2+1 ROADS WITH CABLE BARRIERS – TRAFFIC SAFETY AND TRANSPORT QUALITY EFFECTS

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Abstract

With the objective to improve traffic safety, the Swedish National Road Administration decided to replace the traditional 13 m road with a 2+1 design, i.e. a middle lane changing direction every 1-2.5 km, with a median cable barrier separating the two directions of travel. The decision to implement this new concept as a standard was based mainly on the expected traffic safety effects, which are found to be substantial. The number of severe and fatal injuries is significantly reduced, yielding traffic safety effects not far from those of a full extension to motorway. However, the question is raised whether the new lane arrangement in combination with a physical barrier has a negative impact on serviceability. A model for vulnerability analysis is developed and applied to two road objects of 2+1 design with a median cable barrier, describing their traffic performance during abnormal conditions. Reduced serviceability is found to be the result to some extent from physical obstructions and quite often due to winter weather, while temporary increases in travel demand can cause rather great disturbances. The concluding discussion touches on the trade-off between traffic safety and serviceability in terms of transport policy goals.

Keywords: Median cable barrier; Traffic safety; Vulnerability analysis; 2+1 roads
Topic area: E2 Performance Measurement

1. Background

1.1 Introduction

There is a significant gap in traffic performance, safety, investment and maintenance costs, land requirement and intrusion between 2-lane and four-lane cross-sections. In Sweden, this gap has so far been filled by a 13 m cross-section with two traffic lanes of 3.75 m each with 2.75 m hard shoulders and dotted road markings. The Swedish national road network of approximately 10 000 km includes some 3 600 km of 13 m roads with speed limit 90 or 110 km/h and an average annual daily traffic (AADT) varying from 4000 to 20 000 vehicles per day. Only some 300 km are semi-motorways, i.e. grade separated with full access control and no pedestrians, bicycles or slow-moving traffic. In the last official guidelines from the 90's, 13 m roads are stated to be a realistic alternative in the traffic interval from 2000 to 12 000 vehicles per day (AADT opening year).

The safety performance on 13 m roads has been found to be some 10 % better than on normal two lane roads with a 9 m cross-section. Still, almost 100 people are killed and about 300 people are severely injured every year on these high speed 13 m national roads in Sweden due to their huge traffic load. This equals 25 % of all fatalities and 20 % of all severe injuries on national roads (Bergh, 1999). The main problem on all 2-lane roads (including 13 m cross-sections) is run-off and head-on/meeting accidents, which account for more than 50 % of all casualties. With the objective to improve safety, alternatives to the 13 m cross-section with wide shoulders were introduced in the 1990's. Some 800 km were converted to 5.5 m lanes with 1.0 m hard shoulders separated with embossed edge markings and some 100 km were converted to road marking based 2+1-designs, i.e. with a middle lane changing direction every 1-2.5 km. However, wide lanes have not turned out to be a traffic safety success so far (Brüde et al., 1996) and the very limited Swedish experiences from 2+1-designs with road markings (Brüde et al., 1997) have not been by far as promising as the German findings (Brannolte, 1993).

1.2 2+1 Roads with median cable barriers

In 1998, the Director General of the Swedish National Road Administration (SNRA) decided on a full-scale program to improve traffic safety on existing 13 m roads using low-cost measures, preferably within existing right-of-way, as the traditional road design did not cope with governmental budget allocations and traffic safety targets. The main alternative solution was the 2+1-solution with a separating median cable barrier, henceforward denoted 2+1cb. This design concept had in fact been discussed by practitioners for a long time and was advocated by Näätänen and Summala already in 1973. The cable barrier was initially chosen due to width, cost and emergency requirements. The main objectives were to develop design and maintenance standards for the new road type, some of the critical issues being:

(a) Would it be acceptable not to widen the 13 m cross section, despite risks for blockage and other problems on narrow 1-lane segments?

(b) Would maintenance operations, especially for expected frequent median barrier repairs, be acceptable?

(c) Would the public accept the concept?

The traffic safety effect was judged to be absolutely obvious and major, up to a 50% reduction in the number of severe injuries and fatalities. The full-scale program also included two narrow 2+2 objects with a separating cable barrier. These were included to meet the rather harsh public and internal criticism encountered at that time. However, the SNRA-team judged the extra safety gain from the 2+2 section to be minor and costs to be major, compared to governmental budget allocations and safety targets.

The experiences from the first pilot project on the E4 semi-motorway Gävle-Axmartavlan (172 km north of Stockholm) were already after 18 months very promising and eventually, in spring 2001, the SNRA decided to replace the traditional 13 m road with the 2+1cb concept as a standard cross-section for new constructions as well as for rehabilitation measures. Up to the 1 January 2004 a total of 420 km semi-motorways and about 530 km on ordinary 13 m roads (i.e. non-grade separated and allowing pedestrians, bicycles and slow-moving traffic) have been opened to traffic with 2+1cb cross-sections. The 2+1cb road is a less spacious and hence cheaper alternative for avoiding head-on/meeting accidents than a full extension to motorway, which has been the most effective solution so far. The SNRA's long-term investment plan indicates that another 1000 km will be opened within the next five to ten years.

The design concept for a 2+1-design with a median cable barrier on an existing 13 m road is as follows. One continuous lane runs in each direction and one middle lane changes permitted direction of travel at intervals of 1.5-2.5 km, depending on road alignment, locations of intersections etc. At long bridges expensive to widen and on sections with frequent access roads, pedestrians and bicyclists, where grade separation is costly or impossible, 1+1-designs can be used. On the other hand, 2+2-sections may also be used in order to avoid 1-lane segments on uphills and to improve traffic performance on sections where widening is possible at low costs.

The proposed cross-section within the existing paved width on normal 13 m roads is a 1.50 m median with a continuous cable barrier, 3.25 m wide traffic lanes in the 2-lane direction and 3.50 m in the 1-lane direction. If not semi-motorway, outer hard shoulders of 0.75 m facilitate very low volumes of pedestrians and bicyclists, although these should be separated when possible at reasonable costs. Access roads should also be taken away and remaining ones designed as "right turns". The barrier, so far normally a cable barrier, should among other things fulfil CEN containment class N2 requirements, be accepted by the emergency authority, not be wider than 0.15 m and give minor impact in the lateral position. The main problem is the narrow 1-lane segments and it is judged on a project-basis whether to widen the cross-section, normally to 14 m, in order to facilitate passage of break-down vehicles etc.

Transition zones from 2 to 1 lane are 150 m long in each direction (i.e. total length of 300 m), with delineators on the cable poles at a distance of 10 m, double-sided lane closure information signs 400 m ahead and at the start of the transition zone. Quick-locks were originally recommended in order to make it possible to open the cable barrier in each transition. Transition zones from 1 to 2 lanes have a total length in the range of 50-150 m. Barrier conspicuity has been judged a major problem and alternative designs of reflectors and road markings have later been tried.

