Effects of Weather-Controlled Variable Speed Limits and Warning Signs on Driver Behavior

Pirkko Ramä

This study was designed to investigate the effects of weather-controlled speed limits and signs for slippery road conditions on driver behavior on the Finnish E18 test site. Local weather and road conditions were monitored from two unmanned road weather stations. The speed limits were lowered automatically during adverse road conditions, and in some cases signs for slippery road conditions were displayed as well. Speed and headway data were obtained from loop detectors. The results showed that in winter the change of the posted speed limit from 100 km/h to 80 km/h decreased the mean speed of cars traveling in free-flow traffic by 3.4 km/h, in addition to the average mean speed reduction of 6.3 km/h caused by adverse weather and road surface conditions. When poor road conditions were difficult to detect (e.g., there was no rain or snowfall or the rain was insignificant), the effect was 1.9 km/h higher (i.e., the reduction was 5.3 km/h). When road conditions were such that signs for slippery road conditions were also displayed, the variable speed limit system reduced the mean speed by 1.8 km/h, whereas the reduction caused by the weather was 9.3 km/h. In addition to the effects on mean speed, lowering of the speed limit decreased the speed variance. There was no remarkable effect on headways. The signs decreased speeds also on the road section next to the equipped section. The main implication of the study is that the system improved traffic safety by decreasing mean speeds and speed deviation.

Traffic safety is impaired during adverse road conditions. The accident risk is higher when there is rain or snowfall or when there is snow on the icy. When the road surface is icy, the risk is highest, approximately 20 times higher compared with the risk in good road conditions (1). Drivers should adapt their speed according to the prevailing road conditions, but it has been shown that speed reduction is not sufficient (2.3). Consequently, the possibilities for drivers to control the movements of the vehicle are much poorer than under good road conditions. Furthermore, one might assume that this would be the case, particularly when poor road conditions are not easily detectable by drivers.

Because of the high accident risk in winter, speed limits are decreased during the winter season in Finland. On most two-lane roads, the speed limits are decreased from 100 km/h to 80 km/h and on limited-access highways from 120 to 100 km/h. The winter season limits are normally in force from the beginning of November to the beginning of April. This measure has proved to be effective in improving traffic safety (4). However, there are several arguments for further development of a more flexible system including variable speed limit signs and warning signs.

First, the weather and road conditions might be so poor that speed limits should be lowered by more than 20 km/h, especially in situations not easily detectable as dangerous by drivers, such as "black ice." Second, it might also be justified to decrease speed limits in sum-

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Technical Research Centre of Finland, P.O. Box 1902, FIN-02044 VTT, Finland.
middle of the weather-controlled road (northbound). The reliability of operation of the weather-controlled system was also assessed.

METHODS

Description of System

The site of the experiment was on Finland's southern coast on interurban Highway E18. Road conditions may change rapidly on the site, and changes are exceptionally frequent. The experimental highway was a 14-km-long limited-access highway (Figure 1). All speed limits (a total of 36 signs) on the road section were variable. In addition, there were five information displays. All VMSs on the experimental road section employed fiber-optic technology. They were of the standard size used on limited-access highways in Finland.

The speed limits were automatically controlled on the basis of data from two unmanned road weather stations that collected standard meteorological data. In addition, the weather stations determined the road surface status via four road surface condition sensors embedded in the road. A cable transmitted the station data to a central computer at 5-min intervals for storage and analysis (9,10).

Road and weather conditions were classified in three categories: poor, moderate, or good. The automatic classification was based on several factors. The most important included rain or snowfall, rain intensity, road surface conditions, visibility, and wind velocity. If necessary, manual control was used by the traffic control center operators, who cooperated with the maintenance personnel.

