TO WHAT EXTENT CAN THEORY ACCOUNT FOR THE FINDINGS OF ROAD SAFETY EVALUATION STUDIES?

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ABSTRACT

This paper proposes a conceptual framework that can be used to assess the extent to which the findings of road safety evaluation research make sense from a theoretical point of view. The effects of road safety measures are modelled as passing through two causal chains. One of these, termed the engineering effect, refers to the intended effects of a road safety measure on a set of risk factors related to accident occurrence or injury severity. The engineering effect of road safety measures is modelled in terms of eight basic risk factors, one or more of which any road safety measure needs to influence in order to have the intended effect on accidents or injuries. The other causal chain producing the effects of road safety measures is termed the behavioural effect, and refers to road user behavioural adaptations to road safety measures. The behavioural effect is related to the engineering effect, in the sense that certain properties of the engineering effect of a road safety measure influence the likelihood that behavioural adaptation will occur. The behavioural effect of a road safety measure is modelled in terms of five conditions that influence the likelihood that behavioural adaptation will occur. The eight generic risk factors representing the engineering effect of a road safety measure, and the five items representing the likelihood of behavioural adaptation can be used as checklists in assessing whether or not the findings of road safety evaluation studies make sense from a theoretical point of view. 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.

Key words: road safety, evaluation study, theory, explanation, engineering effect, behavioural effect, checklists
INTRODUCTION

One of the major problems of road safety evaluation research, is the fact that most of this research does not have a strong theoretical basis, which guides the design of studies and the interpretation of study findings. The lack of a strong theoretical basis for research means that few results of road safety evaluation studies can be ruled out on theoretical grounds. In this respect, there is sharp contrast between road safety evaluation research and research in more theoretically mature disciplines. When an iron rod is heated, we expect it to expand. This always happens, and the amount of expansion can be measured very accurately and hardly varies from trial to trial. When, on the other hand, road lighting is installed on a road, no well-established theory can rule out the possibility that the (true long term expected) number of accidents increases, although this is perhaps not what is most likely to occur. Results of road safety evaluation studies that initially strike us as counter intuitive, can usually be given some ad hoc and post hoc explanation, but could not have been predicted in advance based on law like relationships or other precise theoretical notions. Road safety evaluation research is any research designed to estimate the effects on accidents or injuries of one or more road safety measures.

The objective of this paper is to outline a conceptual framework and propose a simple theoretical model, which is intended to serve as a basis for assessing whether or not the findings of road safety evaluation studies make sense from a theoretical point of view. The conceptual framework developed and the model proposed do not constitute a fully developed theory intended to explain in general terms the findings of every road safety evaluation study. The concepts proposed and the model developed can, at the present stage of development, serve as a framework for analysis only, as an aid in generating and sorting out ideas when searching for explanations of the findings of road safety evaluation studies.

THE ROLE OF THEORY IN ROAD SAFETY EVALUATION RESEARCH

Many attempts have been made to develop theories designed to predict or explain the findings of road safety evaluation research. Reviewing these theories would detract from the main objective of this paper. It will suffice it to note that none of the theories proposed so far, in particular Wilde's theory about risk homeostasis (Wilde 1982, 1994), or various theories of human behavioural adaptation to road safety measures (OECD 1990, Evans 1991, Adams 1995), are widely applied in road safety evaluation research or enjoy widespread approval among road safety evaluation researchers.

In reviewing the extent to which road safety evaluation research is based on behavioural theory, Elvik (1999) notes that most of this research is not based on behavioural theory, and mostly refers to it only informally or not at all. The following functions that behavioural theory could ideally serve in road safety evaluation research are listed (Elvik 1999, p 6):

1. Serve as the basis for designing roads and vehicles that are optimally adapted to human limitations with respect to perception, the possibility of making errors and the consequences of erroneous action,

2. Serve as the basis for regulating human behaviour within a given technical system in a way that is conducive to road safety,
3. Propose hypotheses about human behaviour to be tested in studies designed to evaluate the effects of road safety measures,

4. Specify the behavioural mechanism through which road safety measures are intended to affect safety, and

5. Specify possible unintended behavioural adaptations to road safety measures, which may in part or in whole offset the effects of those measures on safety.