The existing roadside areas should be smoothed within the right-of-way, i.e. solid objects, trees etc. should be taken away and culvert ends tapered. Side cable barriers should be used at dangerous locations such as right bends in rock cuts and on low cuts, as well as on all embankments in forest areas. The maintenance standards include that bridge inspections, overlay repairs etc. should be co-ordinated to minimize the number of traffic diversions. Delineator post washing etc. should be performed during low traffic volume conditions. Snow should be removed in the first 0.4 m of the median and edge lines should be visible. Special traffic management plans for standard maintenance operations were prepared and approved. Permanent emergency openings in the cable barrier are to be established every 3-5 km in order to allow rescue vehicles to turn.

1.3 Scope of this paper

The very first 2+1cb object on E4 north of Gävle was from the start in June 1998 subject to extensive studies of traffic safety performance etc. and new 2+1cb roads have been included in this systematic follow-up concurrently with their opening to traffic (Carlsson and Brüde, 2003). The decision to actually implement the 2+1cb was based mainly on the expected traffic safety effects and the main scope was to work out design and maintenance routines. The second part of this paper presents the results from a traffic safety analysis summarised for all 2+1cb semi-motorway objects opened to traffic so far in Sweden. However, there is a need to find a balance between traffic safety on the one hand and level of service on the other, and the decision was therefore preceded by thorough discussions regarding the acceptability of introducing this concept without widening the road section. Some of the main problems/difficulties are connected to maintenance operations such as snow clearing, cable barrier repairs, new overlays, roadside grass cutting, delineator post washing etc., especially on 1-lane segments. Also there is the risk of road blockage due to e.g. vehicle breakdowns on these segments. In order to assess what implications the new lane arrangement in combination with a physical barrier has on passability, a case study was carried out, aiming to characterise the 2+1cb solution from this vulnerability perspective (Berdica, 2002b). The main results from that study are presented in the third part of this paper. The fourth section then presents a concluding discussion.

For simplicity, the 2+1cb denomination henceforward refers to *semi-motorways* with median cable barriers *only*, thus excluding the converted so called ordinary 13 m roads mentioned earlier. This paper is produced jointly by the authors, although Bergh, Carlsson and Berdica assume main responsibility for the first, second and third part, respectively.

2. Traffic safety on semi-motorways

2.1 Introduction

The main reason behind the 2+1-design with a median cable barrier is to decrease the number of meeting- and overtaking accidents with severe and fatal consequences. In the feasibility study (Bergh, 1997), cable separation in combination with roadside area measures was estimated to reduce the number of severe injuries and fatalities in the range of 20-30, maybe up to 50% (including road side area measures). This should be compared to the reduction of 65 % resulting from a full extension to motorway, which is probably the maximum effect attainable. On the other hand it was judged that the number of slight accidents without personal injuries would increase due to the cable barrier and narrow 1lane segments.

An analysis of the alternative consequences, would a median cable barrier have been installed, was performed for 41 accidents with fatal or severe injuries which all occurred on E4 Gävle-Axmartavlan before 1999. The results indicated that a median barrier could have reduced the severity of the consequences in 27 cases, which equals almost 70%. For the object on E18 Västerås (106 km southwest of Stockholm) the same type of analysis estimated that as severe consequences could have been avoided in over 80% of accidents.

2.2 Accident analysis

For a general safety assessment all accidents that occurred up until 1 July 2003, on all 2+1cb semi-motorways in operation, have been analysed. These 25 objects constitute a total length of 380 km and a total traffic mileage of 2660 million axle pair km (Mapkm).
About half of this mileage has been executed on 13 objects with a 110 km/h speed limit and the remaining half on objects with a speed limit of 90 km/h. The average annual daily traffic (AADT) is 9900 axle pairs, ranging from 6000 to 22 000. They are with a few exceptions not widened but have on average new over-lays and major roadside improvements, as well as slight betterments of entry lanes at interchanges. The maintenance standard is considerably increased.

The total outcome is about 330 accidents with personal injuries on road links (i.e. excluding junctions, as well as accidents involving game) with in total 346 injuries, of which two are fatal and 52 are determined as severe. There is a complete follow up of all accidents on nine objects (180 km with 1400 Mapkm). The average accident rate on these 180 km is 0.32 per Mapkm, which is about 45 % higher than the rate on ordinary semi-motorways with a corresponding 50/50-distribution of mileage on 90/110 km/h stretches of road. The median barrier design gives a number of “new” accidents with property damage only, of which median cable crashes are the most common. The average injury rate is 0.13 persons per Mapkm. This is about 6% lower than on ordinary semi-motorways, for which the corresponding value is 0.14 for road links.

The most valuable and interesting comparison, though, is for the rate of severe injuries and fatalities. For all 25 objects this rate is 0.0203 per Mapkm. This is significantly lower than for ordinary semi-motorways, for which this rate is 0.042 per Mapkm on road links. This is an average for semi-motorways with 90 and 110 km/h speed limits, without any special measures for the roadside area. A more detailed comparison with corresponding values for different road types with a 50/50 mileage distribution on 90/110 km/h stretches gives the following results:

(a) Semi-motorway with roadside area C, i.e. no special measures: 0.0418 per Mapkm, which implies a reduction of 51%

(b) Semi-motorway with roadside area B, i.e. cleaning and smoothing: 0.0376 per Mapkm, which implies a reduction of 46%

(c) Semi-motorway with roadside area A, i.e. side barrier or flat slopes: 0.0334 per Mapkm, which implies a reduction of 40%

(d) Motorway with median barrier: 0.0149 per Mapkm, which is 27% lower than for 2+1cb roads

(e) Motorway with median barrier and roadside area A: 0.0119 per Mapkm, which is 41% lower than for 2+1cb roads

The design of the roadside area on the 25 objects prior to reconstruction into 2+1-roads was varying but on average the standard can be said to have been corresponding to class B. This means that all the measures taken on 2+1cb roads (i.e. median cable barrier, 2+1 lanes, roadside area measures, new pavements etc.) have resulted in a 46% reduction of the rate for fatal and severe injuries on road links, when considering the outcome during the time each individual object has been open to traffic. The best motorway design has a rate which is 41% lower, and if the comparison is limited to motorways with a 110 km/h speed limit the difference is a mere 13%.

In the 1990’s the SNRA made a special investigation of traffic safety on motorways. This investigation showed a rate for fatal and severe injuries of 0.014-0.020 (depending on the roadside area standard) per Mapkm on stretches with the speed limit 110 km/h. Thus the 2+1cb roads from the beginning of the 21st century have an average rate which is about the same as for motorways with median barriers and corresponding roadside standards from the 1990’s.

The traffic safety outcome presented above can also be used to assess the expected reduction in injuries etc. from implementing the 2+1cb design. The SNRA safety prediction model (SNRA, 2000), used in the cost-benefit calculation program for investment planning, was used to calculate the expected (predicted) accident outcome on an ordinary semi-motorway link with speed limit 90/110 km/h (50/50 distribution) and roadside standard C. Table 1 presents a comparison of these predicted numbers of accidents, injuries and fatalities to the actual outcome (observed numbers) on the 25 objects.

Table 1. Expected number of personal injuries compared to actual outcome up until 1 July 2003, on all 2+1cb semi-motorways in operation (=25 objects).

