TSR TRAFFIC SAFETY RESEARCH
AN INTERDISCIPLINARY JOURNAL

Research article

Which is the more important for road safety—road design or driver behavioural adaptation?

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Handling editor: **Aliaksei Laureshyn**, Lund University, Sweden

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Received: 5 April 2022; Accepted: 2 August 2022; Published: 9 August 2022

Abstract: Studies consistently show that sharp horizontal curves increase accident rate. One would therefore expect roads with many sharp curves to have a higher accident rate than roads with few sharp curves. This is not the case. The differences in road safety between roads with different profiles of horizontal road alignment are quite small. There are even studies suggesting that areas having roads with many curves have a lower number of accidents than otherwise identical areas with less curvy roads. The question arises: How can it be true both that sharp curves increase accident rate and that areas with roads with many sharp curves do not have a higher accident rate than areas with less demanding alignment? The answer is likely to be found in behavioural adaptation among drivers. The accident rates both in curves and on straight sections are strongly influenced by how drivers adapt behaviour to the number of curves per kilometre of road. This paper shows how behavioural adaptation can be quantified by means of the 'human feedback parameter' proposed by Evans. This parameter takes a value of -1 if drivers adapt behaviour so as to completely eliminate a risk factor. Values close to -0.7 for horizontal curves were estimated on the basis of micro-level studies. Thus behavioural adaptation reduces the increase in risk to about 30% of what it would have been without behavioural adaptation. In addition, a high frequency of curves leads to lower speed on the straight sections between curves.

Keywords: accident rate, behavioural adaptation, feedback parameter, horizontal curve

1 Introduction

Horizontal curves increase the accident rate. This has consistently been found in many studies. Results of some recent studies are shown in Table 1. The increase in accident rate is particularly sharp in curves with a radius of 150 metres or less. The studies listed in Table 1 suggest that, all else equal, accident rate can be reduced by 45%–65 % by flattening curves from a radius of 50 to a radius of 100 metres. Flattening from 50 to 150 metres could reduce accident rate by 60%–75%.

It is also well-established that if there are many sharp curves on a road, each curve is associated with a smaller increase in accident rate than if there are few sharp curves. Elvik (2019a) developed a numerical example showing that the overall accident rate on a road with 7 curves per kilometre is not necessarily higher than on a road with 1 curve per kilometre. Thus, variation between roads with respect to their horizontal alignment does not necessarily imply that the roads have different accident rates, even if one of the roads consists of more curves than the other road. How is this possible? All else equal, a road that has a large number of sharp curves would be expected to have a higher accident rate than a straight road with just one curve.

Table 1 Relative accident rate in curves as a function of radius—set to 1.00 for a radius of 1200 metres

Curve radius (metres)	Banihashemi (2016)	Gooch *et al.* (2016)	Gooch *et al.* (2018)	Geedipally *et al.* (2019)
1200	1.00	1.00	1.00	1.00
600	1.83	1.08	1.09	1.09
500	2.15	1.12	1.13	1.13
400	2.62	1.17	1.19	1.18
300	3.36	1.27	1.29	1.29
200	4.80	1.48	1.54	1.53
150	6.17	1.73	1.83	1.81
100	8.80	2.38	2.57	2.53
50	16.13	6.11	7.22	6.97

This paper suggests that the explanation can be found in how drivers adapt their behaviour to road alignment. Driver behaviour is guided by expectations formed through experience. The frequent occurrence of curves generates an expectation that the road will continue to be curvy (Alexander & Lunenfeld 1986). Drivers are then better prepared for the next curve than on a road where there are fewer curves. Fuller (2005) suggests that drivers try to maintain a stable level of task difficulty when driving. If driving does not demand the full attention of the driver, it becomes boring and may induce drowsiness. Driving in curves demands more attention than driving on straight road sections. Drivers will adapt to variation in task difficult mainly be varying speed.

The main research question explored in this paper is how and to what extent drivers adapt behaviour to varying frequencies of horizontal curves when driving along a road. To indicate the extent of behavioural adaptation, the concept of human feedback parameter, introduced by Leonard Evans (Evans 1985), will be applied. The main research problem is whether it is possible, and gives plausible results, to quantify the degree of driver behavioural adaptation to a high frequency of horizontal curves. More specifically, can an estimate of the 'human feedback parameter' proposed by Evans (1985) be developed?

