

Accident risks and marginal costs for railway level crossings: Evidence from Sweden 2000-2012

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Abstract

The purpose of the present study is to estimate accident risks and marginal costs for railway level crossings in Sweden. The marginal effect of train traffic on the accident risk is used to derive the marginal cost per train passage that is due to level crossing accidents. The estimations are based on Swedish data from 2000 to 2012 on level crossing accidents, train volume, and crossing characteristics. In this study we estimate the accidents risk for both motorized road traffic and vulnerable road users. As a proxy for road traffic flow we use three categories of road type, and to capture the influences of pedestrians and bicyclists we use information about the number of persons living nearby the level crossing. The results show that both protection device, road type, traffic volume of the trains, and number of persons living nearby the level crossing have significant influences on the accident probability. The marginal cost per train passage regarding motor vehicle accidents is estimated at SEK 1.50 on average in 2012. Corresponding number for accidents with vulnerable road users is 3.32. The cost per train passage varies substantially depending on type of protection device, road type, the traffic volume of the trains, and number of persons living nearby the crossing.

Keywords: Railway, Marginal cost, Accident probability, Level crossings

JEL Codes: D62, H23, R41

1 INTRODUCTION¹

Railway is in general a very safe transport mode but collisions between road users and trains at level crossings are still a problem due to the, often severe, outcome of the accidents. During the years 2008-2012, 59 level crossing accidents (of which 37 were collisions with motor vehicles) occurred on the Swedish railway network, in all rail operations except metro and tram. As a consequence of these accidents, 34 fatalities and 29 severe injuries occurred among the road users. Corresponding numbers for years 2003-2007 were 83 accidents (of which 65 were collisions with motor vehicles), leading to 41 fatalities and 47 severe injuries among the road users. Suicides and attempted suicides are not included in these numbers. (Trafikanalys, 2013b)

Marginal cost pricing is an important keystone in Swedish transport policy. The infrastructure charge made by the Swedish Transport Administration to the train operators includes a component for rail-road level crossing accidents that should be based on the marginal cost principle. This means that the train operators should be charged with the expected cost due to level crossing accidents that results from driving one more train on the line. The cost of interest here is the cost that without a charge completely falls on the road users or the rest of society and is therefore external to the train operators. Charging the operators for this external marginal cost even though they do not legally bear the responsibility for the accidents is a way of internalizing the effect that train traffic has on the accident risk of the road users. For an overview of the development of the Swedish accident charges, see Lindberg (2002; 2006).

The purpose with this study is to estimate the marginal cost associated with rail-road level crossing accidents, i. e. to find out how much the expected accident cost due to collisions between trains and road vehicles at a given crossing will change when one more train passes the crossing. Separate models will be estimated for accidents involving motor vehicles and accidents involving vulnerable road users (here, pedestrians and bicyclists). The expected accident cost depends on both the relationship between train volume and accident risk and the expected cost per accident. The relevant accident cost is the cost that falls on the road users and is taken from the official Swedish values of fatalities and injuries used in cost benefit analysis.

As far as we know, no other country, apart from Sweden, include the external marginal level crossing accident cost in the infrastructure charge for railway traffic. Studies on the relationship between train traffic and accident risk for road users at level crossings are therefore rare.

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2 MARGINAL COST CHARGING AND LEVEL CROSSING ACCIDENTS

Accidents between road users and trains at level crossings are almost always caused by some kind of misbehaviour from the road user. Either by not looking for trains, not observing flashing lights or closing barriers, or even by intentionally disregarding warning signs. It might therefore seem remarkable to put a charge on the train operators that internalizes the costs that otherwise are completely borne by the road users.

A theoretical motivation for using marginal cost based charges can be found in the accident and law literature on how liabilities and costs should be split between involved parties to achieve optimal risk reduction at lowest cost (Shavell, 2004). Accidents between road users and trains at level crossings are bilateral as the actions in the form of care taking and the activity level of both the road user and the train affect the accident risk. Even though it is almost impossible for an engine driver to take any action to avoid a crash when approaching a crossing with a car standing on the track (due to the long stopping distance), the level of activity, i.e. the number of times a train passes a crossing, does affect the accident risk. That means that the train operator has the possibility to reduce the risk by driving fewer trains, even if this probably is not that easy to put into practice. For the road user both the amount of care taking when crossing the railway and the number of times he crosses the railway (the activity level) affect the accident risk.