Number of:	**Predicted**	**Observed**
injuries	369	346
severe injuries and fatalities	110.6	54
fatalities	28.3	2

The observed number of severe or fatal injuries indicates a reduction of 51% and it is significantly different from the predicted one. With a probability of 95% the effect is a reduction of 33-69% in severe injuries. The outcome of two fatal injuries also implies a significant difference compared to the predicted 28.3 fatalities. The observed total number of injured is about 6% lower than the predicted, but this is not a significant difference. On the other hand, the observed number of accidents on 9 objects is greater than the predicted, a significant difference of about 45%. This is in agreement with the expectations in the feasibility study, though, being that the number of slight accidents without personal injuries would increase. Table 2 lists the total number of personal injuries in terms of type and severity. One of the fatal accidents must be characterised as an extreme exception, since it involved a bicycle running in the wrong direction toward oncoming vehicles on a semi-motorway, in the dark without lighting.

Table 2. Distribution of the 346 observed personal injuries on accident type and severity.

Accident type	**Number of injuries**		
	total	**severe+fatal**	**fatal**
Meeting	12	1	
Single	145	34	
Overtaking	37	1	
Catching up	121	15	
Various	25	1	
Crossing/turn off	1		
Vuln. Road users	5	2	2
SUM	***346***	***54***	***2***

As can be observed, there are still some meeting accidents. These accidents are vehicles entering the road in the wrong direction and in some cases collisions with a vehicle that has crashed into the median cable barrier and expanded the cable. Single accidents display the majority of severe injuries. The number of single accidents with severe injuries has been reduced with 30% on 90 km/h objects but there is no observed reduction on 110-objects. The severe injuries normally appear in right hand run-off accidents, sometimes after bouncing on the median barrier. It should be noted that the most serious single accidents have occurred on both one and two lane segments. Also, most of the severe single accidents start with the vehicle running outside of the pavement to the right, resulting in the driver losing control of the vehicle. This was the course of events in a single accident where the vehicle overturned the median barrier and crashed in the ditch on the other side of the road**.** All the five occupants in the car were belted, which – in combination with otherwise very lucky circumstances – resulted in only one slight injury. However, the majority of single accidents are property damage only, after a crash into the cable barrier. There is just one overtaking accident with severe consequences – such accidents generally constitute about 6 % of all severe injuries. However, there have been two overtaking accidents in which there was a collision with a stationary vehicle in the left lane, resulting in totally crashed vehicles, although no one got severely injured. Catching up accidents have increased on 110-objects but are unchanged on 90-objects. These accidents have occurred in both one and two lane segments.

A reasonable conclusion drawn from the data presented above is that accidents with severe consequences have been effectively prevented by the cable barrier and converted into cable crashes, mainly with property damage only. This is valid for meeting accidents in particular but also for single accidents, which have turned out to involve significantly less severe injuries in general. These results provide a basis for an adjustment of the initial judgement of traffic safety effects of 2+1cb roads presented in the feasibility study. The long term effect on severe injuries and fatalities can in a conservative manner be estimated to be a reduction in the range of from at least 40% and up to 55% (including roadside area measures). This should be compared with motorways where the maximum reduction attainable is 65%. The effect regarding only fatalities is probably higher. This reduction for an extension to motorway is 80%, wherefore the effect of the 2+1cb road may be estimated to a 65-75% reduction in the number of fatal injuries.

It can be added that a special analysis of the accident data has been performed, dividing it by speed limit (90 and 110 km/h). The results show that the 110 km/h roads have a worse accident outcome than the 90 km/h objects. The rate for injured persons is 0.15 compared to 011. The rate for fatal or severe injuries is 0.025 per Mapkm for the 110-roads, which is about 50% higher than for motorways with a median barrier and the same speed limit. The corresponding value for the 90-roads is 0.016, which is about 25 % higher than motorways with 90 km/h (and 7 % lower than for motorways with 110 km/h). The most serious accidents with overturned vehicles and catching up vehicles have occurred on 110 km/h roads.

2.3 Median cable crashes

From the beginning it was expected that the number of median cable crashes would be high, in the range 0.5-1.0 per Mapkm. The outcome so far is on average 0.59 for all objects. On roads with higher traffic volumes the rate is in the interval 0.60-0.80, although no significant traffic flow relation has been found. The most extensive/comprehensive data for cable crashes is reported from E4 Gävle-Axmartavlan and includes a total of 300 crashes since the time it was first opened, about 5 years ago. About 30 % of these are also reported to the police and can be investigated. Then again, only 30 % of these police reported crashes were primarily direct cable crashes and then probably due to lack of concentration. The remaining 70% were all preceded by skidding in winter times, flat tyres, uncontrolled manoeuvres including driving outside the right asphalt edge and similar incidents.

About 60 % of all cable crashes have occurred in 1-lane segments and only 5% have occurred in a transition zone from 2 to 1 lane. This proportion is slightly less than the proportional length of transitions, which is about 10 %. About 50 % of the crashes have occurred during winter, December-March. The proportion of the yearly mileage executed during these months is only 25-27 %. Skidding is often the primary cause for a cable crash, another problem being very bad sight conditions during “snow-smoke” (i.e. dry snow whirling around behind heavy vehicles).

There is one other object with comprehensive reports of cable crashes, and that is E4 Ljungby. Here 230 crashes have occurred over the course 32 months, of which about 75% were in 1-lane segments and only 5 crashes in the transition zone from 2 to 1 lane. Of the crashes, 46% have occurred during the winter period. This is a higher share than the corresponding proportion of “wintertime” since the object was opened to traffic. As for the normally lower traffic volumes during winter, the value for comparison is about 30%. An influencing element of winter surface conditions can be observed on this object as well, although not as strongly as for E4.

The rate of cable crashes shows a decreasing tendency, especially on E4 Gävle-Axmartavlan. After October 1999 the cable crash rate has decreased with 35% compared to the first 15 months after opening. The rate decreased after the pavement width in 1-lane segments was increased by one meter (from 4.75 up to 5.75 m). However, the reduction is just slightly larger in 1-lane segments compared to 2-lane segments. The reason behind this reduction in the cable crash rate is not so easy to explain. It could be the widening of the pavement – about 59% of the cable crashes occurred in 1-lane segments after the widening as opposed to 65% for the time before – or road users are growing more accustomed to the design. As an attempt to reduce cable crashes the painting of the edge line towards the median barrier in the southbound direction was changed. In June 2001 the earlier smooth edge line was replaced by a so called “profiled rain flex” line with higher visibility. This has to some degree affected the number of cable crashes. Since June 2001 there have been 63 crashes in the southbound direction compared to 81 in the northbound.

As mentioned above there is no obvious relation between the rate of crashes and traffic volumes. However, roads with high volumes have higher rates in general and almost all 2+1cb objects with a rate over 0.60 per Mapkm have an AADT of more than 9 000 axle pairs per day. A relevant reason for this is that the proportion of vehicles driving in the left lane in 2-lane segments is in general higher. About 25-35% of the crashes occur in 2-lane segments at an AADT of 9-10 000 axle pairs. Assuming a constant rate in 1-lane segments, this implies that a higher proportion of vehicles in the left lane will give a total higher crash rate. The number of times that vehicles catch up, and consequently the number overtaking, is proportional to the traffic volume squared. Thus the proportion of vehicles in the left lane causing cable crashes is proportional to the total traffic flow. In theory, if the AADT value is doubled the cable crash rate will increase by 30%, which would explain the difference between low volume and high volume roads.