2 The degree of surprise of a curve

Nearly 50 years ago, Norwegian researcher Nils Skarra (Skarra 1973) introduced and formalised the concept of 'degree of surprise' to predict accident rate in horizontal curves. His idea was that a sharp curve encountered after driving on a long straight section will be more surprising to drivers than a sharp curve following immediately after another sharp curve. To formalise this idea, he measured lateral acceleration and its standard deviation each 10 metres when driving at normal speed, continuously updating these statistics as running averages for a given length of road. On a straight road section lateral acceleration will be close to zero and hardly vary. When a sharp curve is entered, lateral acceleration will increase rapidly. Denoting lateral acceleration by X, he defined degree of surprise as:

$$\text{Degree of surprise} = \Psi = \frac{\Delta X}{S_x} \tag{1}$$

Delta of X (ΔX) is an instantaneous change in lateral acceleration and S_x is the standard deviation of lateral acceleration for a given length of road. The computer program estimating degree of surprise was subsequently run on all national roads in Norway and curves identified as surprising were signposted. This improved safety in the curves (Elvik 2012). Empirical Bayes estimates of the effects of signing surprising curves range from 15% to 30% accident reduction.

3 Application of accident prediction models

To get an idea about the extent to which driver behavioural adaptation influences differences in safety between roads with a different number of curves with different horizontal radius, accident prediction models developed by Dietze & Weller (2011) have been applied. These models were chosen because they, unlike most other models, contain a term for the length of the straight road section preceding a curve. The following model was developed for curves:

$$\text{Number of accidents} = \\ = e^{(-7.406+\ln(AADT)\cdot 0.638+\ln(length)\cdot 0.260+0.001\cdot(length\ of\ straight\ section)-0.004\cdot(radius))} \tag{2}$$

AADT is Annual Average Daily Traffic. *Length* is length of a curve in metres. *Length of straight section* is the length in metres of a tangent section preceding the curve. *Radius* is radius of the curve in metres. Based on the data given, an AADT of 1500 has been assumed. It has been assumed that the radius of curves varies between 50 and 500 metres and that the length of curves is identical to their radius. This means that each curve is a radian, i.e. has a deflection angle of 57.3 degrees. For straight road sections, the following model was developed:

$$\text{Number of accidents} = \\ = e^{(-11.308+\ln(AADT)\cdot 0.480+\ln(length)\cdot 0.890-0.004\cdot(curvature\ change\ rate))} \tag{3}$$

AADT and *length* are defined as above. *Curvature change rate* is the curvature of the section in gon/km. According to the authors, most road sections had values of gon/km less than 100, and in the application of the model, the term was omitted, i.e. only the coefficients for *AADT* and *length* were applied (gon = a metric degree system according to which the circumference of a circle is 400 degrees). The variables included in the model for curves define curvature change rate and the variable is therefore superfluous in the model for sections as a road is assumed to consist of straight sections (curvature change rate = 0) and horizontal curves. An AADT of 1500 was used when applying the model.

Eight numerical examples have been developed based on the models. These examples will be explained by reference to Table 2.

In each numerical example, a road section of 1 kilometre is considered. This section consists of either 2, 4 or 8 horizontal curves with a radius of 50 or 100 metres or of 2 or 4 horizontal curves with a radius of 150 metres. The curves have been assumed to be located as far from each other as possible. In the first example, the two curves are located at the beginning and end of the road section and have a 900 metres straight section between them. Remember that the length of each curve is equal to its radius. When the road has 4 curves with a radius and length of 50 metres, the total length of the curved sections is 200 metres. Again, two of the curves are located at the beginning and end of the road, the other two are located as far apart as possible.