It is argued that most road safety measures have to influence human behaviour in order to be effective. Seat belts must be worn in order to protect from injury; headlights must be turned on in order to make the car more visible; drivers must stop at red traffic signals for these to function as intended, and so on. It is, however, not always the case that human behaviour needs to be influenced for a road safety measure to be effective. Road lighting, for example, does not require road users to change their behaviour in any way. Guardrails and other energy absorbing structures fitted to roads or vehicles protect road users from injury, while not requiring that road users modify their behaviour in any way.

Logically speaking, a road safety measure must influence one or more risk factors that are associated with accident occurrence or injury severity in order to affect the number of accidents or the severity of injuries. In an earlier paper (Elvik 2001), the concept of a causal chain was introduced in order to describe the process through which a road safety measure affects safety. In its simplest form, the causal chain through which a road safety measure influences road safety can be modelled like this:

There are three basic shortcomings in using this simple model as a basis for developing a theory intended to explain the findings of road safety evaluation studies:

1. The number of risk factors that influence road accidents, and that can be influenced by road safety measures, is very large. There is a need to develop a typology of these risk factors.

2. Very many road safety evaluation studies do not explicitly identify, let alone measure, the risk factors that are influenced by a road safety measure.

3. Some road safety measures lead to behavioural adaptation among road users, that is, they influence not just the risk factors that are the target for the road safety measure, but other risk factors as well.

The two first of these points both suggest a need to reduce the multitude of risk factors influencing road accidents and injuries to a simple typology, stated in abstract and general terms. The third point, the issue of behavioural adaptation, has been extensively discussed in the research literature. The most lucid contribution from a theoretical point of view has been made by Leonard Evans (1985, 1991), who suggested that a road safety measure normally influences road safety by way of two causal chains: (1) The engineering effect, and (2) Human behavioural feedback to engineering changes (“the behavioural effect”). A model based on these concepts is shown in Figure 1.
A distinction is made between two categories of risk factors that may be influenced by a road safety measure: (1) The target risk factors, by way of which the engineering effect of the measure is generated, and (2) Other risk factors, by way of which behavioural adaptations on the part of road users are generated. Such behavioural adaptations may in part or in whole offset the engineering effect, thus reducing the effect a measure will have on accidents or injuries.

**MODELLING THE ENGINEERING EFFECT OF ROAD SAFETY MEASURES**

The next step in developing a conceptual framework for explaining the findings of road safety evaluation studies, based on the model presented in Figure 1, is to propose a typology of the generic risk factors for road accidents and injuries that are normally targeted for influence by means of road safety measures. This typology will serve as the basis for modelling the engineering effect of road safety measures. It is proposed that all these risk factors can be reduced to one or more of the following general types:

1. Kinetic energy
2. Friction
3. Visibility
4. Compatibility
5. Complexity
6. Predictability
7. Individual rationality
8. Forgiveness

The movement of people and vehicles produces kinetic energy. The amount of kinetic energy produced is a function of the mass of a body and its velocity (speed) (Noon 1994):

\[ E = \frac{1}{2} mv^2 \]
This basic law of physics identifies the speed and mass of a vehicle as basic risk factors for accidents. However, kinetic energy is a hazard only. It does not cause harm as long as it is controlled. When control of the movement of a body is lost, the possibility of bringing the body to a stop is decisive for avoiding accidents or reducing injury severity. Hence, the friction between vehicles and the road surface should be considered a basic risk factor for accidents. Another basic risk factor is visibility. Visibility is the possibility of seeing something at a distance. The greater the distance at which an object can be seen and identified, the greater is visibility.

When different vehicles or road users crash, their compatibility in terms of mass and speed exert a decisive influence on the outcome of an accident (Harms 1992). Compatibility refers to the differences between categories of road users in terms of the kinetic energy produced by their movements. The smaller these differences, the more compatible are road users. One way of reducing incompatibility is to separate in time or in space groups of road users that are highly incompatible.

Speed, vehicle mass, friction, visibility, and compatibility are all risk factors that are closely related to the physical laws governing the movement of bodies across a surface. It is often argued, however, that human factors represent most important risk factors for road accidents. The taxonomy proposes to reduce the very many human factors that contribute to accidents to five basic categories. The first of these is complexity. Complexity is a property both of the traffic system and of traffic as such. Complexity refers to the amount of new information a road user has to process per unit of time. In dense urban traffic, complexity will typically be high, because road users have to pay attention to a rapidly changing traffic situation, in addition to performing the usual perceptual-motor tasks of walking, cycling or driving a motor vehicle.