The five message displays consisted of two sign modules. The upper sign module was capable of presenting three standard traffic icons: slippery road, general warning, or road construction ahead. When these symbols were not needed, the sign module was dark (Figure 2). In the current study, the VMSs displayed a symbolic slippery road or the sign was dark. The lower section of the message display was a text information light-emitting diode (LED) sign module consisting of two lines of 10 characters each. The character height was 225 mm and the resolution was 7 x 5 pixels. The textual information was displayed with or without the symbolic information. Neutral textual messages, such as air and road temperature or “Have a nice trip,” were included in the study. The brightness of each sign was automatically controlled according to the ambient light level.

During the time period from April 1 to October 28, the speed limit distribution was as follows: 77.4 percent at 120 km/h, 19.5 percent at 100 km/h, and 3.1 percent at 80 km/h. From October 29 to March 30 the speed limit distribution was as follows: 79.5 percent at 100 km/h and 19.5 percent at 80 km/h. The sign for slippery road was used 0.5 percent of the total time at one site and 2.0 percent of the total time at another site.

The control road was used to estimate effects of road and weather conditions on speed. No before-and-after design was possible because the experimental road was a new road section on which the VMS system had been in operation from the beginning. The control road (a limited-access highway) was located about 100 km to the west of the experimental highway. The site was selected so that it represented the same type of road with the same speed limits in good conditions and equal weather circumstances, and it was located as close as possible to the experimental road section. There were no VMSs on the control highway section. The speed limits on the control highway were 120 km/h in summer and 100 km/h in winter.

Design

The main analyses were based on comparisons of the mean speed on the experimental highway and on the control road. More specifically, the effects of VMSs were computed by subtracting the effects of adverse road conditions (determined by the data from the control road) from the total effects found from the experimental highway. The following three formulas were used:

FIGURE 1 Weather-controlled road: description of test site and measurements.

FIGURE 2 Speed limit sign and variable message display.
Winter season:

\[ \Delta \mu_{s,3} = (\mu_{s,3} - \mu_{s,2}) - (\mu_{c,3} - \mu_{c,2}) \]  

Summer season:

\[ \Delta \mu_{s,2} = (\mu_{s,2} - \mu_{s,1}) - (\mu_{c,2} - \mu_{c,1}) \]  

\[ \Delta \mu_{s,1} = (\mu_{s,1} - \mu_{s,0}) - (\mu_{c,1} - \mu_{c,0}) \]

where

\[ \mu = \text{mean speed} \]

\[ m = \text{VMS (speed limit, slippery road sign, or both)} \]

\[ E = \text{experimental road} \]

\[ C = \text{control road} \]

The second index refers to the prevailing speed limit and the third index to the road and weather classification (w1 = good, w2 = moderate, and w3 = poor road and weather conditions).

The data from the experimental and the control roads were matched. In the matching process the primary criterion was the road and weather classification, and day of the week and time of day were the secondary criteria. For each parameter, the minimum number of observations was 750. Vehicles with a maximum speed of 40 km/h were excluded from the analyses.

The effects of VMSs on the standard deviation of speed, the 15th-percentile speed, and the 85th-percentile speed were computed similarly to those on mean speed.

For computing the effects on the road section next to the equipped section (a two-lane road heading north from the middle of the experimental road), the control direction was used to estimate the effect of weather. The experimental direction was defined to be the direction of traffic driving from the weather-controlled road and the control direction to the weather-controlled road.

**Data Collection**

Speed and headway data were obtained from loop detectors. There were three automatic traffic data collection stations on the experimental highway and one station on the control road. The minimum distance between the loop and the variable speed limit sign varied from 10 to 100 metres. Correspondingly, the minimum distance between the loop and the variable warning sign varied from 3 to 4200 m. In addition, there was a loop on the two-lane road section next to the experimental road section (at a distance of 10 km).

The road and weather conditions at the loop locations were estimated by the data from the automatic road weather stations. The weather conditions were classified in one of three categories (good, moderate, or poor). In total, data from five road weather stations were included. The distances from the road weather stations to the traffic measurement points varied from 0 to 15 km.

In statistical analyses, significant differences between means were determined by the t-test. The p-value is given when statistical testing has been made.