Further investigations show that a total paved width of 14 m instead of 13 m is not enough to significantly reduce the number of cable crashes and high rates can be a fact despite a wider pavement. There is, however, one 2+1cb object with low traffic volumes and a 14 m cross-section where the rate is extremely low. On the other hand, that road has a median width of 2.25 m. Hence a median width of more than 2 m could reduce the number of cable crashes, although this has not been investigated further.

It is obvious that the number of cable crashes depends on the winter road surface conditions. On roads with a high degree of snowy and icy conditions there are significantly higher rates of crashes during the winter period. The 25 semi motorway objects together with 18 objects on ordinary 13 m roads have been divided into two groups, the first one consisting of the roads in the northern part of Sweden (north of Lake Mälaren) and the second one of the roads located in the southern part/close to the coasts, the following results are obtained:

(a) The roads in group 1 have an average rate of 0.59 per Mapkm.

(b) The roads in group 2 have an average rate of 0.41 per Mapkm, only 70% of the rate for the northern ones.

(c) At the most 8% of the difference of 0.18 per Mapkm can be explained by the lower average traffic volumes during winter.

The most important conclusion of the cable crash analysis is that the major part of observed differences in crash rates can be explained by road conditions during winter time, a special problem being snow-smoke. Other conclusions are that there seems to be an effect of the driver getting accustomed to the design in that the crash rate is decreasing with time. No significant difference has been detected for a wider, 14 m paved width but it seems that a wide median has positive effects, keeping the vehicles more to the right. Changing the edge line towards the median has had some notable effect so far.

2.4 Safety aspects of maintenance operations

As mentioned previously, the 2+1cb design gives rise to some new problems regarding road maintenance operations that in some respects influence traffic safety. Cable repairs are the biggest problem, with work zone area safety being a major concern. So far, the work is conducted from the overtaking lane (closed by a heavy lorry with TMA-protection at the back), i.e. with full traffic in one remaining lane in each direction. However, passing traffic shows little consideration and one serious incident has occurred when a passenger car simply crashed into the road closure device at high speed. Winter maintenance also causes some problems. The snow clearing speed is unaffected but the snow plough drivers complain that their task is more stressing compared to working on normal roads. There have been some incidents with minor collisions between cars and the snow plough vehicle, luckily with no personal injuries so far. Normal fixed works as delineator post washing, bridge washing, ditches and roadside cultivation etc. is recommended to be performed during low traffic volume conditions. On E4 Gävle-Axmartavlan these tasks are carried out with one-way traffic, the other direction being redirected to a parallel road by means of stationary re-directional signs and variable message signs at each end of the 2+1cb object.

3. Transport quality

3.1 Introduction

The 2+1-design with a median cable barrier is a less spacious and thereby cheaper way of avoiding head-on and overtaking accidents, compared to building motorways. However, apart from the expected safety effects – which have been found to be substantial – introducing this type of road should also affect traffic performance, on the one hand during normal conditions due to the strict control of overtaking possibility, on the other hand during various incidents due to limited space on 1-lane segments. Is it hence possible that, with the new lane arrangement in combination with a physical barrier, another kind of vulnerability has been built in? Vulnerability is here regarded as a susceptibility to incidents that may cause considerable reductions in road network *serviceability* (Berdica, 2002a). In this chapter we present some results from a case study, in which a model for vulnerability analysis in general is developed, proposing a number of indicators of reduced serviceability (Berdica, 2002b). This is then applied to two 2+1cb roads in Sweden, aiming to describe their traffic performance focusing on abnormal conditions. The main situations that are dealt with are physical obstructions (accidents, break-downs, management operations etc.), extreme weather (mainly snow) and temporary increases in travel demand (peak hour as well as holiday traffic), the underlying hypothesis being that 2+1cb roads are sensitive to disturbances in these circumstances.

3.2 Vulnerability analysis model and indicators

Road vulnerability analysis can be regarded as the hub for a whole battery of transport studies needed to gain insights into how well our transport systems work in different respects. Vulnerability problems have also received increasing attention in the past decade or so and an extensive review of various related theoretical and empirical analyses can be found in Berdica (2002a). In the present paper, the aim is to illustrate the traffic performance, or serviceability, of a stretch of road in different key situations using a number of suitable indicators. This is done by on the one hand describing the propensity for serviceability reductions, on the other hand describing the reduced serviceability itself. In other words, the first is attributed to probabilities while the other is a measure of consequences. These two together can then be said to describe the risk for experiencing a reduced serviceability level. The conceptual model proposed here is described schematically in Figure 1, setting out from the supposition that different events in the transport system give rise to disturbances, which in turn can be detected in terms of speed reductions in traffic measurement data.

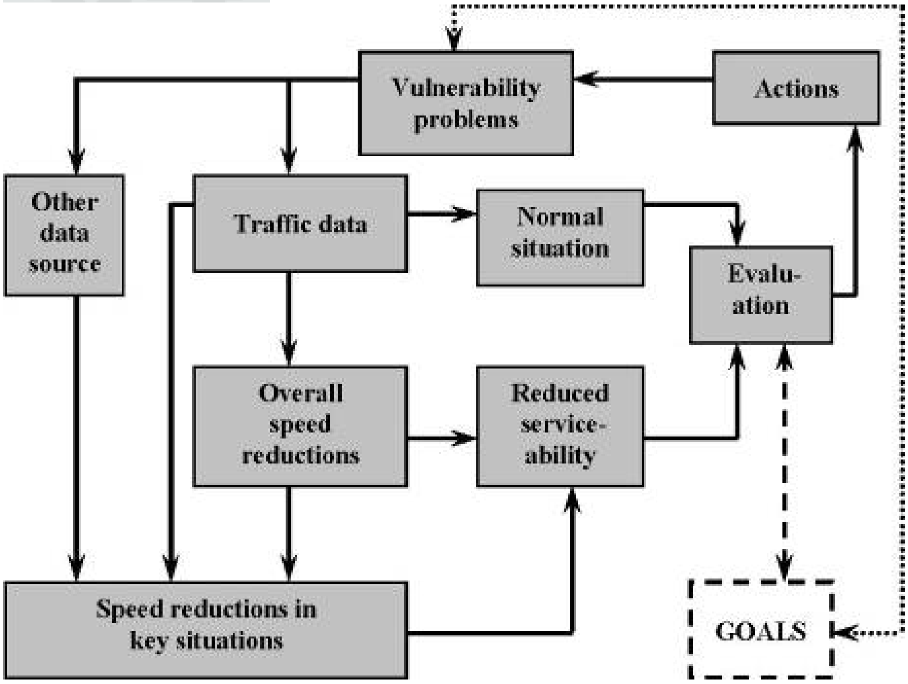


Figure 1. Schematic model for vulnerability analysis.

The basic measure of traffic performance chosen is the weighted average speed for all vehicles. Please note that it is a point measurement and the value calculated is the arithmetic average of vehicle speeds during a certain time interval (time mean speed), which could hence differ from average speed defined in some other way or calculated by some other method. First, overall average speed V is calculated, as well as to which extent it has fallen below a chosen criterion level v. The latter is expressed in two ways:

(a) $D(v)$ = share (%) of total number of days for measurement on which average speed has fallen below v km/h for at least one hour (depending on the time interval chosen for aggregation of traffic data).

