Road Barrier Repair Costs and Influencing Factors

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Abstract: This paper presents a study that examines repair costs for different road barrier types and factors that influence these costs. The analyses focused on w-beam and cable barriers used as median barriers. To some extent, pipe barriers, Kohlswa-beam barriers, and concrete barriers were also studied. The influencing factors included in this study were road type, speed limit, barrier type, and seasonal effects. A case study was conducted in four regions of the Swedish Road Administration. Data were collected from 1,625 barrier repairs carried out during 2005 and 2006. The results show that the number of barrier repairs and the average repair cost per vehicle kilometer are higher along collision-free roads than along motorways and 4-lane roads. The results also show that the number of barrier repairs and the average repair cost per vehicle kilometer are higher for cable barrier than for other barrier types. No conclusion can be drawn regarding influence of speed limits on barrier repairs and associated costs as the result from the regions are divergent and not statistically significant. **DOI: 10.1061/(ASCE)TE.1943-5436.0000227.**

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Introduction

When selecting a type of road barrier, the focus is often on safety performance and investment costs. Life-cycle costs are often ignored, mainly because of insufficient knowledge regarding barrier maintenance. The most frequent maintenance measure for road barriers is damage repair, mainly caused by vehicle collisions or impacts by snow removal equipment. Repair costs for barrier damages constitute a considerable share of road maintenance costs. However, such repair costs are seldom considered during road design and the subsequent selection of barrier types to be used. Limited information concerning repair costs and other influencing factors obstruct an adequate consideration of maintenance aspects when selecting a barrier type during the road design process. This fact is confirmed by a study showing that one of the problems preventing sufficient consideration of maintenance aspects during the road planning and design process is insufficient knowledge regarding maintenance measures and the associated costs (Karim and Magnusson 2008).

Maintenance costs for road barriers differ depending on various factors such as barrier type, barrier design, barrier placement, road type, road alignment, road cross-section, speed limit, and seasonal effects. Knowledge regarding the influence of these factors on barrier repairs and the costs involved is very limited. The actors involved in road maintenance have often acquired a great deal of experience, but this knowledge is seldom documented. The limited amount of literature found on this subject confirms that there is a great need for research, evaluation, and documentation regarding this issue. The need for research regarding barrier repairs and the costs involved has become more evident in Sweden in the past few years, since many roads have been reconstructed to collision-free roads, or 2-plus-1 roads as they are called in some countries. This road type is a specific category of three-lane roads, with two lanes in one direction and a single lane in the opposite direction, alternating every few kilometers. The two opposite directions are separated using road barriers, mainly cable barriers, to prevent crossover collisions (Carlsson and Brüde 2004).

Literature Review

Road barriers are used to prevent vehicles from veering off the roadway into oncoming traffic, crashing into solid roadside objects, or driving off into ravines. Road barriers are also used to protect pedestrians and cyclists from vehicular traffic (AASHTO 2006). Conditions that warrant shielding by roadside barriers are height of the embankment, side slope, and presence of roadside obstacles within the clear zone. The need for median barriers is determined by the width of road medians, road type, speed limits, and obstacles (AASHTO 2006). These criteria are developed on the basis of research studies of median crossover accidents and encroachments. For Swedish conditions, such criteria are specified by Swedish Road Administration (SRA) in the Road Design Manual (SRA 2004).

Road barriers are usually categorized as flexible, semirigid, or rigid, depending on their deflection characteristics on impact. Flexible systems, such as cable barriers, generally impose lower impact forces on vehicles than other categories, since more of the impact energy is dissipated by the deflection of the barrier (AASHTO 1996). This is because the impact event occurs over a large lateral distance, thus extending the time of the impulse event. On the other hand, this is also a disadvantage as the barrier damages usually are extensive.

There are many types of road barriers used around the world. Some of these consist of steel or a mix of wood and steel with a high deflection capacity. Other types consist of rigid reinforced

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concrete elements with very limited deflection capacity or none at all. Design characteristics for barrier categories are basically the same around the world, with minor modifications attributable to different conditions in some countries.

High-tension cable barriers, w-profile barriers, pipe barriers, Kohlswa-beam barriers, and concrete barriers are common barrier types in Sweden. Kohlswa-beam barriers have approximately the same design as w-beam barriers. Kohlswa-beams are designed with thicker steel and lower profile height. There are also other barrier types specifically designed for use on bridges or along specific roads in urban regions for aesthetic reasons.

Performance requirements for barriers are characterized by containment level, impact severity, and deformation or level of working width. The containment level is the ability of a road barrier to contain and redirect errant vehicles safely for the benefit of the occupants and other road users. These criteria are specified by the standard EN 1317-5 (European Committee for Standardization 2008).

Barrier damages attributable to vehicle collisions generally require repairs as fast as possible because the damaged barriers usually lose their efficiency after impacts. In some cases, damaged parts of the barriers, such as damaged posts or beams on the road surface or protruding in the traffic area, constitute additional hazards for road users. These parts must be removed immediately. However, repairs for some barrier types, such as w-beam barriers, are given a low priority after minor impacts mainly because of insufficient maintenance budgets. As long as the beams remain elevated, road authorities believe that these barrier types retain some degree of efficiency after a minor impact, i.e., an impact with low kinetic energy, because of the rigidity of their components (AASHTO 2006). This is in agreement with experience from Sweden that also indicates that high-tension cable barriers used for median barriers lose most of their efficiency even after minor impacts. This is because impact events with flexible barrier types normally occurs over a large lateral distance, damaging a high number of posts (AASHTO 1996). Consequently, the cables lose the required height. However, no scientific studies have been conducted to establish any criteria to determine whether the damaged barriers remain effective.

Barrier damage caused by snow removal equipment is another maintenance issue. This is often caused by contact between barriers and snowplows at a very small impact angle, resulting in superficial scratches on the beams. W-beam and Kohlswa-beam barriers still retain a high degree of efficiency after such damage and do not require repairs as long as the beams remain elevated. The posts also remain undamaged as they are protected by the beams. Conversely, cable barriers usually have to be repaired after snowplow impacts because the posts are knocked down and the cables lose the required height.