**RESULTS**

**Speed Analyses**

The main analysis of driver behavior focused on the mean speed effects in different sign and weather conditions. Only cars traveling in free-flow traffic were included in the analysis of mean speeds. Cars were defined as driving in free-flow traffic when their following distance ahead was more than 5 s. On average, 57 percent of cars traveled in free-flow traffic on the experimental road.

In winter, when the road conditions were good, the speed limit was set at 100 km/h. At those times the mean speed on the experimental road was 99 km/h and on the control road it was 104 km/h.

The proportion of drivers who exceeded the posted speed limit by more than 10 km/h was smaller on the experimental road than it was on the control road.

**Effects on Mean Speed in Winter**

**Speed Limit**

The mean effect of lowering the speed limit from 100 to 80 km/h was 3.4 km/h (p < .001). The decrease in the mean speed (i.e., the effect of the VMSs and weather conditions) was on average 9.7 km/h on the experimental road, whereas the decrease in the mean speed (i.e., the effect of weather conditions) was 6.3 km/h on the control road (Table 1). In the reference situation, road conditions were good, the speed limit was 100 km/h and there was no significant information on the displays. Sample size varied between 3,218 and 62,555 (p < .001).

For a more detailed analysis, the data on the adverse weather and road conditions with lowered speed limits were divided in two parts according to rain intensity. The rationale of the division was the hypothesis that the system would be less effective under adverse conditions easily detectable by the drivers such as rain and snowfall, and vice versa.

The “no rain” situations were regarded as road conditions not easily detectable as adverse by the drivers. In 94.1 percent of the situations there was no rain or only light rain, and in 5.9 percent of situations there was moderate or heavy rain. On the control road, the corresponding proportion of moderate or heavy rain was about 15 percent.

The results showed that in the “no rain” data there was an additional decrease in mean speed of 1.9 km/h as compared with the total data (Table 2). In the reference situation, road conditions were good, the speed limit was 100 km/h, and there was no significant information on the displays. Sample size varied between 3,112 and 59,647. The speed reduction due to the speed limit was 5.3 km/h (p < .001).

When there was moderate or heavy rain, the decrease in the mean speed caused by bad weather on the control road was greater than

<table>
<thead>
<tr>
<th>Site</th>
<th>Direction</th>
<th>Experimental road km/h</th>
<th>Control road km/h</th>
<th>Effect km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-7.0</td>
<td>-13.3</td>
<td>-6.3</td>
</tr>
<tr>
<td>2</td>
<td>-7.6</td>
<td>-11.4</td>
<td>-1.1</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-9.1</td>
<td>-9.5</td>
<td>-4.1</td>
<td></td>
</tr>
</tbody>
</table>

- variable speed limit
- fixed speed limit
TABLE 2  Mean Speed Effects of Reduced Speed Limits and Adverse Road Conditions with No Moderate or Heavy Rain for Cars Traveling in Free-Flow Traffic in Winter Time

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Experimental road</th>
<th>Control road</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
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<td>8.8</td>
<td>-1.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-13.1</td>
<td>-6.0</td>
</tr>
<tr>
<td>Site 2</td>
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<td>-1.9</td>
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<tr>
<td></td>
<td>2</td>
<td>-11.3</td>
<td>-5.5</td>
</tr>
<tr>
<td>Site 3</td>
<td>1</td>
<td>-8.8</td>
<td>-3.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-9.7</td>
<td>-5.7</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>-9.5</td>
<td>-4.2</td>
</tr>
</tbody>
</table>

Explanation of the symbols:
- **variable speed limit**
- **fixed speed limit**

the decrease caused by weather and variable signs combined on the experimental road.

Sign for Slippery Road

When the sign for slippery road was displayed in addition to the decreased speed limit because of snow or ice, the speed reduction caused by the VMSs was smaller, on average 1.7 km/h (p < .001). However, under these severe conditions, the effect of the poor weather was substantial on the control road, 9.3 km/h (Table 3). In the reference situation, road conditions were good, speed limit was 100 km/h, and there was no significant information on the displays. Sample size varied between 2,334 and 18,879 (p < .001).