(b) $T(v)$ = share (%) of total number of hours (see previous foot note) for which an average speed below v km/h has been registered.

$D(v)$ can be said to estimate the probability that the hourly average speed at least once during one day falls below v, while $T(v)$ estimates the probability that average speed falls below v in an hour picked at random. One could also chose a vehicle at random and ask for the probability that it will pass during an hour with average speed below v, in which case the hours should be weighted with the number of passing vehicles before $T(v)$ is estimated. Consequently, the probability that average speed will keep at an “acceptable” level is $1-T(v)$. This can be regarded as a measure of actual serviceability, which may be preferred as an indicator depending on the context.

The next step focuses on a number of key situations for which $Tx(v)$ is calculated. The consequences are then described by calculating the weighted average speed $Vx(v)$ for the occasions when speed has fallen below v, as well as giving their frequency distribution $Freq(x)$ when deemed appropriate (see Figures 3 and 4). The index x is picked in a manner suitable to distinguish between chosen key situations. In this way, average effects as well as the worst-case scenarios are illustrated. The picture may be supplemented by other factors such as rescue operations (see special survey in section 3.3), total closures etc, which may contribute to describing the situation. The reduced serviceability described in this fashion can then be evaluated/compared to the normal situation *Vx* defined in some suitable manner. For e.g. incidents, average speed for the *days in question* could be used as the “normal value” (see Table 5), in order to eliminate concurrent effects of a bad winter state of the road, while snow effects and high demand could be compared to average speeds over the whole *measurement period*.

It deserves mentioning that the proposed model in Figure 1 makes the wheel come full circle via “actions”. An interaction with set serviceability goals is also indicated, although this is more of wishful thinking at present since no such goals have been introduced as yet. A further elaboration on these two issues was, however, outside the scope of the study.

3.3 Vulnerability on 2+1cb roads

The two stretches of road chosen for the case study are E4 Gävle-Axmartavlan and E18 Västerås. The E4 object is 32 km long with a cross-section of 14 m, due to the addition of an extra meter of paved shoulder on 1-lane segments. The length of 1-lane/2-lane segments varies between 1 and 1.8 km. The annual daily traffic (AADT) is 7 500 vehicles per day with 15% heavy vehicles. The E18 object is 29 km long with a cross-section of 13 m, although there is a supporting strip added inside the side barrier where such are present on 1-lane segments. The 1-lane/2-lane segments are between 1 and 2.5 km in length. The AADT varies between traffic interchanges along the way from about 10 000 to 19 000 vehicles per day, with a distance weighted average of about 12 500 and 14% (range 1116%) heavy vehicles. There is one permanent point for flow and speed measurements on E4 and two on E18 (A1 and A2). The former is situated roughly in the middle of the object, at the end of a 2-lane segment northbound/beginning of a 1-lane segment southbound. The two latter are located as shown in Figure 2. On this part (about 5 km long) the speed limit is lowered to 90 km/h, while it is otherwise set to 110 km/h on both objects. According to SNRA (2001b), free-flow speed for cars on 2+1cb semi-motorways is 107 km/h where the speed limit is 110 km/h and 96.5 km/h where the speed limit is 90 km/h.

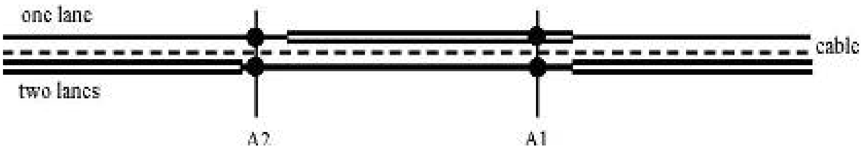


Figure 2. Location of traffic data measurement points on E18.

The case study was started in late summer 2001 and most of the data material belongs to the period from June 2001 to May 2002, with some variation between different sources and between the two road objects. Already established sources of information used were the SNRA Traffic Information Centres (TIC), police reports, SNRA Road Weather Information Stations (VVIS), operations management contractors’ records and traffic data measurements. In addition, a special survey was carried out in co-operation with the rescue corps working on each stretch of road, in order to gain information on incidents not serious enough to attract the attention of e.g. the police but still with a potential for causing traffic disturbances and queues. This provides a so far unused opportunity to gain more direct information on frequencies for incidents, reasons for different types of break-downs and the resulting consequences. Therefore some results from this particular study are presented before going on to the application of the proposed vulnerability analysis model.

Results from special survey

A total of 245 reported rescue operations over a period of 330 days give a frequency of 0.026 per km and day and a rate of 2.03 per million vehicle kilometres of travel (MVKT) on E18. The corresponding figures for E4 are 201 rescue operations over 354 days, yielding frequency 0.018 and rate 2.34. These figures can be compared to statistics from the Road Assistance Service in Stockholm, whose purpose is to quickly intervene and restore passability when breakdown cars, accidents or other incidents block/disturb traffic. From April 1996 to May 1999 a total of 956 alarms were registered for a section of motorway 1.9 km long (Berdica, 2000). With an AADT of 100 000 vehicles per day this yields an alarm rate of 1.9 per MVKT. All in all the special survey gives a rate a little over 2 rescues per MVKT, which is roughly 10% higher. The figures are of the same magnitude but further conclusions are difficult to draw due to considerable differences in both traffic load and design.

The proportion of rescues involving light and heavy vehicles is roughly equivalent to their respective total traffic share, which indicates that the “risk for being rescued” is not connected to type of vehicle. The different reasons for rescue are dominated by various types of technical vehicle problems, the main reason being engine failure. As seen in Table 3, vehicle breakdowns are a little less common on E18, while collisions occur more often, than on E4. This is the first study of its kind for ordinary roads and therefore data for a comparison is hard to come by. An international study of safety in tunnels (PIARC, 1995) can, however, be used for an overall assessment. It states a rate of 3 to 6 vehicle breakdowns per MVKT for one-way motorway tunnels. The categories correspond well with those used in present case study and the values above may seem notably low. The PIARC figure for accidents is 0.3-0.95 per MVKT, compared to which the collision rates on both E4 and E18 seem similar. An explanation could be that our data only includes vehicles that have actually been towed. Even if it is not stated exactly how the data in the tunnel study was collected, it is reasonable to suspect a higher rate of detection by e.g. camera surveillance systems. There is also reason to believe that outside help is called for more often, due to the restrictions – both actual and perceived – that being in a tunnel implies. That the collision rate shows a better correspondence also seems reasonable, since an accident or a collision should result in a rescue operation to a greater extent regardless of location.