In Sweden, cable barriers are preferred before other barrier types mainly because of their low acquisition cost. In addition, insurance companies pay for the entire repair cost of cable barrier damages to encourage a more widespread use of this barrier type, as it is considered to have a high safety performance. However, it is worth noting that both w-beam barriers and cable barriers fulfill the minimum requirements for safety performance.

Barrier damage and the associated costs are affected by several factors, such as impact angles, impact speed, vehicle type, vehicle mass, barrier type, barrier location, and type of road section. In studies by Carlsson and Brüde (2004, 2005, 2006), performance on collision-free roads were evaluated. They found that the damage risk for cable barriers, expressed in the number of repairs per million vehicle kilometer, along roads with a speed limit of 110 km/h is 20% higher than on roads with a speed limit of 90 km/h. Because of this fact, the annual repair costs for cable barrier damages are probably higher for barriers along roads with a speed limit of 110 km/h as well.

According to their studies, the damage risk for cable barriers along collision-free roads in the northern regions of Sweden proved to be 20% higher than in the southern regions. This difference is mainly attributable to icier road conditions in the northern regions. More damages also mean higher repair costs in northern Sweden.

Carlsson and Brüde (2004, 2005, 2006) also showed that the number of barrier repairs along collision-free roads is lower for 14-m-wide roads than for 13-m-wide roads because of wider road medians. However, an ideal distance between barrier and road edge to reduce the number of damages has not been identified. All the previously noted studies were limited to cable barriers along collision-free roads and to impacts that resulted in severe injuries or fatalities. Most collisions with road barriers do not cause severe injuries or fatalities; the results might be different for such accidents.

There are also other issues related to barrier maintenance. For instance, barrier maintenance measures disturb traffic, impair accessibility, and expose the repair staff to a risky work environment (Hans Thorman and Ylva Magnusson, unpublished M.S. thesis, Dalarna University, 2004).

Objective and Delimitation of the Study

The aim of this study was to analyze how factors such as road barrier type, road type, speed limits, and seasonal effects influence the number of barrier repairs and the associated costs. The scientific contribution of this study lies in the fact that it provides long-awaited information regarding the maintenance aspects of road median barriers. For road authorities and road design consultants, this information is a crucial and much needed piece of a puzzle for life-cycle cost (LCC) analyses. Such LCC analyses must include costs for investment and maintenance as well as socioeconomic costs.

Investment costs are fairly easy to find from the manufactures and from the rather conclusive documentation of the installation costs for new barriers. Regarding socioeconomic costs, some studies have been presented and a few others are underway. These studies can be used in LCC analyses. The problem in performing LCC analyses is that the maintenance costs are completely unknown and very hard to calculate. This is the reason why this study focuses on repair costs. Investment costs, socioeconomic costs, and safety performance were beyond the scope of this study, as these aspects have been the subject of many other studies.

The study was performed on the basis of 1,625 repairs conducted in four regions of the SRA. Cable barriers, w-beam barriers, Kohlswa-beam barriers, pipe-beam barriers, and concrete barriers were studied. The analyses focused on high-tension cable barriers and w-beam barriers because they are the most common barrier types in Sweden. Furthermore, the analyses focused on median barriers, as the data concerning roadside barriers were too limited. For the same reason, only three road types—motorways, four-lane roads, and collision-free roads—were analyzed.

As the study draws on Swedish data, the conclusions can be applied to other Nordic countries where weather conditions and road design are similar. However, the methodological approach of this study is very general and may be applied in other studies on a similar topic in a different setting.

Methodology

The focus was on investigating barrier damage repairs and the associated costs to analyze the influence of different factors. It was not possible to conduct experiments, as the number and combinations of influencing factors were too high. It would be very difficult to simulate such a high number of accidents; therefore, the study focused on barrier repairs that already had been carried out. Data were collected using an assortment of sources, such as repair invoices issued by maintenance contractors, databases, observations of damage repairs, and interviews with road authorities and contractors. A method called "Case Study Research Method" was used. One of the distinctive characteristics of this method is its ability to deal with a full variety of evidence, such as documents, archival records, interviews, and observations. A case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and the context are not clearly evident (Yin 2003). A case study deals with a situation in which there are many more variables of interest than data points. The case study research strategy is preferred in examining current events, when the relevant behavior can not be manipulated. Furthermore, a case study can be performed on the basis of a mixture of quantitative and qualitative evidence or be limited to either quantitative or qualitative evidence.

The case study presented in this paper started by defining the research question, research propositions, units of analysis, and logic of linking data to the propositions. The research question to be answered was "How do factors, such as speed limits, road types, barrier types, and seasonal effects, affect barrier repairs and the associated costs?"

The following research propositions were formulated on the basis of common opinion expressed by interviewed maintenance experts:

- The number of barrier repairs and the associated costs are higher for cable barriers than for other barrier types;
- The number of barrier repairs and the associated costs are higher along collision-free roads than along other road types;
- The number of barrier repairs and the associated costs are higher along roads with a speed limit of 110 km/h than along roads with a speed limit of 70 km/h or 90 km/h;
- The number of barrier repairs and the associated costs are higher during winter than during summer.

Each proposition directed attention to something that should be examined within the objective of the study.

For this investigation, a holistic multiple-case study was selected in four regions in the SRA: the Northern, Central, Western and Southeast Region. The regions were the most appropriate units for analysis, because information about barrier repairs within each region was archived separately. Each region is unique regarding costs, subsidiary prices, and climate. It was important to investigate more than one region to establish a strong base for the analyses and generalization of the findings.

To link the data to the propositions, pattern matching logic was chosen (Trochim 1989). The empirically based data pattern (i.e., the findings from each unit of analysis) was linked to the predicted patterns (i.e., the propositions). The findings from each unit were compared to determine whether they predicted the same results or not. If the findings coincided, they were considered as an actual empirically based pattern. Subsequently, the findings were compared with the propositions to support or reject them. The findings were presented as the number of repairs per vehicle kilometer (vkm) and repair cost per vehicle kilometer. The reason for using these two terms was to neutralize the effects of barrier length and annual average daily traffic (AADT) on the rate of recurrence of barrier repairs.