Table 2 Accidents in curves: eight numerical examples

Panel A. Expected number of accidents as a function of curve radius and number of curves

Radius of each curve (m)	Number of curves	Total length of curves (m)	Length of each straight section (m), number of sections in parentheses	Accidents in each curve	Accidents on each straight section	Total accidents in curves	Total accidents on straight sections	Accidents in total
50	2	100	900 (1)	0.515	0.175	1.030	0.175	1.205
50	4	200	266.7 (3)	0.271	0.059	1.096	0.177	1.273
50	8	400	85.7 (7)	0.228	0.022	1.824	0.154	1.978
100	2	200	800 (1)	0.457	0.157	0.914	0.157	1.071
100	4	400	200 (3)	0.228	0.046	1.004	0.138	1.142
100	8	800	28.6 (7)	0.211	0.008	1.688	0.056	1.744
150	2	300	700 (1)	0.376	0.140	0.752	0.140	0.892
150	4	600	133.3 (3)	0.214	0.032	0.856	0.096	0.952

Panel B. Driver speed adaptation in curves and predicted number of accidents with modified regression coefficients

Radius of each curve (m)	Number of curves	Total length of curves (m)	Length of each straight section (m), number of sections in parentheses	Mean speed on straight section (km/h)	Mean speed in curves (km/h)	Speed reduction (km/h)	Maximum safe speed in curve (km/h)	Accidents with modified coefficients
50	2	100	900 (1)	76.9	63.1	13.8	69.7	2.891
50	4	200	266.7 (3)	70.9	58.9	12.0	69.7	2.198
50	8	400	85.7 (7)	59.0	50.5	8.5	69.7	2.450
100	2	200	800 (1)	78.1	70.5	7.6	95.7	2.503
100	4	400	200 (3)	72.1	66.3	5.8	95.7	1.791
100	8	800	28.6 (7)	60.1	57.9	2.2	95.7	1.857
150	2	300	700 (1)	79.3	74.3	5.0	114.7	2.072
150	4	600	133.3 (3)	73.3	70.1	3.2	114.7	1.346

There will, in this case, be three straight road sections between the curves, with a total length of 800 metres. Each straight section will have a length of 800 / 3 = 266.7 metres. All other cases have been defined the same way.

For the first case, the expected number of accidents in each curve is estimated as follows:

$$\text{Expected number of accidents} = \\ = \mathrm{e}^{(-7.046+\ln(1500)\cdot 0.638+\ln(50)\cdot 0.26-0.004\cdot 50+0.001\cdot 900)} = 0.515 \tag{4}$$

The first term is the constant term, the second is AADT (traffic volume), the third is the length of the curve, the fourth is the radius and the fifth and final term is the length of the straight section ahead of the curve. Since there are two curves, the expected number of accidents in curves is 0.515 · 2 = 1.030.

The expected number of accidents on the straight sections is estimated as follows:

$$\text{Expected number of accidents} = \mathrm{e}^{(-11.308+\ln(1500)\cdot 0.48+\ln(900)\cdot 0.89)} = 0.175 \tag{5}$$

The first term is the constant term, the second is AADT and the third is the length of the straight section. The total number of accidents becomes 1.030 + 0.175 = 1.205.

The other cases have been estimated the same way, the only differences being a different number of curves and a different number of straight sections and the share of total road length (1 kilometre) covered by curves and by straight sections. AADT has been kept constant in all estimates.

It is seen that the increase in the number of accidents is small when the number of curves increases from two to four, but somewhat larger when the number of curves increases to eight (this case was not included for curve radius 150 metres). As far as flattening curves is concerned, the estimated differences in the expected number of accidents are quite small. Thus, for two curves, increasing the radius of each curve from 50 to 100 metres is estimated to reduce the number of accidents by about 11%, from 1.205 to 1.071. Increasing the radius from 50 to 150 metres is estimated to reduce the number of accidents by 26%, from 1.205 to 0.892. Estimated effects remain small when the number of curves is greater. If there are eight curves per kilometre, increasing their radius from 50 to 100 metres is estimated to reduce the number of accidents by about 12%, from 1.978 to 1.744.

These results are close to those found by Hauer (1999) in his analysis of safety and the choice of degree of curve. He found, for example, that increasing curve radius from 175 metres to 583 metres would reduce the expected number of accidents by 16%. However, both the models applied in this paper and the analysis presented by Hauer show that: (*1*) a smaller curve radius and (*2*) a larger number of curves per length of road, are consistently associated with a higher number of accidents. It is therefore quite surprising that some studies made at the aggregate level have found that areas with more curvy roads tend to have fewer accidents than areas with less curvy roads. The next section reviews some of these studies.