There are two major rules of accident liability. Strict liability implies that the injurer is liable for the harm he causes regardless of whether he was negligent or not. Under the negligence rule on the other hand the injurer is only liable if his level of care is below some minimum standard specified by the court. As Shavell (2004) shows, the rules of liability affect both the behaviour and chosen activity level of the injurer and the victim but no liability rule, neither strict liability nor negligence, will in itself lead to an optimal level of activity for both parties in bilateral accidents. A condition for an optimal choice of activity level of both parties is that they both bear the accident losses. The charges that the train operators pay in Sweden for the expected increase in accident costs for road users due to level crossing accidents is one way to make both the train operators and the road users pay for the accident losses that their use of infrastructure results in. The largest part of the losses from a level crossing accident comes from injuries of the passengers in the road vehicle and material damage to the road vehicle. These are borne by the road user and the rest of society when it comes to health care. By charging marginal cost based charges the train operators will also take into account the effect on the accident risk from train traffic. In this way, both parties, the train operator and the road user, each face the full accident consequences from level crossing accidents and will therefore both choose the optimal level of traffic.

We will here adopt a marginal cost theory proposed by Lindberg (2002; 2006). It says that the number of accidents where trains are involved (in the present paper we call it Y), is a function of the traffic volume of trains (Q_T) and other explanatory variables, including the traffic volume of cars at level crossings (for accidents between trains and motor vehicles):

$$Y = f(Q_T, \dots) \quad (1)$$

Y should be seen as a vector with rows representing different degrees of severity, which is also the case for the cost components: the willingness-to-pay of the involved user (a),

the willingness-to-pay of relatives and friends (**b**), and system external cost, i.e. mainly medical costs paid by the social security system (**c**). The marginal cost (**MC**) with respect to Q_T follows from the total cost (**TC**):

$$TC = Y(a + b + c) \quad (2)$$

$$MC = \frac{\partial Y}{\partial Q_T}(a + b + c) \quad (3)$$

The component (**b**) is relatively uncertain and is normally not included in calculations of the external marginal cost for traffic accidents (Isacsson & Liss (2016)). Therefore, we will only use the cost components (**a**) and (**c**) in our calculations of the marginal costs. Both these components are included in the official Swedish values of fatalities and injuries that were mentioned above. These values are about 25.4 MSEK² for fatalities, 4.7 MSEK for severe injuries, and 0.2 MSEK for light injuries (Trafikverket, 2016).

The *external* marginal cost is calculated by:

$$MC^e = MC - PMC, \quad (4)$$

where *PMC* is the private marginal cost already internalised by the train operator.

The private marginal cost could include delay costs for the operator and any costs due to injuries of the driver or passengers that the operator compensate the passengers for. If we ignore the train operator's own accident cost, the external marginal cost at level crossings is the same as the marginal cost (Lindberg, 2002; 2006). When we henceforth discuss the external marginal cost, we mean the cost that falls on the road user or the rest of society due to injuries when an accident between a train and a road user occurs.

3 DATA

The information on crossings, traffic and accidents is all obtained from the Swedish Transport Administration. The information on traffic volume (no. of trains) is collected on a yearly basis and is an average over the whole track section with imputed data for the station areas. Track sections with a traffic volume of less than one train per year are excluded from the analyses. The number of track sections varies over the years as sections are divided or merged, new sections open and some are closed. The number of different track sections used in the analyses, i.e., sections where we have information on both traffic and existing crossings are 213³. The length of the track sections varies from less than one km to nearly 274 km and the number of crossings at each section varies from only one or two (or even zero for some of the years) to almost 300 crossings. Also, the amount of traffic on each section/crossing varies substantially, as shown in Figure 1. The distribution is skewed with a mean traffic volume of 6 836, i.e. 19 trains per day, and a median value at 4 619, i.e. 13 trains per day. In Figure 1 we have excluded the 456 crossings that have more than 50 000 passing trains per year.