Data Sources

For data collection, many types of sources were utilized, such as interviews with maintenance experts and examination of documentation, archival records, and databases containing information about studied roads and barrier repairs. This approach, called data triangulation, is considered to be one of the major strengths of case study research. Data triangulation increases the reliability of the data and the process of gathering it. In the context of data collection, triangulation serves to corroborate the data gathered from different sources (Tellis 1997). Findings or conclusions in case studies are likely to be much more convincing and accurate if they are generated on the basis of different sources of information (Yin 2003). The data necessary for this case study was mainly collected from four data sources, described subsequently.

Invoices for Repair of Barrier Damages and Damage Notifications

Most data were collected from the repair invoices and attached repair notifications, photos, and police reports. The invoices are usually issued and sent by the maintenance contractors to SRA's regional offices after each repair. The invoices contain the expenses for

- Repair staff;
- Vehicles and machinery used for the repair;
- Replaced barrier parts, such as posts, foundations, and beams;
- Replaced material around the road barrier, such as gravel and asphalt; and
- Material used for temporary traffic arrangements.

With each invoice, a damage notification is attached, including

- The date when the damage was noticed;
- The person who observed the damage;
- The number and the name of the road;
- The location of the damage; and
- The type and registration number of the vehicles involved in the collision, if known.

The SRA requires photos of the damages before and after repairs. The significance of what was shown in the photos was frequently judged subjectively. Reliable information from night photos was difficult to obtain. For each maintenance area, invoices issued during a specific year are collected in folders and saved in archives. Access to the folders was easy to acquire. However, it was difficult to find the barrier repair invoices, as they are mixed in folders with repair invoices for other components, such as lighting posts, fences, and road signs. The forms for damage notifications also differ between maintenance contractors, as the SRA does not require a standard form. Also, the archive systems differ, as no nationwide system exists. These factors made the data search difficult and time-consuming.

Swedish National Road Database

The Swedish National Road Database (NVDB) is a nationwide road database containing up-to-date information that fulfills particular quality standards. The aim of the database is to meet the immediate and long-term needs for fundamental road information. Both the public and private sectors have access to such information. The database contains geometrical, technical, and topographical descriptions of the Swedish road network. It also contains information about other road-related characteristics, such as speed limits, road numbers, road classes, and road bearing capacity. It is also possible to obtain information from NVDB about distances between locations on the roads. Unfortunately, NVDB does not contain any information about the length or type of median barriers, nor the existence of roadside barriers.

Annual Average Daily Traffic Map

The annual average daily traffic map (AADT-Map) is a Web-based database containing information about roads administered by the SRA. In this application, the Swedish road network is categorized into homogeneous sections. For each section, the traffic volume is measured regularly using temporary or permanent traffic measuring stations. The AADT is then calculated and shown on digital maps or in tables.

Interviews with Experts

The interviews were carried out with maintenance contractors or maintenance project leaders to collect information regarding the types of median barriers along the studied road sections, procedures for repair actions, problems faced during the repairs, and factors influencing repairs and associated costs. Semistructured interviews (Trost 2005), a suitable interview type for this kind of study, were used.

Data Saving

Because of the great number of variables and factors included in this case study and for more practical data treatment, the collected data were saved in more than one database in the form of Microsoft Excel sheets. The data for each studied region was collected, analyzed, and saved separately.

Data regarding Barrier Repairs

The following data regarding barrier repairs were collected:

- Date the damage was detected;
- Road number and the location of the barrier damage;
- Type of damaged barrier;
- Barrier position (i.e., roadside barrier or median barrier);
- Speed limit where the damage occurred; and
- Total repair cost and cost items.

Dates for the damage observations were used to study seasonal effects. The dates were obtained from the damage notifications, as repair dates were seldom given in the invoices. According to maintenance contracts, barrier repairs must be conducted within 2 weeks after damage is detected. Barrier damages observed between October 15 and April 14 were defined as winter damage, and damages observed between April 15 to October 14 were defined as summer damage.

The road number and the location of the barrier damage were obtained from the damage notifications. This information was used to find out other factors, such as speed limit and road type. In cases where the location of the damage was poorly described, the maintenance contractor was consulted.

Information regarding barrier type was found in the invoices or in the photos attached to the invoices. The photos made it possible to distinguish between barrier type and barrier position. In cases of poor quality photos or missing information in the invoices, the maintenance contractor was contacted for this information.

Information about speed limits was obtained from NVDB. Sometimes the database contained information not valid for the year in question. For example, the speed limits given in the database in some cases differed from the speed limits that were valid during the time of damage. In case of doubt, this had to be further investigated, for example, by consulting the maintenance contractors.

The total repair cost is defined as the amount of money invoiced by the maintenance contractor after each barrier repair. The total repair cost consists of several cost items: staff/machinery costs, costs for replaced barrier parts, materials used for temporary traffic arrangements, and other costs, such as costs for hiring repair tools. Information regarding total repair costs and cost items was found in the invoices.

Data regarding Road Links

To determine traffic work, roads included in this study were divided into road links. A road link was defined as a road section with the same road type, median barrier type, speed limit, and annual average daily traffic. A new link started at the point where one of these factors changed. The starting point for each link was the same as the end point for the previous link. The distance between these points was the length of the link. The traffic work for each link was calculated by multiplying the length by AADT. For calculation of the traffic work, the following data concerning each road link were collected:

- Type of median barriers;
- Road types and speed limits;
- Length of the road link;
- AADT; and
- Traffic increase factors for the road link.

For identification of barrier types along the road links, NVDB was used for the most part. If information was missing in this database, photos were used or maintenance contractors were consulted. When a specific type of median barrier was found in the photos at the location of the damage, this type of barrier was assumed to exist at that link until new information was obtained. This assumption was made on the basis that roads are usually designed with the same type of median barrier for long distances. Unfortunately, a similar assumption was not possible in the case of roadside barriers. These types of barriers exist intermittently for rather short distances. As a result, it was not possible to estimate the length of the roadside barriers in the same way as for a median barrier. Information regarding speed limits and road types was also found in the NVDB.

The lengths of the links were measured using a specific function in the NVDB developed to measure the distances between locations on roads.

AADT was found in the AADT-Map. The recorded AADT was often not valid for the year in question, as traffic measurements are not done yearly. Traffic increase factors were used to transform the recorded AADT to the year of repair. The traffic increase factors were also obtained from the AADT-Map. If such information was missing, the factor was assumed to be 2% per year.