Predictability denotes the reliability with which the behaviour of a road user can be predicted in a given situation. Lane-keeping is an example of very predictable behaviour. When driving on an undivided two-lane road, most drivers do not expect oncoming traffic to suddenly enter their own driving lane – and most of the time this prediction is correct.

Individual rationality refers to the extent to which road users behave in ways that satisfy their preferences (maximise utility). In the context of road safety rationality can be defined as the ability of road users to correctly perceive hazards and take appropriate action to prevent hazards from developing into accidents. This definition of rationality assumes that nobody wants to become involved in an accident. Hence, to the extent that road users are able to act rationally, accidents will be avoided. Factors that may inhibit rationality include both elements of roads and vehicles (badly designed roads and vehicles increase the likelihood that errors will be made) and the state of the individual. Excessive consumption of alcohol or drugs, lack of sleep, illness or other more or less permanent individual traits may inhibit rationality.

Forgiveness denotes any element of roads or vehicles that either prevents errors made by road users from leading to accidents or that absorbs energy in case an accident occurs, thus making serious injury less likely. Forgiveness is typically built into roads by making them wider, by installing rumble strips, or by installing guardrails or crash cushions. Cars are made more forgiving by having seat belts, airbags, collapsible steering columns, laminated windshields, and so on.

The typology proposed above is intended to be exhaustive. It is proposed that the engineering effect of any road safety measure can be described in terms of one or more of these eight generic risk factors. Unless it is possible to identify at least one of the eight generic risk factors as a key element of the engineering effect of a road safety measure,
there is simply no reason to believe that the road safety measure will be effective. A road safety measure has to influence factors that systematically produce accidents or injuries; otherwise it cannot be effective. Any risk factor or set of risk factors targeted for influence by a road safety measure should belong to one or more of the eight categories of the taxonomy. The basic hypothesis is that if one or more of the basic risk factors are favourably influenced (kinetic energy reduced, friction increased, and so on), then, ceteris paribus, one would expect road safety to improve.

MODELLING ROAD USER BEHAVIOURAL ADAPTATION TO ROAD SAFETY MEASURES

The ceteris paribus clause in the above hypothesis is needed mainly because it is notoriously difficult to predict road user behavioural adaptation to road safety measures. Hence, the fact that there is a favourable engineering effect does not by itself guarantee that road safety will be improved. Road safety will improve only if there is no offsetting behavioural adaptation.

Can road user behavioural adaptation be predicted or explained in general terms? Wilde’s theory of risk homeostasis (Wilde 1982, 1994) can be interpreted as an attempt to formulate a general theory of road user behavioural adaptation. However, the logical structure of Wilde’s theory is such as to make it incapable of falsification, and hence unfruitful as a basis for empirical research. Basically, the theory of risk homeostasis states that unless the target level of risk (which is determined by each road user) changes, no permanent changes in safety can be attained. However, the theory does not explain (except in very general and vague terms) how an individual determines his or her target level of risk, nor does it state how to measure target level of risk empirically. This means that the theory can be invoked to explain any finding: If the number of accidents remains unchanged, then this is exactly what the theory predicts if the target level of risk does not change. If the number of accidents is reduced, then the target level of risk must somehow have changed. Clearly, this theory is entirely vacuous: in trying to explain everything, it actually explains nothing.

What is needed to explain road user behavioural adaptation is a set of more specific, yet general hypotheses. Bjørnskau (1994) has proposed hypotheses designed to explain road user behavioural adaptation to road safety measures. He identifies the following generic conditions influencing road user behavioural adaptation:

1. How easily a measure is noticed
2. Antecedent behavioural adaptation to generic risk factors
3. Size of the engineering effect on generic risk factors
4. Whether or not a measure primarily reduces injury severity
5. Whether or not additional utility can be gained

Each of these points will be elaborated.

Road users continuously assess the risk of accidents by scanning the road, its surroundings and the traffic situation. If a road user notices a change in any element of the system, he or she may perceive this as a change in the level of risk. If, as an example, sight distance along a road is increased, by flattening the road and removing roadside obstacles most road users would probably perceive this as a gain in safety margin. If, on the other hand, cars are
equipped with collapsible steering columns, drivers would not notice it and might not even know it. Measures that introduce changes to the road or to vehicles that are easily noticed by road users are more likely to lead to behavioural adaptation than measures that road users do not easily notice.