In some cases, the speed limit was not reduced but the slippery road sign was displayed, for example, when the right lane was in good condition but the left lane was slippery. The mean effect of the sign for slippery road then was 2.5 km/h. However, an examination of the results based on driving direction showed that effects were more substantial and significant (p < .001) for westbound traffic only (Table 4). In the reference situation, road conditions were good, the speed limit was 100 km/h, and there was no significant information on the displays. Sample size varied between 751 and 42,260.

The effects presented in parentheses were not statistically significant; for others, p < .001.

TABLE 3  Mean Speed Effects of Reduced Speed Limits, Sign for Slippery Road, and Adverse Road Conditions for Cars Traveling in Free-Flow Traffic in Winter Time

<table>
<thead>
<tr>
<th>Site 1</th>
<th>Direction</th>
<th>Experimental road</th>
<th>Control road</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>1</td>
<td>-10.1</td>
<td>-12.9</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>-14.6</td>
<td>-12.4</td>
<td>-2.2</td>
</tr>
<tr>
<td>Site 2</td>
<td></td>
<td>-11.2</td>
<td>-10.7</td>
<td>-0.6</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>-10.6</td>
<td>-7.9</td>
<td>-2.8</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>-8.8</td>
<td>-2.8</td>
<td>-5.9</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>-11.1</td>
<td>-9.3</td>
<td>-1.7</td>
</tr>
</tbody>
</table>

Explanation of the symbols:
- **variable speed limit**
- **variable slippery road sign**
- **fixed speed limit**

Effects on Mean Speed in Summer

In the summer season, the speed limit was decreased from 120 to 100 km/h if road and weather conditions were adverse. The mean effect of the variable speed limit was on average 5.1 km/h (p < .001). The decrease in mean speed on the experimental road was 7.2 km/h, whereas on the control road the decrease was less than in winter, 2.0 km/h (Table 5). In the reference situation, road conditions were good, the speed limit was 120 km/h, and there was no significant information on the displays. Sample size varied between 24,632 and 145,175 (p < .001).

At one site 80 km/h was used because of poor road weather conditions (not shown in the Table 5). The resulting speed effect was on average 8 km/h (p < .001). The mean speed decreased on the experimental road in both directions by 14.1 km/h, whereas on the control road it was on average 6.1 km/h.

Speed Distribution

In addition to the main analysis of mean speeds, the standard deviation and the 15th- and 85th-percentile speeds for the total traffic flow were analyzed. The results (Table 6) showed that in winter under poor road conditions the VMS system decreased the standard
deviation of speed. The mean reduction was 2.4 km/h (Table 6). In the reference situation, road conditions were good, the speed limit was 100 km/h in winter and 120 km/h in summer, and there was no significant information on the displays. The sample size varied between 1,399 and 33,053 (winter), 13,279 and 124,185 (summer), p < .001. Specifically, on the experimental road the 85th-percentile speed decreased usually more than the mean speed, and 15th-percentile speed decreased less than the mean speed. Consequently, the standard deviation of speed decreased slightly. On the control road the standard deviation of speed increased under adverse weather and road conditions. The 15th-percentile speed decreased more than the mean speed and the 85th-percentile speed less than the mean speed. A similar pattern was observed when the sign for slippery road was displayed with the speed limit, the reduction of the standard deviation being 4.7 km/h. When only the sign for slippery road was used, there was no similar effect on the standard deviation of speed.

In summer, the lowering of the speed limit decreased the standard deviation by 2.1 km/h on average (Table 6). There were no substantial changes in the speed distribution on the control road. On the experimental road the lowered speed limit decreased the highest speeds especially. More specifically, the 85th-percentile speed decreased more than the mean speed.