Equations Used for Calculation of Average Repair Cost per Vehicle Kilometer

The average repair cost per vehicle kilometer for different combinations of road types, barrier types, and speed limits was calculated in three steps: (1) calculation of the annual traffic work, (2) calculation of the average cost per repair, and (3) calculation of the average repair cost per vehicle kilometer. The average repair cost per vehicle kilometer could only be calculated for median barriers, as the lengths of the roadside barriers were unknown.

The annual traffic work for each road link was calculated by

$$\text{AADT}(l,r,b,s) = \text{AADT}^{\circ}(l,r,b,s) \bullet T \tag{1}$$

$$\text{ATW}(l,r,b,s) = \text{AADT}(l,r,b,s) \bullet \text{LL}(l,r,b,s) \bullet 365 \tag{2}$$

where ATW = annual traffic work for the link in vehicle kilometer; AADT = annual average daily traffic for the studied year in vehicles per day; AADT$^{\circ}$ = annual average daily traffic in vehicles per day for the year of the measurement; T = traffic increase factor; LL = link length in kilometers; l = road link; r = road type, which has three categories [motorway (MW), collision-free road (CFR), and four-lane road (4L)]; b = barrier type, which has five categories [cable barrier (CB), w-beam barrier (WB), Kohlswa-beam barrier (KBB), pipe barrier (PB), and concrete barrier (CTB)]; and s = speed limit, which has three categories (70, 90, and 110 km/h).

The total annual traffic work for all road links with the same combination of road type, barrier type, and speed limit was calculated using the following equation:

$$\text{TATW}(r,b,s) = \sum_{l=1}^{l=n} \text{ATW}(r,b,s) \tag{3}$$

where TATW = total annual traffic work in vehicle kilometer; and l, r, b, and s are as defined previously.

The average cost per repair for all road links with the same combination of road type, barrier type, and speed limit in each region was calculated using the following equations:

$$\text{TARC}(r,b,s) = \sum_{\text{BR}=1}^{\text{BR}=n} \text{RCBR}(r,b,s) \tag{4}$$

$$\text{AVCR}(r,b,s) = \frac{\text{TARC}(r,b,s)}{\text{NR}(r,b,s)} \tag{5}$$

where TARC = total annual repair cost; RCBR = cost for the single barrier repair (BR); AVCR = average cost per repair; NR = number of damage repairs during the studied year; and r, b, and s are as defined previously.

The average repair cost per traffic work for the different combinations of the studied road types, barrier types and speed limits was calculated using the following equations:

$$\text{ARC}(r,b,s) = \frac{\text{TARC}(r,b,s)}{\text{TATW}(r,b,s)} \tag{6}$$

or

$$\text{ARC}(r,b,s) = \text{RQ}(r,b,s) \bullet \text{AVCR}(r,b,s) \tag{7}$$

$$\text{RQ}(r,b,s) = \frac{\text{NR}(r,b,s)}{\text{TATW}(r,b,s)} \tag{8}$$

where ARC = average repair cost per vehicle kilometer; RQ = number of repairs per vehicle kilometer; and r, b, and s are as defined previously.

Statistical Analysis

To analyze the influence of factors such as barrier types, road type, speed limit, and regional effect on the barrier repairs and the associated costs, the methods of linear and generalized linear models were used (Olsson 2002).

The variable, average repair cost per vehicle kilometer (ARC), is a positive and continuous variable having a positively skewed distribution. To normalize the variable, a log transformation is applied. The log-transformed average cost per vehicle kilometer is used as the response variable for further analysis. However, for practical application, $\log(1 + \text{ARC})$ is the response variable because some of the costs were zero, where a log transformation does not make any sense. The influence of factors mentioned previously on the response is analyzed through the following linear statistical models:

$$\log(1 + \text{ARC}) = a + b + \varepsilon_1 \tag{9}$$

$$\log(1 + \text{ARC}) = a + r + \varepsilon_2 \tag{10}$$

$$\log(1 + \text{ARC}) = a + s + \varepsilon_3 \tag{11}$$

$$\log(1 + \text{ARC}) = a + rg + \varepsilon_4 \tag{12}$$

where b, r and s are as defined previously; α = regression intercept term representing the overall average repair cost per vehicle kilometer; rg = region and has four categories [Central Region (C), Northern Region (N), Southeastern Region (SE), and Western Region (W)]; and the last term ε_i (i = 1, 2, 3, 4) is the classical regression error term.

If the research purpose is to test the influence of different factors on some response variable, a conventional practice is to include all the factors and their possible interaction in one and the same single model. Henceforth, any inference of interest is drawn from the complete model. Therefore, a model with all the factors together is also tried for this data set. However, no interesting conclusion could be drawn from the results of the complete model, since most of the parameter estimates turn out to be insignificant because of the lack of sufficient observations compared with the number of factor levels. Furthermore, the models represented by Eqs. (10)–(12) are also estimated independently for each region, but in most cases, the parameter estimates were insignificant because of an insufficient number of observations. For reasons given, the results of those analyses are not included in this paper.

The second interesting response variable, beside ARC, is the number of repairs per vehicle kilometer (RQ). This variable is a discrete one, although the ratio between the number of repairs and the total annual traffic work (TATW) can be treated as a rated variable that gives the number of repairs per vehicle kilometer. These kinds of rated data are often analyzed using a Poisson model where the discrete count, RQ in this case, is assumed to follow a Poisson distribution. Furthermore, the logarithm of the denominator of the rated variable, TATW in this case, enters into the Poisson model as an offset (Olsson 2002). The Poisson model is a special case of the generalized linear models. A detailed specification of the Poisson model for analyzing the effect of the barrier type is given as

$$\left.\begin{array}{c}\log(\mu) = \alpha + b + \text{Offset} \\ E(\text{RQ}) = \mu; \text{RQ} \sim \text{Poisson}(\mu)\end{array}\right\} \tag{13}$$

where α and b are as defined previously; $\log(\text{TATW})$ = offset term whose regression coefficient is fixed to 1; and E = mathematical expectation.

To analyze the effects of the region, speed limit, and road type, the term b is to be replaced with rg, s, and r, respectively.