Road users adapt their behaviour to perceived changes in risk. If road users have already adapted their behaviour to the risk factor, which a road safety measure is meant to affect, the measure is more likely to lead to behavioural adaptation than if antecedent behavioural adaptation has not taken place. To give an example: periodic inspections of private cars is probably more liable to behavioural adaptation than road lighting, because road users try to compensate for technical defects in cars by driving more carefully. There is, on the other hand, little evidence to suggest that road users adapt their behaviour to reduced visibility at night by slowing down or by being more alert.

The size of the engineering effect refers to the size of the changes made in, for example, sight distance, separation between incompatible road users or complexity of the road and traffic environment. Large changes in these generic risk factors are more easily noticed than small changes and are more likely to be perceived as major additions to the safety margin, which has been built into the system. Hence, the greater the engineering effect, the more likely is behavioural adaptation to occur.

Risk is often defined in terms of expected loss (Haight 1986):

$$\text{Risk} = \text{Probability of an unwanted event} \times \text{Consequences of the unwanted event}$$

In road traffic, accidents are the unwanted events, their consequences are the losses associated with them in terms of property damage and personal injury. It seems reasonable to assume that if an accident were to occur, road users would prefer the consequences of that accident to be as small as possible. Hence, measures that increase the forgiveness of the system, in particular measures that reduce injury severity are less likely to lead to behavioural adaptation than measures that (are perceived to) reduce the probability of accident occurrence. Measures that primarily reduce injury severity are, depending on how easily road users notice them, perhaps also less likely to be perceived as an increase in the safety margin built into the system than measures that primarily reduce the probability of accident occurrence.

According to the definition of rationality given earlier in the paper, road user behaviour can be modelled as utility maximisation. Road users derive utility not just from safety, but from reaching their destination on time, from observing a beautiful landscape along the road, from listening to the radio while driving, or from feeling a powerful engine respond when the accelerator is pushed down. Several models of road user utility functions have been proposed; reviewing them is beyond the scope of this paper. In the present context, the point is simply that one of the most basic conditions for road user behavioural adaptation to occur, is that road user can gain a higher utility by adapting their behaviour. For some road safety measures, it is difficult to see how road users could gain any benefit by changing behaviour. The use of automatic gates to protect railroad-highway grade crossings is a case in point. It is difficult to think of a behavioural adaptation to gates at level crossings between roads and railroads, which would give any benefit to road users. Driving in a zigzag pattern between gates after they have been lowered in order to save time is extremely dangerous and may damage the vehicle if one hits the barriers. The vast majority would hardly perceive this as beneficial or comfortable. Reducing alertness confers no benefit either, because it
only means that one would react later to lowered gates and have to brake harder in order to stop in front of them.

THE RELATIONSHIP BETWEEN THE ENGINEERING EFFECT AND THE BEHAVIOURAL EFFECT OF ROAD SAFETY MEASURES

The engineering effect of road safety measures consists of changes made in the generic risk factors listed previously. The output of these changes can be termed the structural safety margin built into the road system. This term is to be understood in a wide sense; it is not necessarily limited to the technical components of road traffic, but includes ways of increasing the rationality and reliability of human performance as well. Structural safety margins can be described in technical terms. Examples of variables that can be used to describe the structural safety margins of road traffic are: sight distance, lateral distance to the edge of the road or to oncoming traffic, speed, friction coefficient, frequency of specific errors made by road users, and time to collision for vehicles on collision course.

Properties of changes in the structural safety margin that result from the engineering effect of road safety measures influence the likelihood that behavioural adaptation to the measures will take place. These properties, as identified by the hypotheses proposed by Bjørnskau (1994) include the size of the change in safety margin, how easily the change is noticed by road users, whether road users have already adapted their behaviour to the generic risk factors that are influenced by the road safety measure, whether safety margin is increased by reducing the probability of accident occurrence or the severity of the consequences of an accident, and whether a measure creates an opportunity for gaining utility. Figure 2 is a further development of figure 1 that makes explicit the relationship between the engineering effect and the behavioural effect of a road safety measure.