4 Studies at the aggregate level

Haynes *et al.* (2007) studied district variations in road curvature in England and Wales. Curvature was measured as: number of curves per kilometre of road; the ratio of actual distance to straight distance; the share of road length that was straight; the cumulative angle turned per kilometre and the mean angle turned per curve. Subsequent studies by Haynes *et al.* (2008) and

Jones *et al.* (2012) have used a similar set of variables to indicate curvature. Applying negative binomial regression, these studies have consistently found negative coefficients for the number of curves per kilometre of road and cumulative deflection angle. The values of the coefficients vary from study to study, but all studies indicate that areas that have roads with many curves and large deflection angles have fewer accidents than areas with fewer curves making more gentle turns of direction.

In a similar vein, Høye (2014) found an interaction between speed limit and the influence of the number of curves on the number of accidents. Employing negative binomial regression, Høye (2014) estimated coefficients for the number of curves per kilometre of road by speed limit on national and county roads in Norway. A curve was defined as any section with a length of at least 50 metres and a radius of 300 metres or less. The estimated relationships are presented in Figure 1.

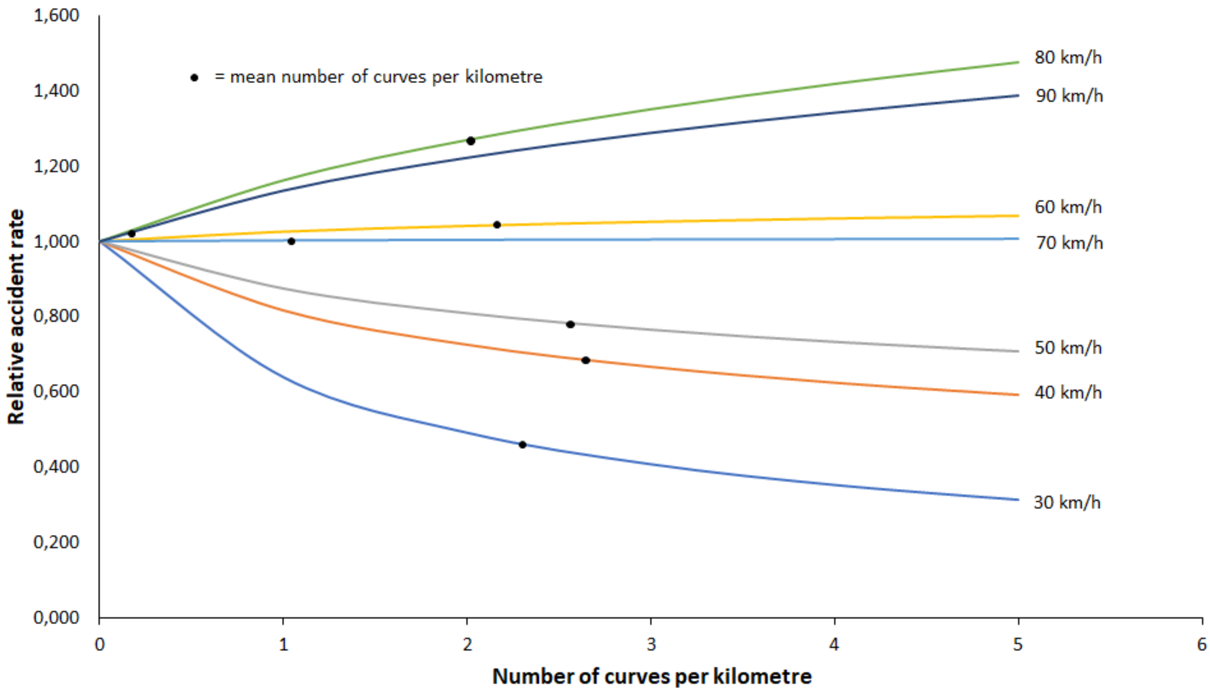

Figure 1 Influence of curves on accident rate on national and county roads in Norway by speed limit. *Source*: Høye (2014)

On roads with speed limits of 30, 40 or 50 kilometres per hour, curves are associated with a reduced accident rate. On roads with these speed limits, a driver may not have to reduce speed to safely negotiate a curve but has to pay attention to the course of the curve. In short, curves are likely to make drivers more alert and pay more attention to the driving task. On roads with speed limits of 60 km/h or 70 km/h, accident rates are not associated with the number of curves per kilometre of road. On roads with speed limits of 80 km/h or 90 km/h, accident rate increases as the number of curves per kilometre increases. On these roads, drivers may have to slow down in curves.