For seasonal effects, it was not possible to relate the repair costs to the traffic work, because the traffic work was not measured for summer and winter. However, measurements of the seasonal traffic work made in the early 1990s in Sweden showed that the accumulated traffic work for the summer (April15–October 14) constituted 55.5% of the annual traffic work compared with 44.5% for the winter (October 15–April 14). This difference is small and will probably not affect the differences in the number of repairs between the seasons. Because of this, seasonal effects are analyzed using repair costs for median barriers observed during the studied period without any consideration of traffic work.

To analyze the seasonal effect on repair costs, a linear model is fitted with log(Cost) as the response variable and "season" as the covariate. To test the seasonal effect on the number of repairs, a Pearson's Chi-squared test is carried out to find out whether the proportion of repairs is equal for both summer and winter against an alternative hypothesis that the proportion is higher in the winter than in summer.

The data was manipulated in Microsoft Excel to set the data in the format necessary for further analysis. To perform the analyses mentioned previously, the data was then imported in R 2.8.0, which is free, open-source software downloadable from www.r-project.org. The quasi models are fitted with the aid of the MASS library (Venables and Ripley 2002) in R.

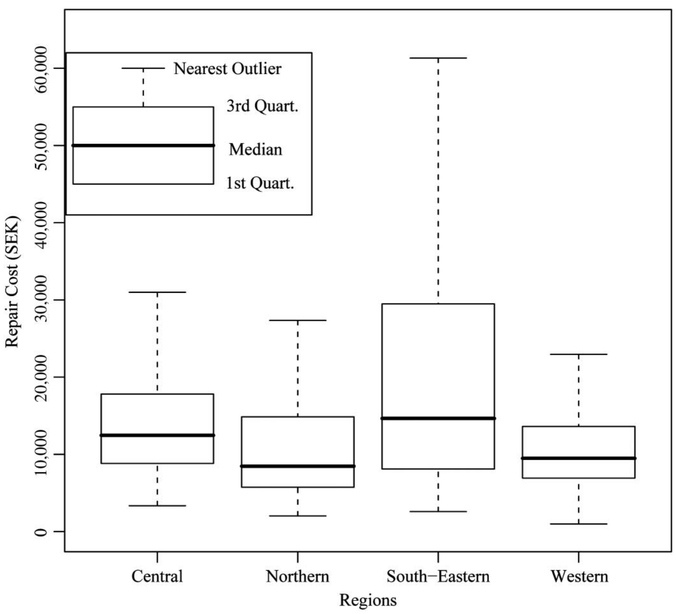

Fig. 1. Plot-box of the costs for barrier repairs performed in the four regions, regardless of barrier type, barrier position, speed limit, and road type

Results and Analyses

The results show that the average cost per repair as well as most cost items differ between the regions (Fig. 1 and Table 1). Table 1 also shows that the staff/machinery cost is the highest cost item. The cost for replaced parts is the second-highest cost item. The third-highest cost item is the cost for materials required for temporary traffic arrangements, whereas the lowest cost item is "other costs", e.g., the cost for hired repair tools. Costs for installing temporary traffic arrangements are included in staff/machinery costs. The proportions of these cost items differ to some extent between regions, as the costs included in each cost item differ between regions. Other factors contributing to this divergence are differences in traffic volumes, subsidiary prices, climate, barrier types, and road types. For example, staff/machinery costs in the Western and Southeastern region are higher than in the Central Region (Table 1). An explanation for this is that the cost for installation of temporary traffic arrangements in the Western and Southeastern regions is higher because of higher traffic volumes and roads that are more sensitive to traffic disturbances. This requires complicated temporary traffic arrangement measures that are usually conducted at night. This is also indicated by the differences in material costs required for temporary traffic arrangements in those regions (Table 1). The underlying factors for the differences between the regions are discussed in detail subsequently.

Effect of Barrier Type

The analysis of the effect of median barrier types had to be limited to the Western and Southeastern regions, since only cable barriers are used as median barriers in the Northern and Central regions. Table 2 shows that, in the Western and the Southeastern regions, the average repair cost per vehicle kilometer is higher for median cable barriers than for median w-beam barriers. This difference is also statistically highly significant ($P-\text{value}=0.0001$) (Table 3). This difference is attributable to the fact that the number of repairs per vehicle kilometer is two to three times higher for cable barriers than for w-beam barriers. This difference is statistically highly significant ($P-\text{value}=0.0001$) (Table 3). The relatively weak construction of cable barriers is probably a major factor contributing to a higher number of repairs per vehicle kilometer for this type of barrier. Cable barriers lose most of their efficiency even after minor impacts. In contrast, w-beam barriers are often not repaired after minor impacts, as they retain some degree of effectiveness; this is explained in the literature study.

Table 2 also shows a higher average repair cost per vehicle kilometer for Kohlswa-beam barriers, compared with cable barriers and w-beam barriers in the Western Region. The underlying factor for this difference is that the number of repairs per vehicle kilometer for Kohlswa-beam barriers is higher than for the w-beam barriers. This result is in contrast to the good reputation that the Kohlswa-beam barrier has as a strong barrier type that can withstand minor

Table 1. Barrier Repair Costs for Roadside and Median Barriers

Regions	Number of annual damage repairs	Total annual repair cost (SEK)	Average cost per repair (SEK)	Average cost for staff/machinery per repair (SEK)	%	Average cost for replaced parts per repair (SEK)	%	Average material cost for traffic arrangement per repair (SEK)	%	Other costs (SEK)	%
Northern	115	1,434,100	12,470	4,990	40	4,490	36	2,620	21	370	3
Central	402	6,425,800	16,000	6,140	38	5,530	35	3,210	20	1,100	7
Western	683	7,729,900	11,300	5,270	47	3,220	28	2,730	24	100	1
Southeastern	425	9,373,000	22,100	8,600	39	7,500	34	5,510	25	440	2

Note: SEK is Swedish currency (1 SEK = 0.9 Euro).

