationale of the method is explained in terms of indifference curves which are expressed by the formula for similarity; the methods is easy to understand and to apply
<b>ELECTRE</b> founder/year characteristic	<p>ÉLimination Et Choix Traduisant la RÉalité</p> <p>B. Roy, 1968</p> <p>outranking based on pairwise comparisons followed by a concordance analysis; an alternative outranks another if it is preferred for at least one attribute, and not less preferred for any of the other attributes</p>
approach	(1) express attributes (any category) in their original units; (2) normalise attribute vectors; (3) establish attribute weights by subjective judgement; (4) apply attribute weight vector to alternative vectors; (5) establish kernel of alternatives (each alternative in the kernel is not outranked by another in the kernel, and each alternative outside the kernel is outranked by at least one in the kernel), based on concordance and discordance relationships (not detailed here)
comments	the method has some clear limitations: no ranking of all alternatives is provided, and no ranking of alternatives in the kernel; the choice of the average values of concordance and discordance critical indexes as decision thresholds is quite arbitrary; the net concordance and discordance indexes, defined to provide some kind of ranking, are not able to unambiguously solve the ranking issue
<b>PROMETHEE</b> founder/year characteristic	<p>Preference Ranking Organisation METHod for Enrichment Evaluations</p> <p>J.P. Brans, 1982</p> <p>outranking based on comparison of the pairwise outranking relationships between attributes, after applying a 'generalised criterion' to each attribute; in principle</p>

approach	many generalised criteria might be defined, in practice 6 standard generalised criteria are used; these generalised criteria are further specified by parameters, which depend on the situation (1) express attributes (any category) in their original units; (2) identify for each attribute the applicable generalised, and determine the parameter(s) of the preference function; (3) determine weights for each of the attributes; the weights may be set to equal; (4) determine for each pair of alternatives $x_1, x_2$ the value of the preference function, and sum the values for which $x_1$ is preferred over $x_2$ , as well as (separately) the values for which $x_2$ is preferred over $x_1$ ; (5) represent these values in the so-called preference index of $x_n$ by $x_n$ ; horizontally for each alternative the row of resulting values of being preferred over the other alternatives, vertically the column of values of the other alternatives being preferred over the specific alternative; (6) per alternative the sum of its rows (the so-called leaving flow) minus the sum of its column (the entering flow) is calculated, resulting in one number (the net flow) per alternative; (7) the net flows provide the so-called complete pre-order, a complete ranking of the alternatives, of version II of the method; the partial pre-order of version I is said to contain more realistic information, as it may reveal incomparability; this partial pre-order is achieved by not calculating net flows, but comparing both leaving and entering flows for each alternative pair.
comments	although the method has a quite elegant appearance, the assumption of generalised criteria and use of the preference functions leave the impression that some kind of mysterious magic is applied; because of this the result is not very transparent
<b>fuzzy</b> founder/year approach	L. Zadeh, 1960s based on fuzzy set theory, and the assumption that in reality crisp attribute values do not exist; therefore attribute values should be stated in words, describing sets with fuzzy boundaries, for which crisp values can have memberships from 0 to 1, including values in between
comments	fuzzy evaluation is useful as a thinking model, also in combination with other methods; application is complex, costly, not transparent, and cursed with a high level of subjectivity

## APPENDIX 2 - Overview of GRA Normalisation Procedures

This appendix provides a summary overview of the main normalisation (or data pre-processing) procedures that are proposed and discussed in the GRA literature (Deng 1998, Wu & Cheng 1999, Chang 2000).

In the GRA (Deng 1989) no normalisation needs to be applied (implying that the values are directly comparable) if the original input attributes satisfy three conditions (which are the assumptions of GRA): 1) the difference between the maximum and minimum input values (taken over all attributes) is less than an order of magnitude of two; 2) all attributes are of the same type (benefit, cost, or maximum value); and 3) all attributes have the same measurement scale, and if in a quantitative scale, have the same unit or without unit. In the GRA literature these conditions are (in a not so clear way) referred to as *scaling* (for the order of magnitude), *polarisation* (for the attribute type), and *non-dimension* (for the measurement scale). However, a clear proof of this argument has not been given.

### Basic approach

If the attributes satisfy the three comparable conditions and have different units, the normalisation, so-called grey relational generation, approach is division by the unit, anyone value, the average within each attribute vector, or a specific value.

$$x_i^*(k) = x_i(k) / x_j(k), i, j = 1, 2, \dots, m$$

1. initialisation  $x_j(k) = x_j(1)$ ;
2. maximisation  $x_j(k) = \max x_i(k)$ ;

3. minimisation  $x_j(k) = \min x_i(k)$ ;
4.  $x_i^*(k) = x_i(k) / \bar{x}_i(k)$  ( $\bar{x}_i(k)$  denotes the average of a series); and
5.  $x_i^*(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)}$

### Effect measurement approach

1. benefit task (goal): expected effects as large as possible  $x_i^*(k) = \frac{x_i(k)}{\max x_i(k)}$
2. cost task (goal): expected effects as small as possible  $x_i^*(k) = \frac{\min x_i(k)}{x_i(k)}$
3. specific task (goal): expected effects as close to a certain value as possible  

$$x_i^*(k) = \frac{\min(x_i(k), \text{specific value})}{\max(x_i(k), \text{specific value})}$$

### Linear data approach

1. the-larger-the-better:  $x_i^*(k) = \frac{x_i(k) - \min_k x_i(k)}{\max_k x_i(k) - \min_k x_i(k)}$

where  $\max_k x_i(k)$  is the maximum value of attribute  $k$  for alternative  $i$ , and  $\min_k x_i(k)$  is the minimum value of attribute  $k$  for alternative  $i$ .

2. the-small-the-better:  $x_i^*(k) = \frac{\max_k x_i(k) - x_i(k)}{\max_k x_i(k) - \min_k x_i(k)}$
3. optimisation a specific value between max and min

$$x_i^*(k) = 1 - \frac{|x_i(k) - x_{ob}(k)|}{\max\{\max_k x_i(k) - x_{ob}(k), x_{ob}(k) - \min_k x_i(k)\}}$$

where  $x_{ob}(k)$  denotes the expected (objective) value of attribute  $k$ , which can be determined, e.g. by a certain policy goal.

### Standard approach

If the attributes do not satisfy the comparable conditions (i.e. non-dimension, scaling and polarization), Chang (2000) provides a new method:

1. the-larger-the-better  $x_i^*(k) = \frac{x_i(k)}{\max x_i(k)}$
2. the-small-the-better  $x_i^*(k) = -\frac{x_i(k)}{\min x_i(k)} + 2$
3. optimisation - a specific value between max and min,

$$x_i^*(k) = \begin{cases} \frac{x_i(k)}{x_{\text{exp}}} & \text{when } x_i(k) \leq x_{\text{exp}} \\ -\frac{x_i(k)}{x_{\text{exp}}} + 2 & \text{when } x_i(k) > x_{\text{exp}} \end{cases}$$

where  $x_{\text{exp}}$  denotes the expected (objective) value of attribute  $k$ , which can be determined, e.g. by maximum, minimum value or a certain value in between.