Figure 2: Revised model of causal chain that generates the effect of road safety measures

The result of behavioural adaptation is termed the behavioural safety margin. This concept refers to how road users assess their safety margin when travelling; contrary to the structural safety margin it is not a concept that can be measured in physical terms. This means that precise measurement of the forms and degree of behavioural adaptation to road safety measures will never be possible. If road users adapt their behaviour by becoming slightly less alert, there is no way of measuring this sort of adaptation very precisely.
Behavioural adaptations in terms of increased speed are readily measurable; the more subtle forms of behavioural adaptation related to the ways in which road users pay attention to the road and to traffic are more difficult to measure.

**A CASE ILLUSTRATION OF USE OF THE CONCEPTUAL FRAMEWORK TO EXPLAIN THE FINDINGS OF ROAD SAFETY EVALUATION STUDIES: ROAD LIGHTING**

To show how to use the conceptual framework and models developed in this paper to explain the findings of road safety evaluation studies, a case illustration will be given. The case concerns studies that have evaluated the effects of road lighting.

According to a systematic review of evaluation studies (Elvik 1995), installing road lighting on a previously unlit road is associated with a mean reduction of the number of fatal accidents in darkness of 64%, a mean reduction of injury accidents in darkness of 28%, and a mean reduction of property-damage-only accidents in darkness of 17%. All these estimates are statistically significant at the 5% level of significance.

It may appear unsurprising to find that road lighting reduces the number of accidents in darkness. Many people would say that it is obvious that road lighting will reduce the number of accidents at night, by making it easier to see in the dark: a more sophisticated explanation of the findings of studies that have evaluated the effects of road lighting on accidents is not needed. Things are not so simple, however. Although road lighting in most cases reduces the number of accidents, it is by no means certain that it does so in every case. According to the systematic review of evaluation studies (Elvik 1995), 19% of the estimates of effect indicated an increase of the number of accidents. Moreover, we would like to know whether the effects of road lighting on accidents are consistent with what one would expect on the basis of the engineering effect of road lighting. Are these effects smaller or greater than the increase in structural safety margin would lead us to expect? Is there any evidence of behavioural adaptation to road lighting?

Table 1 shows how to use the model of the engineering effect of a road safety measure as a checklist to assess the main components of the engineering effect. As far as road lighting is concerned, the major factor influenced is obviously visibility. Better visibility may in turn influence road user rationality, in particular by making errors in observation less likely and by giving road users more time to correct any errors. A potentially adverse effect of road lighting is the presence of lighting supports close to the road.

The increase in the detection distance to given objects in the dark, measured under controlled conditions, can be used as a measure of the engineering effect of road lighting. According to Ketvirtis (1977), the detection distance increases from a maximum of 50 to 75 metres with correctly installed vehicle headlights (dipped headlights) as the only source of light, to around 250 metres when the road has road lighting providing an intensity of 1-2 candela per square metre. At a driving speed of 78 km per hour (observed in a Norwegian study; see below), with a reaction time of one second and a friction coefficient of 0.8, the stopping distance is about 52 metres. Road lighting thus provided an increase in the safety margin from 75 – 52 = 23 metres before it was installed to 250 – 52 = 198 metres after it was installed. The engineering effect of road lighting corresponds to an increase by a factor of almost 9 (198/23 = 8.6) in the structural safety margin. Ceteris paribus, this can be interpreted a potential decrease in accidents in the dark of at least 80% (using the inverse value of the safety margin, 1/23 and 1/198 respectively, as a measure of risk). The actual
decrease in accidents varies between 64% and 17%, depending on accident severity, which suggests that behavioural adaptation may be taking place.

According to a Norwegian study (Bjørnskau and Fosser 1996; Assum et al 1999), road users do indeed adapt their behaviour to road lighting. Three forms of behavioural adaptation were found:

1. Speed increases once road lighting is provided.
2. Road users tend be somewhat less alert when road lighting is provided.
3. Some road users who did not travel in the dark before the road was lit have started to do so.