Table 2. Barrier Repair Costs for Different Median Road Barrier, Regardless of Speed Limit or Road Type

Region	Barrier type	Number of damage repairs	Annual traffic work (Mvkm)	Number of repairs per vehicle kilometer (Rep/Mvkm)	Total annual repair cost (SEK)	Average repair cost per vehicle kilometer (SEK/Mvkm)
Northern	Cable	97	248.8	0.39	1,065,360	4,281
Central	Cable	329	878	0.37	4,885,197	5,564
Western	Cable	165	713	0.23	1,790,282	2,511
	W-beam	243	3,095	0.08	2,531,702	818
	Kohlswa-beam	7	20.7	0.34	72,262	3,491
Southeastern	Cable	306	2,115.4	0.14	6,580,932	3,111
	W-beam	16	213.7	0.07	561,461	2,628

Table 3. Major Statistical Findings

Factors	Variable categories	Influence on average repair cost per vehicle kilometer (from linear models)			Influence on number of repairs per vehicle kilometer (from Poisson models)		
		Estimate	Standard errors	*P*-value	Estimate	Standard errors	*P*-value
Barrier type	Intercept	1.5	0.15	0.0001	−1.45	0.11	0.0001
	CB	0.00[a]	—	—	0.00	—	—
	WBB	−1.07[b]	0.25	0.0001[c]	−1.09[d]	0.23	0.0001[e]
	KBB	0.00	0.46	0.99	0.37	1.22	0.77
	CTB[f]	−1.5	0.39	0.0001			
Speed limit	Intercept	1.1	0.27	0.0003	−1.76	0.17	0.0001
	70	−0.22	0.38	0.58	−0.46	0.62	0.47
	90	−0.12	0.37	0.96	−0.1	0.38	0.8
	110	0.00	—	—	0.00	—	—
Road type	Intercept	1.55	0.25	0.0001	−1.13	0.15	0.0001
	CFR	0.00	—	—	0.00	—	—
	4L	−0.87	0.36	0.02	−1.29	0.45	0.01
	MW	−0.7	0.33	0.04	−0.99	0.2	0.0001
Region	Intercept	1.34	0.22	0.0001	−0.98	0.14	0.0001
	N and C	0	—	—	0.00	—	—
	SE and W	−0.54	0.29	0.0007	−1.11	0.18	0.0001
Season[g]	Intercept	9.34	0.04	0.0001			
	Summer	0.00	—	—			
	Winter	−0.02	0.04	0.7			

[a]A zero (0.00) estimate of the influence of the factors, followed by a dash as a value for standard errors and *P*-values, indicate the effect of the factor was constrained to 0.00, hence it serves as the base category for the comparison; a blank dash (—) means that the factor has not been included in the analysis.
[b]The estimate of influence of the factors in the linear models can be interpreted as the usual regression coefficients. For example, the effect of w-beam barrier equals −1.07, which indicates that the average repair cost per vkm in the log scale for w-beam barriers is 1.07 units less than for base category, which is cable barriers in this case.
[c]A corresponding *P*-value equals to 0.0001 indicates the difference is statistically significant at a 0% level of significance.
[d]The effects of the factors on number of repairs per vkm should be interpreted in a slightly different way. A negative estimate, same as the linear models, indicates a lower number of repairs compared with the base category, whereas a positive estimate indicates the opposite. The coefficient estimate associated with w-beam barriers equals −1.09, indicating that, on an average, the number of repairs per vkm for w-beam barriers is only 33% ($\exp(-1.09) \times 100$) of the number of repairs per vkm for cable barriers.
[e]An associated *P*-value equaled to 0.0001 indicates the difference is statistically significant at a 0% level of significance. Note that a *P*-value greater than 0.05 would indicate the effect is insignificant at 5% level. All other effects can be explained in the same way.
[f]The effect of a concrete barrier on the number of repairs could not be analyzed since there was no repair for that category and a Poisson model cannot handle the situation where the observed frequencies, i.e., the number of repairs, are exactly 0 for some factor level (Venables and Ripley 2002).
[g]To test the effect of seasons on the number of repairs, a Pearson's Chi-squared test was carried out to test whether the proportion of repairs is equal for both the summer and the winter against an alternative hypothesis that the proportion is higher in the winter than in summer. The data rejects the null hypothesis at 0% level of significance (Pearson's Chi-squared statistic = 63.834 on 1 DOF). This implies that the proportion of accidents is significantly higher in winter than in summer.

impacts without need for repair. It is noteworthy that the use of Kohlswa-beam barriers as a median barrier in the Western Region during the studied year was limited to a barrier length of 12 km installed along road sections with a very high traffic volume and a high accident risk. In addition, only seven repairs of the Kohlswa-beam were conducted during the studied year. These two facts probably contribute to a low reliability in the results. A limited number of repairs may also indicate that many of the damaged barriers did not need to be repaired, as Kohlswa-beam barriers retain some degree of effectiveness after minor impacts.

Table 4. Barrier Repair Costs for Median W-Beam and Cable Barriers along Motorways, Regardless of Speed Limits

Region	Barrier type	Number of damage repairs	Annual traffic work (Mvkm)	Number of repairs per vehicle kilometer (Rep/Mvkm)	Total annual repair cost (SEK)	Average repair cost per vehicle kilometer (SEK/Mvkm)
Western	Cable	105	514	0.20	1,117,101	2,173
	W-beam	207	2,453	0.08	2,249,959	917
Southeastern	Cable	165	1,403	0.12	5,192,246	3,701
	W-beam	15	189.8	0.08	523,369	2,758

Unfortunately, data pertaining to the number of nonrepaired damages were not available, because such damage is usually not reported to SRA.

To make a more in-depth analysis of the effect of barrier type, barrier repairs on the same type of road were compared. This was only possible for cable barriers and w-beam barriers installed as median barriers along motorways in the Western and Southeastern regions. Table 4 shows that the average repair cost per vehicle kilometer is higher for cable barriers than for w-beam barriers in both the Western and Southeastern regions. This difference is because the number of repairs per vehicle kilometer for cable barriers is two to three times higher than for w-beam barriers.

No repairs of concrete barriers were conducted along the studied roads during 2005 and 2006 in any of the studied regions, despite that 41 kilometers of the studied roads in these regions were equipped with concrete median barriers. These road sections were located in urban regions with an AADT within the range of 5,000 to 56,000 vehicles per day. The total traffic work conducted along these road sections was approximately 188 million vehicle kilometers. The limited data regarding concrete barrier repairs may be explained by the fact that normal collisions do not result in any damages to this kind of barrier owing to its stable construction. Collisions that have not been repaired are usually not registered at all. From a pure maintenance perspective, the absence of repairs needed for concrete barriers might indicate that this barrier type can be the most cost effective. Especially along urban road sections with high traffic volumes and high risk for collisions, concrete barriers may be the best alternative.