Can these results be reconciled with the estimates developed by means of the models developed by Dietze & Weller (2011)? Is it possible both that accident rate increases in horizontal curves and that areas with roads with many horizontal curves are safer than areas with roads with few horizontal curves?

To answer these questions, it is important to remember that the coefficients estimated in statistical models are uncertain. Small changes in their value could be associated with large changes in the predicted number of accidents. To illustrate this, the number of accidents predicted by the models developed by Dietze & Weller (2011) was re-estimated by making the following changes in the coefficients in the model for curves:

The coefficient for curve radius was changed from -0.004 to -0.0036. The coefficient for the length of the straight section ahead of the curve was changed from 0.001 to 0.0012.

In the model for straight sections, the coefficient for the length of the section was changed from 0.89 to 1.20.

The predicted number of accidents with these changes in coefficients are shown in the rightmost column in panel B of Table 2. It is seen that the predicted number of accidents is lower when there are many curves (4 or 8) than when there are few (2). The decline is not monotonous, but nevertheless consistent with the finding that the number of accidents is lower in areas with many sharp curves than in areas with few sharp curves. At the same time, the modified coefficients are consistent with the finding that sharp curves are associated with an increased accident rate, the more so the sharper they are.

5 Driver behavioural adaptation by choice of speed

Drivers adapt their behaviour to curves. The two main forms of behavioural adaptation among car drivers are adaptation of speed and adaptation of alertness. Changes in alertness are difficult to observe, but changes in speed are readily measured. Cardoso (2005) developed speed models for curves and straight road sections that will be applied in order to describe how drivers adapt speed to alignment. The models developed for roads with paved shoulders have been applied. For straight road sections, speed (in km/h) is estimated as:

$$\text{Speed} = -28.52 - 0.047 \cdot S + 15.75 \cdot W + 0.0237 \cdot R \tag{6}$$

S is curvature change rate, measured as gon/km, *W* is the width of the road (metres) and *R* is the radius of the curve preceding the straight section. Applying this to the first row of Table 2, a car entering the section will first drive through a curve with radius 50 metres (and length 50 metres). This curve has the value of 63.7 gon. The width of the road is assumed to be 7 metres and the radius of the curve preceding the tangent is 50 metres. When exiting the section, the car will drive through the second curve. All cars are assumed to travel the entire length of one kilometre. Speed on the straight section is then estimated as 76.9 km/h. This speed is entered in equation (7) when estimating speed in curves (in km/h):

$$\text{Speed in curves} = 16.44 - \frac{158.05}{\sqrt{R}} + 2.12 \cdot W + 0.705 \cdot V_s \tag{7}$$

R is curve radius in metres, *W* is the width of the road and V_s is unimpeded approach speed estimated in equation (6). Speed in a curve with radius 50 metres is estimated to be 63.1 km/h.

If the road section has four curves each with a radius of 50 metres, speed on the straight sections is estimated to be 70.9 km/h and speed in curves 58.9 km/h. To what extent can this adaptation of speed explain why roads with many curves do not necessarily have a much higher accident rate than roads with few curves and may even have a lower accident rate? In 1985, Leonard Evans introduced the concept 'human feedback parameter' to help formalise the analysis of behavioural adaptation to road safety measures (Evans 1985). He defined this parameter as follows:

$$\Delta S_{act} = (1 + f) \cdot \Delta S_{eng} \tag{8}$$

The real change in safety ΔS_{act} is a function of the 'engineering' effect of a measure ΔS_{eng} and the feedback parameter *f*. If there is no behavioural adaptation, the feedback parameter is 0, and the actual safety effect equals the engineering effect. If the feedback parameter is 1, there will be no change in safety, i.e. behavioural adaptation fully offsets the intended effect of a measure. The engineering effect of a safety measure is the level of safety built into it. When designing horizontal curves, engineers must decide on a radius that makes the curve safe to negotiate at the design speed of the road. The minimum radius at a given design speed is given by (Levinson *et al.* 2021):

$$R = \frac{v^2}{g \cdot (e + f_s)} \tag{9}$$

R is radius, *v* is speed (in metres per second), *g* is the acceleration of gravity (9.8 metres per square second), *e* is superelevation in the curve, and *fs* is the coefficient of side friction. Equation (9) can be used not only to decide on a safe radius for a curve, but also to estimate maximum safe speed, given the radius of the curve, its superelevation and the coefficient of side friction. Safe speed in the curves used as examples in this paper has been estimated by assuming a superelevation of 8% (e = 0.08), which is the design standard in Norway, and a side friction coefficient declining linearly from 0.2 at 50 km/h to 0.1 at 100 km/h. The resulting maximum safe speeds are shown in the bottom panel of Table 2.