*Figure 3* shows the changes in mean speed following the installation of road lighting. Mean speed increased both on straight road sections and in curves.
### Table 1:

*Case illustration of the use of the models of the engineering effect and behavioural effect as checklists to explain the effects of a road safety measure on accidents*

<table>
<thead>
<tr>
<th>Generic risk factors</th>
<th>Effect of measure on generic risk factors</th>
<th>Factors eliciting behavioural adaptation</th>
<th>Effect of measure on factors eliciting behavioural adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Kinetic energy</td>
<td>Not affected</td>
<td>1: Ease of noticing measure</td>
<td>Road lighting easily noticed</td>
</tr>
<tr>
<td>2: Friction</td>
<td>Not affected</td>
<td>2: Antecedent behavioural adaptation</td>
<td>Not adequate to eliminate the effect of darkness on accident rate</td>
</tr>
<tr>
<td>3: Visibility</td>
<td>Improved; size of improvement depends on quality of lighting</td>
<td>3: Size of engineering effect</td>
<td>Detection distances increase; by how much depends on quality of lighting</td>
</tr>
<tr>
<td>4: Compatibility</td>
<td>Not affected</td>
<td>4: Affects probability of accidents or consequences of accidents</td>
<td>Both aspects of risk may be affected</td>
</tr>
<tr>
<td>5: Complexity</td>
<td>Not affected</td>
<td>5: Prospects of gain in utility</td>
<td>Road lighting makes travel at night less strenuous (observation is easier)</td>
</tr>
<tr>
<td>6: Predictability</td>
<td>Not affected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7: Road user rationality</td>
<td>Observation becomes easier; fewer errors are likely to be made</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8: Forgiveness</td>
<td>Adversely affected; lighting poles are a new hazard</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 3: Changes in mean speed on straight sections and in curves after road lighting was installed. Source: Bjørnskau and Fosser 1996
The study also found that road users reported that they were somewhat less alert when driving on lit roads than when driving on unlit roads. Using lane drifting (sideways movements within a driving lane) as a proxy measure for road user alertness, it was found that the amplitude of steering manoeuvres to correct lane drifting increased once road lighting was installed, indicated a reduced level of alertness (assuming that an alert driver tries to steer a straight course by continuously monitoring and adjusting lane position, thus only making steering manoeuvres at an amplitude below the one used as a criterion in the study).

While the combined effects of increased speed, a reduced level of alertness and an increase in night-time driving cannot be estimated in meaningful numerical terms, the study nonetheless supports the conclusion that road lighting is associated with road user behavioural adaptation, which partly offsets the engineering effect of the measure.

OUTLINE OF A RESEARCH PROGRAMME DESIGNED TO EVALUATE THE EXTENT TO WHICH THE FINDINGS OF ROAD SAFETY EVALUATION STUDIES CAN BE EXPLAINED IN THEORETICAL TERMS

Hundreds of road safety evaluation studies have been reported. There is apparently no lack of evidence regarding the safety effects of very many road safety measures. The large number of studies and the great amount of detail found in these studies give the deceptive impression that very much is known about the effects of road safety measures. Regrettably, the existence of this large body of research does not mean that the effects on road safety of a large number of road safety measures are well known. Few road safety evaluation studies stand up to critical scrutiny. Many of these studies employ flawed study designs and rely on unreliable data, which means that their findings can be rejected on methodological grounds (Elvik 2002, Hauer 2002).

In the short run, redoing evaluation studies by means of superior methods is not feasible. Can we nevertheless, at least until evidence from better studies starts to accumulate, place some trust in the findings of road safety evaluation studies when these findings make sense from a theoretical point of view? That question motivated the research reported in this paper. As noted in the introduction, it is almost always possible to give an ad hoc and post hoc explanation of the findings of a road safety evaluation study. Inventing a “theory” after looking at the data is usually not very difficult. The explanatory power of such post hoc theories is, however, nil. In order to help make sense of the findings of road safety evaluation studies, a theory must be stated in general terms that are independent of the findings of any specific road safety evaluation study.

Road safety measures influence a set of target risk factors; their intended effect on these can be termed the engineering effect of a measure. There is a multitude of risk factors; in this paper the risk factors affected by the engineering effect of a road safety measure has been reduced to eight generic risk factors. This kind of theoretical reduction and abstraction is an essential first step towards developing a general theory to explain the findings of road safety evaluation studies. The effect of a road safety measure on the generic risk factors is in turn associated with the occurrence of road user behavioural adaptation to the measure. Five conditions affecting the probability of occurrence of behavioural adaptation were identified. This conceptual framework, and the simple causal model developed on the basis of it, can serve as the starting point for a research programme designed to evaluate the
extent to which the findings of road safety evaluation studies can be explained in theoretical terms. In brief, the first steps of such a research programme are:

1. Systematic retrieval of road safety evaluation studies, with the objective of including all studies that have been reported.