Effect of Road Type

Table 5 shows that the repair costs per vehicle kilometer in all regions, except in the Western Region, are higher for barriers along collision-free roads than for barriers along motorways and 4-lane roads. This difference is statistically significant at a less than 5% level (Table 3). The difference is mainly attributable to a higher number of barrier repairs per vehicle kilometer along collision-free roads. One explanation for these differences is that road barriers along collision-free roads are more exposed to damage because of the relatively short distance between the barriers and the edge of the traffic lanes. According to Swedish design specifications, this distance should be within the range of 0.65 to 1.1 m along collision-free roads compared with 1.75 m along normal standard motorways and 4-lane roads. Another explanation for the difference in the number of repairs per vehicle kilometer is that the geometrical standard for motorways is higher than that for collision-free roads, e.g., motorways are usually designed with smoother alignment, better visibility, and wider road median and road verge.

The high number of repairs per vehicle kilometer on collision-free roads can also be because this type of road is mainly equipped with cable barriers. As discussed in the literature review, cable barriers have to be repaired even after minor damage because of their weaker construction. This fact also explains the higher number of repairs per vehicle kilometer for barriers installed along 4-lane roads in the Central Region (Table 5), where cable barriers are the only barriers used. In contrast, the use of cable barriers along 4-lane roads is limited in the Western and Northern regions.

In the Southeastern Region, the average repair cost per vehicle kilometer is higher for barriers along motorways than along collision-free roads, even though the number of repairs per vehicle kilometer is lower for barriers along motorways. An underlying factor for this divergence is that the average cost per repair is higher along motorways than along collision-free roads. This may be because the motorways in the Southeastern Region are mainly equipped with cable barriers, whereas motorways in the Western Region are mainly equipped with w-beam barriers. As mentioned previously, the average repair cost per vehicle kilometer is higher for cable barriers than for w-beam barriers.

Table 5. Barrier Repair Costs along Different Road Types, Regardless of Barrier Type or Speed Limit

Region	Road type	Number of damage repairs	Annual traffic work (Mvkm)	Number of repairs per vehicle kilometer (Rep/Mvkm)	Total annual repair cost (SEK)	Average repair cost per vehicle kilometer (SEK/Mvkm)
Northern	Collision-free roads	93	240.8	0.39	1,038,324	4,312
	4-lane roads	4	33.3	0.12	27,036	812
Central	Motorways	74	269.6	0.27	1,204,090	4,466
	Collision-free roads	235	555	0.42	3,336,907	6,012
	4-lane roads	19	78.5	0.24	337,773	4,303
Western	Motorways	315	2,980	0.11	3,387,036	1,137
	Collision-free roads	60	199	0.30	673,181	3,383
	4-lane roads	40	649	0.06	334,030	515
Southeastern	Motorways	180	1,689	0.11	5,715,615	3,384
	Collision-free roads	142	669.8	0.21	1,426,778	2,130

Table 6. Barrier Repair Costs along Roads with Different Speed Limits, Regardless of Road Type or Barrier Type

Region	Speed limit (km/h)	Number of damage repairs	Annual traffic work (Mvkm)	Number of repairs per vehicle kilometer (Rep/Mvkm)	Total annual repair cost (SEK)	Average repair cost per vehicle kilometer (SEK/Mvkm)
Northern	70	6	21.9	0.27	56,238	2,568
	90	30	39.2	0.77	452,338	11,539
	110	61	213	0.29	556,784	2,614
Central	70		5.9			
	90	50	96	0.52	778,195	8,106
	110	279	776	0.36	4,107,002	5,293
Western	70	63	593	0.11	642,331	1,083
	90	98	1,046	0.09	969,266	927
	110	254	2,141	0.12	2,782,650	1,300
Southeastern	70		3.9			
	90	36	357.8	0.10	345,487	966
	110	286	2,423.2	0.12	6,796,906	2,805

Effect of Speed Limit

The average repair cost per vehicle kilometer in the Northern and Central regions is higher for median barriers installed along roads with a speed limit of 90 km/h than along roads with 110 km/h (Table 6). This difference is mainly attributable to a higher number of repairs per vehicle kilometer for median barriers installed along roads with a 90 km/h speed limit than along roads with speed limit of 110 km/h. A possible explanation is that roads with a speed limit of 110 km/h usually have a better geometrical standard than roads with 90 km/h speed limits. Smother alignment and better visibility probably contribute to a lower risk for damage along roads with a 110 km/h speed limit. Another possible factor contributing to a higher number of repairs per vehicle kilometer for median barriers along roads with a 90 km/h speed limit is that these roads are usually located in urban regions with high traffic density, many connecting roads, and consequently, a higher accident risk.

In the Western and the Southeastern regions, the average repair cost per vehicle kilometer is lower for median barriers along roads with a speed limit of 90 km/h than along roads with a 110 km/h speed limit despite the number of repairs per vehicle kilometer being almost the same for both types of roads (Table 6). The average cost per repair of barrier along roads with a 90 km/h speed limit is lower than along roads with 110 km/h (i.e., barrier damages are greater along roads with a 110 km/h speed limit than along roads with 90 km/h) (Table 6). This is logical, as impact forces increase with the speed of the impacting vehicles.

According to Table 6, the average repair cost per vehicle kilometer for barriers installed along roads with a 70 km/h speed limit are lower than for barriers installed along roads with 90 km/h, even if these two road types often are located in urban regions and have almost the same geometric standard. Table 6 also shows that both the average repair cost per vehicle kilometer and the number of barrier repairs per vehicle kilometer for barriers installed along roads with speed limits of 70 km/h and 110 km/h are almost the same, despite the fact that these two road types have quite different geometrical characteristics.

On the basis of the results from the different regions, it is not possible to present a reliable correlation describing how speed limits affect barrier repairs and the associated costs. The differences in the average repair cost per vehicle kilometer and the number of repairs per vehicle kilometer between the speed limits are not statistically significant ($P - \text{value} > 0.45$) (Table 3).