Headways

The analysis included vehicles driving in car-following situations, that is, vehicles with a maximum headway of 5 s between the themselves and the vehicle ahead. The proportions of headways less than 1.5 s were calculated by sign condition. In general, the proportions were quite low (about 18 to 20 percent) because of the relatively low traffic volume (11,000 to 15,000 daily traffic volume) for the four-lane road. The effects of the VMSs on the proportion of the headways under 1.5 s varied from 1.0 to 6.6 percentage units.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experimental road km/h</th>
<th>Control road km/h</th>
<th>Effect km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>85</td>
<td>8.2</td>
<td>-1.2</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>15</td>
<td>8.2</td>
<td>-1.5</td>
</tr>
<tr>
<td>85</td>
<td>8.3</td>
<td>1.0</td>
<td>-0.3</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>15</td>
<td>8.3</td>
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<td>85</td>
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<td>85</td>
<td>8.5</td>
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</tr>
<tr>
<td>Sensitivity</td>
<td>15</td>
<td>8.5</td>
<td>-1.5</td>
</tr>
</tbody>
</table>

**TABLE 6** Effects of Speed Limits (80 km/h in Winter and 100 km/h in Summer) on Speed Distribution of Total Traffic

Headways

The analysis included vehicles driving in car-following situations, that is, vehicles with a maximum headway of 5 s between themselves and the vehicle ahead. The proportions of headways less than 1.5 s were calculated by sign condition. In general, the proportions were quite low (about 18 to 20 percent) because of the relatively low traffic volume (11,000 to 15,000 daily traffic volume) for the four-lane road. The effects of the VMSs on the proportion of the headways under 1.5 s varied from 1.0 to 6.6 percentage units.

### Mean Speed on Road Section Next to Equipped Section

In order to investigate whether the variable signs and information on the adverse weather and road conditions had any effect on the road network nearby, the mean speed on the two-lane road section next to the experimental weather-controlled road was analyzed. The control direction was used to estimate the effects of the adverse road and weather conditions. In addition, control data were available for 1-month (September-October) before the VMSs had been implemented.

In winter the lowered speed limit and the signs for slippery road decreased the mean speed on the neighboring road section. The mean effects for all vehicles varied from 0.8 to 1.0 km/h (p < .001) depending on the conditions indicated by the signs. In the summer season when the speed limit was lowered from 120 to 100 km/h, the system increased the mean speed on the neighboring road 0.3 km/h (p < .001). However, in the "before" data there was a road conditions-dependent difference between the directions. Specifically, the mean speed in the experimental direction was 2.8 km/h more than the mean speed in the control direction when the weather and road conditions were adverse, but the mean speeds were almost equal when the weather and road conditions were moderate or good. This difference suggests that the speed-decreasing effects might be larger than estimated.

**ASSESSMENT OF SYSTEM RELIABILITY**

System reliability is a key factor if driver behavior is to be influenced. In order to assess system reliability, manual observations of weather and road conditions were collected, and friction measurements were carried out. In total, 139 situations were analyzed. Most of the manual observations were made when weather and road conditions were becoming worse.

Manual observations were cross-tabulated by two factors: the actual sign condition (displayed speed limit or warning) and the appropriate signing that was estimated by the manually collected data. The criteria for the appropriate signing were the set of rules applied in the control strategy for the VMS system.

In 70 percent of the cases, the speed limit and the use of the sign for slippery road were estimated to be appropriate. Furthermore, the results indicated that there was a tendency to use too-high speed limits. In 26 percent of the cases, the speed limit was assessed to be too high or the sign for slippery road was not displayed, although it should have been. In contrast, the actual speed limits were seldom too low compared with the controlling principles of the system.

**DISCUSSION AND CONCLUSIONS**

The purpose of the study was to investigate the effects on driver behavior of variable speed limits and signs for slippery road conditions. The main results indicated that the weather-controlled system decreased both the mean speed and the standard deviation of speeds. On the control highway section (no VMS system) the mean speed was also decreased during adverse weather and road conditions, but less, and the variance of speeds increased.

The average speed reduction was 3.4 km/h in winter. This reduction is at the same level or somewhat lower than has been found in the studies concerning fixed wintertime speed limits in Finland (4). However, the variable speed limits of the present study were used to lower the already lowered winter speed limits.