Table 3. Summary results from Rescue Corps study

Reason	Incid/MVKT E4	Incid/MVKT E18	Av Work Time E18	Blockage E18	Queues E18
Vehicle	1.58	1.25	11 min	15 min[1]	20 veh[1]
Collisions	0.44	0.54	18 min		
Other	0.31	0.32	17 min		

1) median values

From E18 there is information on actual working times on site, vehicle placement and passability problems. A vehicle breakdown takes on average roughly 11 minutes to clear while a collision takes some 18 minutes (significant difference at 99% level). The time needed to rescue a light vehicle is on average 12.8 minutes, while a heavy vehicle takes 27 (significant difference at 99% level). Further subdivision into vehicle type and reason is only relevant (i.e. statistically significant; 95% level) for collisions, which take 12.5/37.5 minutes for light/heavy vehicles. The difference in working time on 1-lane compared to 2lane segments is negligible and it does not matter if it is a car or a truck that is being rescued. This can, however, be a result of some rescue corps having made it a rule to always call for police assistance when going out to a 1-lane segment, which may help to reduce the time taken. Overall, the distribution of rescue operations on 1-lane/2-lane segments is 39% and 61% respectively. Since the distribution between sections is roughly 50/50, this indicates that the driver tries to get to a 2-lane segment where there is more space while waiting for assistance. This is also confirmed by drivers' comments. On 2-lane segments over 50% of the vehicles are left standing in the normal lane, compared to only 25% on 1-lane segments. For the latter the greater share (just over 40%) is left by the roadside. This also supports the hypothesis that drivers do not experience the same necessity to get out of the way on 2-lane segments, since remaining traffic can pass in the overtaking lane. There seem to be no differences in placement connected to vehicle type.

Blockage and/or queues on E18 due to rescue operations have been registered for 66% of the cases on 1-lane segments and 15% of 2-lane cases. A contributing factor could, however, be the police attendance mentioned previously. This could well result in remaining traffic not pushing past on the narrower segments even if there may be some space left. Analysed by vehicle type, rescue of heavy vehicles cause blockage/queues to a greater extent than rescue of light vehicles – 2/3 of cases compared to some 1/4. The average time for registered blockages is about 31 minutes. The variation is great, though, wherefore the median value of 15 minutes may be a more appropriate measure. Average queue length was estimated to 50 vehicles, with a median of about 20. No significant effects on blockage time and/or queue length could be found for either rescue reason or vehicle type.

As for effects detectable in traffic measurement data, one would expect a general decrease in speed with increasing traffic volume, and that speeds would be lower while rescue was under way. This is also in principle the tendency for both road sections, although there is an overrepresentation of vehicles driving at low speed (i.e. trucks etc.) at times with small flows (i.e. late night/early morning) since the analysis is made for all vehicle types together. The speed reduction seems to be less on E4 (rescue: 101.1 km/h; no rescue 102.7 km/h) than on E18 (rescue: 84.5 km/h; no rescue: 90.5 km/h), which could be explained by its wider cross-section and smaller traffic load. It should be noted, however, that the reduction may not be caused by the rescue action but due to bad weather/winter state of the road in general. This in turn may be the reason behind the incident that caused the rescue effort, hence imposing an overrepresentation of low speed hours in this data. Matching separate rescue occasions with traffic data shows no visible effect on E4. The comparison is difficult though, since information on the exact location and direction for the incident is missing. Since traffic data is collected at a point, possible speed effects will dissipate more and more the farther away from the point of measurement the incident has occurred. Location data is present to a greater extent for E18 and for basically all big (in terms of registered work times, blockages, and/or queues) incidents, speed reductions are detectable. However, the earlier mentioned correlation with winter weather is quite clear and an overall low average speed on the day in question indicates that there may be another main reason than the performed rescue for reduced speeds. Another piece of evidence for this synergy effect is that more rescue operations are registered during winter months (November-March) than during the summer season (May-October).

Results from the application of the vulnerability analysis model

In this vulnerability study of 2+1cb roads the criterion level $v = 80$ km/h was chosen. Depending on the context, however, "considerable effects" could mean both higher and lower limits and the choice of v should therefore be discussed for every separate case. The key situations dealt with are physical obstructions, winter weather and temporary increases in travel demand. These are indexed below by i for incident, w for winter roads and h for high demand.

How one chooses to categorise the data material in time (e.g. season) and space (e.g. direction and/or measurement point) etc. as well as the level defining high demand (here set to 1000 vehicles/h) can vary depending on what is suitable or most illustrative from case to case. Summaries for the two road objects, together with explanations, comments and points of discussion, are presented in the following tables.

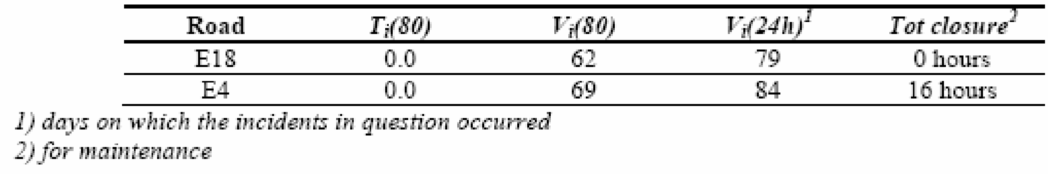
According to the traffic data measurements, the overall time mean speed is 93 km/h on E18 and 105 km/h on E4, with average flows of 403 and 345 vehicles per hour respectively. As stated previously, model free flow speeds (flows up to 500 vehicles/h) are 96.5 and 107 km/h, but the figure for comparison should be the time mean speed, which is generally some 1.5 to 2 km/h higher. The speeds from the case study are hence somewhat low, which is explained by not distinguishing between heavy/light vehicles as well as dry/wet road conditions. On the whole, the two road objects seem to correspond well to “theoretical standards” on average. In more detailed terms (see Table 4), average speed is lower during winter (Nov-Mar) than during summer (Apr-Oct) on both road objects and serviceability is also less during the cold months of the year, although problems occur in summertime as well on E18. Average speed is generally lower and more often below 80 km/h in the eastbound direction on E18, with the most pronounced difference in point A1. This is probably, however, due to the location of the measuring point, at the end of the 1lane segment. On E4 the difference in average speed between directions is negligible. The less frequent fall below 80 in the southbound lane is most likely also attributed to measure point location, at the beginning of the 1-lane segment.

Table 4. Overall results of speed measurements, where *V* is overall average speed (km/h), D(80) is the share (%) of total number of days with average speed (km/h) below 80 for at least one hour, and T(80) is the share (%) of total number of hours with average speed below 80 km/h.

Period	**Point**	**E18 East- / E4 Northbound**			**E18 West- / E4 Southbound**		
		V	***D(80)***	***T(80)***	***V***	***D(80)***	***T(80)***
Winter	A1 E18	85	38.5	8.6	92	19.7	3.5
	A2 E18	92	16.6	3.0	93	16.6	2.3
	E4	102	19.9	2.4	101	14.0	1.6
Summer	A1 E18	88	5.9	0.6	95	2.0	0.1
	A2 E18	94	4.3	0.2	95	6.0	0.4
	E4	107	1.1	0.0	106	0.0	0.0

Very few of the occasions when average speed fell below 80 km/h could with any certainty be attributed to physical obstructions, neither the previously analysed rescue corps activities nor any other incidents. For both E18 and E4 the share of hours when average speed has fallen below 80 km/h is negligible, although weighted average speeds for these few occasions are quite low (see Table 5). A more systematic study, foremost with respect to location and direction information for incidents (rescue actions, maintenance operations etc.) in relation to the points for traffic data measurements, should be conducted. Another contributing factor could be the choice of criterion level. According to the operations management contractors, a routine cable barrier repair takes about 2 hours. Still, no connection could be made to effects visible in traffic data. One aggravating circumstance is that information on the exact time for the repair work is too often missing, although no matches were found for the occasions on E4 for which this data was supplied either. On the other hand, as most repairs are performed from the overtaking lane at such time of day as to minimise any disturbance (i.e. during hours with low traffic flow) speed effects are most likely very local and would only be visible in traffic data if the repairs were made very close to the point of measurement. Data on other maintenance work such as post washing, ditch and roadside clearance etc. was found to be insufficient for further analysis.