2. A procedure for assessing the methodological quality of studies, in order to obtain an overall measure of their quality, to serve as the basis for assessing the strength of methodological interpretations of study findings.

3. Describing the engineering effect of all road safety measures that have been evaluated, based on the checklist proposed in this paper.

4. Assessing the likelihood of road user behavioural adaptation, based on the checklist proposed in this paper.

5. The deduction of the pattern of results expected according to the engineering effect and the behavioural effect.

6. Comparing the actual results of evaluation studies to those expected according to the models of the engineering effect and behavioural effect, while at the same time taking study quality into consideration.

7. Concluding, on the basis of whether or not theoretical expectations are supported, if a theoretical account of current knowledge about the effects of road safety measures makes sense.

When this research programme has been completed, one will hopefully be in a position to evaluate the degree to which the findings of road safety evaluation studies make sense from a theoretical point of view, and identify those road safety measures for which the findings of evaluation research are most difficult to explain theoretically.

**DISCUSSION AND CONCLUSIONS**

Road safety evaluation research is to a large extent non-theoretical. This research is not designed to test very clearly formulated scientific theories by means of well-controlled experiments. Yet, it is perhaps wrong to say that road safety research is entirely devoid of theoretical content. Researchers nearly always have some prior expectations about the results they are going to get. When these prior expectations are violated, the findings are labelled “counterintuitive”. There are many examples of counterintuitive findings in road safety evaluation research:

1. Providing paths for walking or cycling, physically separated from motor vehicles, has – mostly in Scandinavian evaluation studies – not been found to reduce the number of accidents involving pedestrians or cyclists.

2. Marked pedestrian crosswalks are associated with an increase of the number of accidents.

3. ABS brakes on cars do not reduce the number of accidents involving cars with such brakes.

4. Formal driver training does not reduce the accident rate of novice drivers.

Many more examples could be quoted. The fact that these findings were unexpected and go against intuition does not necessarily mean that they do not make sense from a theoretical
point of view. Intuitions can be prejudiced and are as a rule not stated in a form that lends itself easily to empirical testing.

This paper has tried to move beyond intuitions, by proposing a framework for assessing the findings of road safety evaluation studies from a theoretical point of view. The framework proposed consists of a simple model of the intended effect of a road safety measures, referred to as the engineering effect, and a model identifying some factors that influence the likelihood that a road safety measure will lead to behavioural adaptations among road users. Neither of these models is very well established, in the sense that there exists an extensive body of research confirming their validity. It is fair to say that both models are to a large extent based on common sense. In that respect, the models of the engineering effect and behavioural effect of road safety measures may not differ fundamentally from the informal intuitions that most road safety researchers have about what they are going to find when evaluating a road safety measure. However, the models of the engineering effect and behavioural effect of road safety measures are not intended to be more than checklists that researchers can use to assess the extent to which the findings of road safety evaluation research make sense from a theoretical point of view.

Despite the limitations of the models proposed in this paper, the checklists derived from these models can serve a number of useful functions in helping to assess the findings of road safety evaluation studies from a theoretical point of view:

The checklist for the engineering effect of a road safety measure identifies a number of general mechanisms through which a road safety measure can influence accidents or injuries. If it is not possible to describe the engineering effect of a road safety measure in terms of these mechanisms, there is simply no reason to believe that it will have an effect. Any study claiming that the measure is effective would then be suspect.

The checklist for the behavioural effect if a road safety measure identifies conditions that influence the likelihood of behavioural adaptation. If, as an example, most of these conditions are present, and there is evidence of behavioural adaptation, one should not be surprised if the behavioural effect of a measure fully or partly offsets the engineering effect.

If a road safety measure can be expected to have a large engineering effect, and no behavioural effect, finding a large effect on accidents would conform to theoretical expectations.

While falling far short of the rigorous testing of precisely stated theories in the natural sciences, a systematic use of the framework proposed in this paper could at least identify some findings of road safety evaluation studies as more or less plausible and more or less easy to account for theoretically. The more difficult a finding is to explain theoretically, the more likely it is to be attributable to methodological artefacts.

REFERENCES