It is seen that the predicted speed is always below the maximum safe speed, but less so the fewer and sharper curves there are. It is eminently reasonable that accident rate is highest in the curves where the safety margin is smallest. The feedback parameter of equation (8) indicates how much of the built-in-safety margin drivers eliminate by means of behavioural adaptation. However, unlike road safety measures, a horizontal curve is a risk factor. Its engineering effect is to increase risk. Therefore, the question becomes: how much higher would risk in horizontal curves be if drivers did not adapt their behaviour to curves? One may think of driving through a curve at the maximum safe speed as a case of no behavioural adaptation. Thus, the further below the maximum safe speed actual speed is, the more drivers adapt their behaviour to avoid the increase in risk that would otherwise occur. An estimate of the feedback parameter can be obtained by computing how much lower the accident rate is in a curve compared to what it would have been at the maximum safe speed. Applying the exponential model of the relationship between speed and the number of accidents (Elvik 2019b), and a coefficient of 0.045 for injury accidents, it can be estimated for the first case of two sharp curves with a long straight section between them that the ratio of actual accident rate to the rate expected at the maximum safe speed is:

$$\begin{aligned} &\text{Ratio of actual accident rate to rate at maximum safe speed} = \\ &= e^{(-6.6 \cdot 0.045)} = 0.743 \end{aligned} \tag{10}$$

This corresponds to a feedback parameter of 0.743 − 1 = -0.257. Similar estimates for the other seven cases gave feedback parameters varying between -0.385 and -0.866. The median is -0.7 and the mean value is -0.64.

6 Discussion

The sharper a curve, the higher the accident rate in the curve, all else equal. Thus, a road with many sharp curves ought to have a much higher accident rate than a road with few or no sharp curves. Only: all else is *not* equal. Sharp curves tend to be found on roads that have many of them. This influences speed and reduces accident rate. Drivers adapt their behaviour to such an extent that differences in safety between bendy roads and straight roads are in some cases reversed: bendy roads are safer than straight roads, despite the fact that each curve is associated with an increase in accident rate. As illustrated by numerical examples in this paper, such a reversal of safety is mathematically possible even if curves are associated with an increased risk of accidents.

These findings very clearly illustrate the major role of speed for the safety in horizontal curve. This behavioural adaptation is likely to work both ways: If curves are flattened (i.e. their radius increased), speed is likely to increase and any effect on the number of accidents is likely to be considerably smaller than the difference in accident rate between sharp and gentle curves suggest. The potential for improving safety by flattening curves is greatest when the curve is an isolated curve coming as a surprise to drivers. Very curvy roads force speed down and are probably safer if left as they are rather than trying to rebuild them.

7 Conclusions

The main conclusions of the study presented in this paper are:

- Overall accident rate on roads with many sharp horizontal curves is only marginally higher than on roads with few sharp horizontal curves.
- Drivers adapt behaviour to horizontal curves to such an extent that differences in safety between roads with few curves and roads with many curves are almost eliminated.
- It is entirely possible for areas with curvy roads to be safer than areas with straight roads, despite the fact that each curve increases the risk of accident.
- Driver behaviour is much more important for the safety of a road than its geometric design.
- On roads with low speed limits, an increasing number of curves per kilometre of road is associated with a lower accident rate.

CRediT contribution statement

Rune Elvik: Conceptualisation, Data curation, Formal analysis, Methodology, Writing—first draft, Writing—final review.

Declaration of competing interests

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The study presented in this paper was made as part on the ongoing revision of the Handbook of Road Safety Measures, funded by the Norwegian Ministry of Transport and the Norwegian Public Roads Administration, grant number 1175 to the Institute of Transport Economics.

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