Table 5. Overall results for noted physical obstructions, where *Ti(80)* is the share (%) of total number of hours with incidents with an average speed below 80 km/h, *Vi(80)* is the average speed (km/h) for these hours, and *Vi(24h)* is the so called “normal value” for comparison.



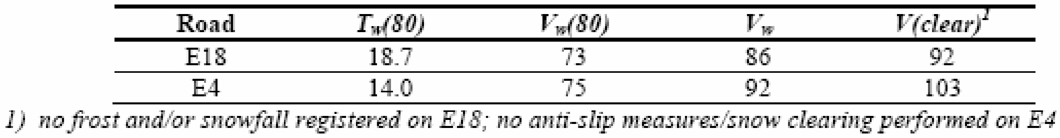
Road	$T_i(80)$	$V_i(80)$	$V_i(24h)^1$	Tot closure^2
E18	0.0	62	79	0 hours
E4	0.0	69	84	16 hours

1) days on which the incidents in question occurred
2) for maintenance

Total closures with redirection of traffic to alternative roads due to maintenance activities etc. are not captured in *D(v)* and *T(v)* as calculated here. In theory, this could be interpreted as speed 0, which is certainly below 80 km/h, and such occasions should then be included in these indicators. This we deemed as somewhat misleading, since such interruptions are planned and the road users are otherwise catered for. The fact that such closures have to be made is, however, an indicator of vulnerability and is therefore presented separately in Table 5 above.

There is a clear correlation between winter roads and lower average speeds and the worse the conditions, the greater the reduction. The speed distributions during summer and on “clear” winter roads differ significantly (1% level) from each other, as do the latter compared to slippery/snow road conditions. Winter roads often cause speeds to fall below the criterion level but average speed still remains over 70 km/h in about 80% and 85% of cases on the two roads respectively (see Table 6 and Figure 3). The levels may seem somewhat high, but it should be noted that it is most likely a question of speeds on *remedied* winter roads. Data from E4 are based on the snow clearing contractors’ work records (anti-slip measures and/or snow clearing), while information for E18 consists of frost and snowfall registrations from three relevant VVIS stations. The reduction due to winter roads as such is deemed to be on average 15 km/h for light vehicles (SNRA, 2001b).

Table 6. Overall results with respect to winter weather, where *Tw(80)* is the share (%) of total number of winter condition hours with an average speed below 80 km/h, *Vw(80)* is the average speed (km/h) for these hours, *Vw* is the average speed during winter conditions in general, and *V(clear)* is the so called “normal value” for comparison.



Road	$T_w(80)$	$V_w(80)$	V_w	$V(clear)^1$
E18	18.7	73	86	92
E4	14.0	75	92	103

1) no frost and/or snowfall registered on E18; no anti-slip measures/snow clearing performed on E4

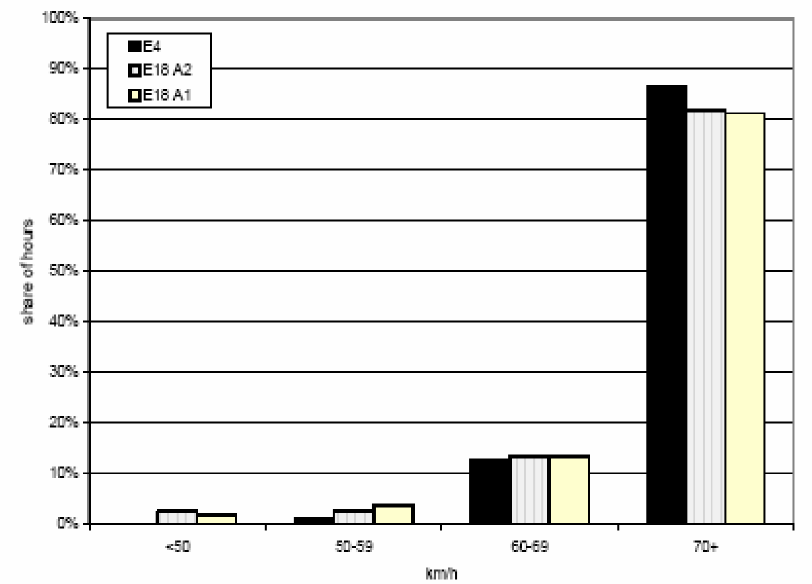


Figure 3. *Freq(w)*, i.e. distribution of average speed below 80 km/h during winter weather conditions on E18 (two measuring points) and E4.

Whether the noted speed reductions in this case study should be attributed to a bad state of the road in general or to vehicles being stuck behind the snow plough (normal speed 30-40 km/h) on 1-lane segments is difficult to say due to the previously mentioned point measurement issues. The E4 has in fact been supplied with maintenance parking bays to allow traffic to pass, thereby minimising queues and the risk for hazardous overtaking. It could also be of interest to study whether road users drive slower in general during winter road conditions on 2+1cb roads, possible reasons being that 1-lane segments seem even narrower during these conditions and/or that the cable prevents the snow from spreading, hence remaining as an "obstacle" in the overtaking lane on 2-lane segments.

Regarding high travel demand, flow rarely exceeds 1000 vehicles/h on E4 and registrations below 80 km/h have not occurred at all. There are clear increases in flow on Fridays and Sundays on, but without remarkable speed reductions. This is also the case during Christmas, New Years and Easter. The serviceability was hence found to be good. However, historical indications of traffic break downs in connection with national holidays exist and this should be looked into further. On E18, higher travel demand with resulting lower average speeds is notable between 4 and 5 pm on weekdays, more still on Fridays, in general. It is unusual, however, that these high flows cause speeds as low as 80 km/h and below even if it does occur in some cases. Whitsun was such an occasion, with speeds as low as 40 km/h. There is a certain sensitivity at hourly flows >1000 vehicles/h, although speeds below criterion level occur relatively seldom (see Table 7). On the other hand, when this does happen average speed is lower than 60 km/h in over 50% of cases at the transition from 2 to 1 lane in the westbound direction (see Figure 4). This indicates great vulnerability with risks for traffic break down on e.g. national holidays. The capacity limit for a 2+1cb semi-motorway according to SNRA standards is estimated to be 1650 vehicles per hour and direction and in this analysis a flow exceeding 1000 vehicles per hour and direction was arbitrarily chosen to represent the level for a "serious disturbance".

Table 7. Overall results with respect to high demand (>1000 vehicles/h) on E18, where *Th(80)* is the share (%) of total number of high demand hours with an average speed below 80 km/h, *Vh(80)* is the average speed (km/h) for these hours, and *Vh* is the average speed during high demand in general.