Adverse weather and road conditions in winter, for example, "black ice," are sometimes difficult to detect as hazardous by drivers. This has been one of the motivations to build up weather-controlled sign systems because one might expect the systems to be most effective in these situations. In order to examine this effect, the data were divided into two parts according to the rain intensity. The results
showed that when there was no considerable rain, the mean speed decreased more (1.9 km/h) than it did on average. Specifically, the effect on the experimental road remained the same, but the average effect of the weather was smaller on the control road. Hence, the system proved to be more effective when the adverse weather and road conditions were not easy to detect.

The combined effects of the lowered speed limit and the sign for slippery road were smaller than expected. However, in these situations the effect of weather as such on speeds was substantial. Evidently, the adverse weather and road conditions were very obvious, and as a result, the effects of the system were less substantial. The effect of the sign for slippery road used without lowering of the speed limit was at the same level as that found earlier (5). The effects of the system on mean speed were substantial during the summer season. Variable speed limits during the summer season are especially justified in spring and fall, when the higher speed limits are allowed but weather conditions may be more or less similar to winter conditions.

The analyses of the speed distribution showed that the speed patterns were different in winter and in summer. In winter, when weather and road conditions became adverse, the speed variance on the control road increased. Specifically, the 15th-percentile speeds decreased substantially more than the 85th-percentile speeds. This finding might indicate that many drivers tended to drive according to the speed limits (i.e., speed limits are understood not only as the highest allowed speed limits but also as speed recommendations). Under adverse weather and road conditions, some drivers on the control road lowered their driving speed when others continued to drive at a speed close to the maximum speed allowed. The use of variable speed limits on the experimental road prevented this increase of the speed variance. In summer, the 85th-percentile speed was decreased more than the mean speed; that is, the highest speeds were "cut off." Conclusively, the weather-controlled system increased the homogeneity of driver behavior, which has a positive effect on traffic safety. In addition, the lowered speed limits decreased the mean speeds on the neighboring road section.

The effect of the weather-controlled system was estimated by subtracting the effect of weather and road conditions found on the control road from the combined effects of road and weather conditions and VMSs. Consequently, the estimated effect was directly dependent on the estimate of the weather effect. In general, the speed decreased considerably on the control road because of adverse weather and road conditions, in some cases even more than expected (11). For a number of reasons, it is likely that the error in the estimate is on the safe side; that is, the effects of the VMS system are underestimated.

First, in the current study the mean speed on the control road was higher than the mean speed on the experimental road under good conditions. One reason for that might be that the variable signs looked different compared with the fixed signs. An earlier study has shown that there is better compliance with variable speed limits shown on signs that use fiber-optic technology (12). In any case, one might assume that there was less potential to reduce speed on the experimental road when the speed level was lower than that on the control road.

Second, the rains came typically from west to east in Finland. The control road was further (about 100 km) toward the west. Because of the time definitions of the data (which were necessary to control some other factors), the control data showed more times when the rain had lasted longer (approximately 1 hour) than did the experimental data. Also, the proportion of heavy rain was greater in the control data than in the experimental data. This effect was examined using the data without the first hour of the experimental data. This treatment had no substantial effect on the results. However, the analysis according to rain intensity showed that when there was heavy rain, the speed decrease was more substantial on the control road than on the experimental road. This finding might imply that the rain had lasted longer and that there was more snow on the road. Under these conditions, the effect of the weather was substantial and decreased the estimate of the effects of the sign system.

The assessment of the system function showed that there is also some need to develop the system technically. Specifically, a more sophisticated system to recognize adverse weather and road conditions and low friction is needed.

In conclusion, the concept of the weather-controlled speed limits and displays on Highway E18 was successful. The weather-controlled VMS system contributed to safer driving during adverse road conditions by decreasing the mean speed and standard deviation of speeds. However, it was found that the speed reductions were not sufficient to make the VMS system socially and economically profitable on this road, which had quite low traffic volumes (13).

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