Seasonal Effects

Table 7 shows that the number of barrier repairs is higher during the winter than during the summer in all regions. This difference is highly significant (Pearson′s Chi-squared statistic $= 63.834$ on 1 DOF) (Table 3). The difference can be explained by poor road conditions, slippery road surfaces, and darkness, which lead to higher collision risks during the winter.

Table 7 also shows that, to some extent, the average cost per repair is higher during the summer than the winter in all regions. Barrier damage from collisions seems to be greater during the summer. This fact is confirmed by Table 8, where the average number of replaced posts for cable barriers in winter is less than in summer in all regions. An explanation may be that lower speeds during winter, because of bad weather and road conditions, lead to lower impact forces at collisions, with less damage to the

Table 7. Barrier Repairs and Associated Costs during Different Seasons, Regardless of Road Type, Barrier Type, Speed Limit, and Barrier Position

Regions	Seasons					
	Summer			Winter		
	April 15—October 14			October 15—April 14		
	Number of repairs	%	Average cost per repair (SEK)	Number of repairs	%	Average cost per repair (SEK)
Northern	36	32	13,082	76	68	12,179
Central	164	41	16,802	238	59	15,421
Western	286	42	11,161	397	58	11,430
Southeastern	160	38	23,300	262	62	21,203

Note: Three repairs in each of the Northern and the Southeastern regions are excluded, as the season was unknown.

Table 8. Average Number of Replaced Posts for Cable Barriers, Regardless of Road Type, Speed Limit, and Barrier Position

	One year		Winter		Summer	
Regions	Number of repairs	Average replaced posts per repair	Number of repairs	Average replaced posts per repair	Number of repairs	Average replaced posts per repair
Northern	97	8.3	68	7.8	29	9.2
Central	341	9.6	218	8.5	123	11.4
Western	172	9.5	111	5.9	61	15
Southeastern	348	9.5	218	8.2	130	11.7

barriers. However, the difference in the repair costs between the seasons is not statistically significant ($P-\text{value}=0.7$) (Table 3).

Differences between the Regions

Results presented in this study indicate that repair costs per vehicle kilometer for barrier damages are higher in the Northern and Central regions than in the Western and Southeastern regions (Tables 2–6), regardless of barrier and road types. This difference is statistically highly significant ($P-\text{value}=0.0007$) (Table 3). The major factor contributing to this difference is that the number of repairs per vehicle kilometer in the Northern and Central regions is higher than in the Western and Southeastern regions. The difference is statistically highly significant ($P-\text{value}=0.0001$) (Table 3). This difference has also been confirmed in previous studies (Carlsson and Brüde 2004, 2005, 2006). In other words, the risk for barrier damage is higher in the Northern and Central regions than in the Western and Southeastern regions, despite the fact that traffic intensity is much higher in the Western and Southeastern regions, and the policies on repairs are the same in all the regions. The higher risk for barrier damage in the Northern and Central regions could be attributable to, among other things, the long, cold, and snowy winters with slippery road conditions and consequently, frequent snow removal activities. This is confirmed by Table 7, where the number of barrier repairs is higher during the winter than during the summer in all regions. Differences in tendered and unit prices for repairs between the regions are factors contributing to the differences in average cost per repair between the four regions. This results in variations in the average repair cost per vehicle kilometer between the regions. For example, the average price for a truck-mounted attenuator with its carrier, which is used to protect the staff, is more than 40% higher in the Central Region than in the Western Region. Higher tender and unit prices in the Central Region indicate poor competition within the road maintenance market.

Another factor contributing to high repair costs per vehicle kilometer in the Northern and Central regions is that the majority of the roads with barriers in these regions are collision-free roads. As mentioned previously, the average repair cost per vehicle kilometer for barriers installed along collision-free roads is higher than for barriers installed along motorways and 4-lane roads (Table 5). The frequent use of cable barriers as median barriers along collision-free roads in the Northern and Central regions also contributes to a higher repair cost per vehicle kilometer in these two regions.

The differences between regions should not depend on differences in guidelines and policies for barrier repairs, as those are the same all over Sweden.

Conclusions and Recommendations

On the basis of the results presented in this paper, the following conclusions can be drawn:

- The most important findings from this study are that the number of barrier repairs and the average repair cost per vehicle kilometer for median cable barriers is higher than for median w-beam barriers, regardless of road type.
- From a purely repair-cost perspective, the use of barriers with a stronger construction, such as w-beam barriers, is more cost-effective for the road authorities. The number of repairs per vehicle kilometer for median barriers along motorways can probably be almost halved by using w-beam barriers instead of cable barriers.
- The number of barrier repairs and the average repair cost per vehicle kilometer for median barriers along collision-free roads are higher than along motorways or 4-lane roads. The risk for barrier damage along collision-free roads is higher than along other road types, probably because of lower geometrical standards along collision-free roads.
- From a purely repair-cost perspective, the use of barriers with stronger construction along collision-free roads and roads with low geometrical standards will be cost-effective for road authorities because this will result in reduced number of repairs and repair costs.
- It is not possible to present a reliable measure to describe how the speed limits affect the barrier repairs and the associated costs.
- The number of barrier repairs being higher during the winter than the summer is probably attributable to poor road conditions, slippery road surfaces, darkness, and damage causedsnowplowsughs. However, barrier damages are greater during the summer because, on average, motorists drive at a higher speed during summer.
- In the Northern and Central regions, which are characterized by long and snowy winters, the number of barrier repairs and the average repair cost per vehicle kilometer for median barriers are higher than in the Western and Southeastern regions.
- From a purely repair-cost perspective, the use of barriers with a stronger construction in regions with long, snowy winter seasons will be cost-effective for the road authorities, as number of barrier repairs will be reduced.

A recommendation to use a specific barrier type must not only be made on the basis of maintenance aspects. There are several other important aspects that have to be considered, e.g., life-cycle costs and safety performance. These aspects together with the conclusions from this study will be used in an ongoing study with the intention to create a model for the calculation of life-cycle costs to compare different barrier types during road planning and design. Difficulties faced during the collection of data pinpoints the importance of systematically collecting maintenance costs to be able to perform any life-cycle cost analyses.

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