Point	**Period**	**Eastbound**			**Westbound**		
		Th(80)	***Vh(80)***	***Vh***	***Th(80)***	***Vh(80)***	***Vh***
A1	Winter	14.3	78	84	3.0	73	93
	Summer	6.7			0.0		
A2	Winter	4.5	77	89	8.3	59	89
	Summer	0.0			5.9		

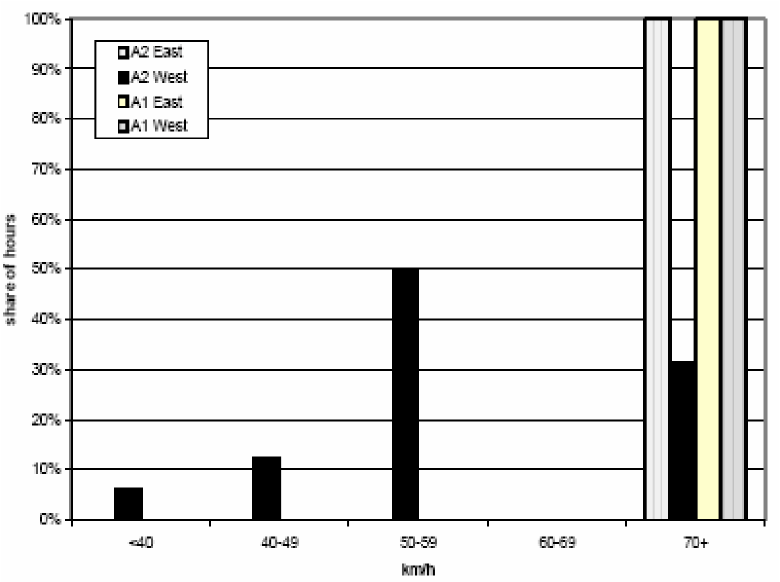


Figure 4. *Freq(h)*, i.e. distribution of average speed below 80 km/h in different directions on E18 during hours of traffic demand >1000 vehicles/h.

Concluding remarks

The key situations in which reduced serviceability could be the case, and that have been analysed in this study, are physical obstructions, winter weather and temporary increases in travel demand. The underlying hypothesis was that 2+1cb roads are sensitive to disturbances in these circumstances. Still, the conclusion in the feasibility study was that these effects were to be minor and even less than the disturbances due to accidents before the 2+1-implementation. The results show that physical obstructions from e.g. rescue operations could cause considerable speed reductions but it takes a relatively long lasting incident in order for it to be detected through traffic data. Routine activities have not been found to show any speed effects. However, this should be studied in further detail, foremost with respect to location and direction information for incidents in relation to the traffic data measurement points. Winter weather accounts for a large share of registered speed reductions, even if the consequences do not seem to be that great. Winter roads are also likely to be the reason behind many incidents that in turn result in rescue operations. Temporary increases in travel demand certainly do not seem to result in average speeds below criterion level all that often, but when it happens the speed reductions can be very great. There are indications of great vulnerability with risks for traffic break down on e.g.

national holidays in the westbound direction on E18. In an overall perspective, however, it seems that the negative consequences of implementing the 2+1cb solution without widening the 13 m cross-section on semi-motorways are fairly moderate so far. One major issue that needs to be resolved, though, is work zone safety when performing maintenance operations etc.

Finally it can be stated that the proposed vulnerability analysis model is based on data that is relatively easy to obtain and a comparison between speed distributions, average speeds, rescue frequencies/rates etc. are easily performed as well as simple to comprehend. It gives an overview of the serviceability on chosen road objects and points to areas where further studies may be needed. The method is flexible in that criterion levels, the so called “normal situation” etc. are simple to adjust depending on the prerequisites and purpose for the study at hand. It also supports a more strictly quantitative consequence analysis in comparison with set goals (although tangible such goals still remain to be set, at least in a Swedish context), with subsequent proposals of remedial measures and a follow-up of the results.

It deserves mentioning that ready availability and ease of collection was one of the underlying reasons for using spot speeds rather than travel speeds calculated over longer sequences, while simplification of calculation and analysis resulted in not distinguishing between heavy and light vehicles. With the benefit of hindsight, the latter proved to be unfortunate and should not be maintained in future studies. Also, the effect of the location of the fixed measuring points may be crucial and is therefore an issue that should be looked into in further detail.

4. Concluding discussion

An accident analysis of all 2+1cb semi-motorway objects opened up to the present indicates that many accidents with severe consequences are effectively prevented by a cable barrier and converted into less severe cable crashes, mainly with property damage only. The traffic safety effect of 2+1cb roads is estimated to be a reduction in severe injuries and fatalities in the range of 40-55%. This should be compared to the alternative situation “changing into motorway”, where the maximum reduction attainable is 65%. The effect regarding only fatalities is probably even higher, with a reduction of some 60-70%. As for serviceability, negative effects of physical obstructions could not be identified in the present case study but this should be investigated further. Winter road conditions is a major cause of reduced serviceability and there are indications of risk for traffic break down when travel demand is high, i.e. we are approaching the capacity limit for this concept. So far, the negative consequences of keeping within the 13 m bounds seem to be limited, apart from work zone safety aspects.

The case study characterises some serviceability aspects of 2+1cb semi-motorways through a number of examples based on experiences and available data. As opposed to the accident analysis, the evaluation as to whether this road type is actually better or worse compared to its predecessor (the ordinary semi-motorway) is never really made. However, traffic safety effects are apparently substantial and this seems to be enough to motivate the inauguration of 2+1cb roads, strictly speaking making it less important whether they are in fact better in terms of serviceability or not. Can it be that, as long as traffic performance is fair, the traffic safety gains make some degree of serviceability loss “worth while”? Hence, the critical issue can be summarised in two questions: At which point is serviceability unacceptable, and how do we keep from reducing serviceability to this point? Among the criteria used by the SNRA it is stated that for a new 2+1cb semi-motorway, AADT in the opening year should not exceed 15 000 vehicles. Traffic on the E18 object is not far from AADT 20 000 and this does seem to cause problems at times. As mentioned before, it is also assessed from case to case whether to widen the cross-section in order to facilitate e.g. passage of break-down vehicles etc. This has been done on the E4, which in some respects seems to "work better" than the E18. Then again, this may also be a result of its lesser traffic load. According to the present study results, none of these effects are that extreme, but the evaluation as to whether they are acceptable or not no doubt needs to be discussed further. Also work zone safety needs to be thoroughly investigated, not only for road maintenance operations but for the rescue corps' crews as well.

To conclude, regular before/after or twin-studies of the 2+1cb design would be useful, not only to see just how much of any effects can actually be attributed to the new cross-sectional design but also to gain information for setting the level for acceptable serviceability etc. Among other things, it would be interesting to study the speed reductions likely to occur during normal conditions, due to the mere fact that there are 1lane segments with no possibility of overtaking. This could be done by for instance developing a theoretical model which, in combination with empirical studies of the kind presented here, should be included in a comprehensive vulnerability analysis. This in turn could prove to be an important tool for the SNRA in their work toward a *reliable* transport system, an aspect recently added to the transport quality goal in the Swedish national transport policy (Prop 2001/02:20). When focus moves toward providing a high level of service during a trip in its entirety, rather than just minimising travel time, vulnerability in the road transportation system becomes crucial in the overall assessment of transport quality.

Acknowledgements

We would like to thank the Swedish National Road Administration and the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning for their financial support.

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