² Price level of 2014. SEK 1 $\approx$ EUR 0.1.

³ Including the the Swedish state-owned rail network and "Inlandsbanan"

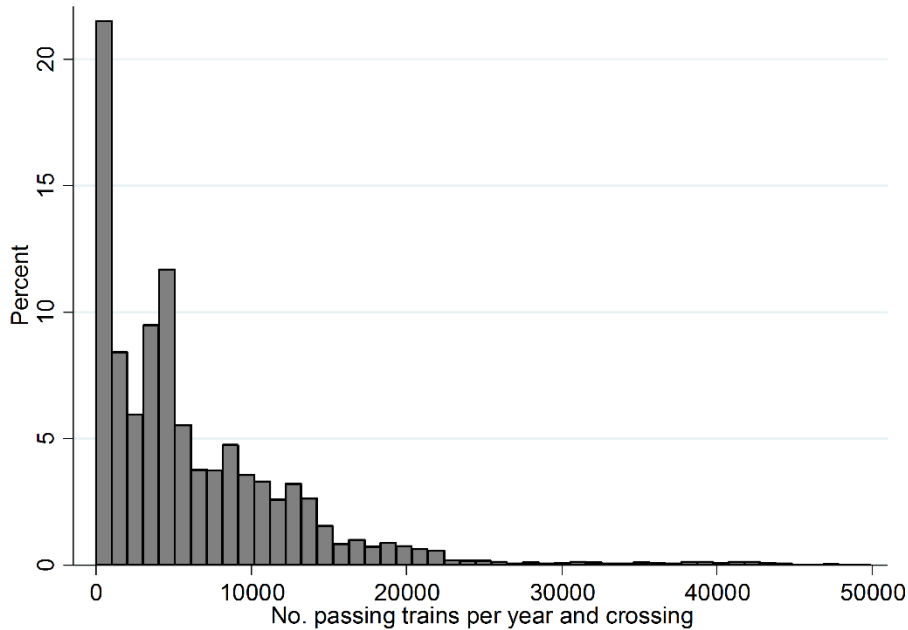


Figure 1. Traffic volume distribution

The Swedish Transport Administration has a comprehensive database (named “plk-webb”) over existing and closed crossings with information on protection devices, speed limits for the trains, and the type of road crossing the railway, among other things. From that database we have gained information about crossings between the years 2008 to 2012. To gain information back in time on crossings that have been closed or changed is harder and the comprehensive dataset we extracted from the database has for the years 2002-2007 been supplemented with information from inspections of crossings. This data is further supplemented by information from 2000 and 2004 that comes from a former analysis over accidents between road users and trains at level crossings presented in Lindberg (2006).

The data on crossings used in the analysis covers thirteen years. During this period some crossings have been closed, others reconstructed with a new type of protection device while also some new crossings have been built.⁴ This means that our dataset is an unbalanced panel but the variation over time within the same crossing when it comes to traffic and protection devices is very small compared to the variation between crossings.

The crossings are divided into four categories based on protection device, which also implies different accidents rates (Cedersund, 2006): full barriers, half barriers, light/sound and totally unprotected/crossings with crossbucks. Full barriers are barriers that close both the approach side of the crossing and also the exit side while half barriers only close the road at the approach side. The category light/sound consists of crossings without barriers but with protection devices in the form of flashing lights and/or sound. The fourth category consists of passive crossings with neither barriers nor lights or

⁴ An inspection of the data shows that 90 level crossings have been reconstructed with a new protection device sometime between 2010 and 2012. However, it is difficult from the information in the data to find out when, and maybe if at all, this reconstruction has been made. For these crossings, we have set the year of the reconstruction to 2010.

sounds. Some of these crossings are equipped with crossbucks or other simple devices while others totally lack protection device. The common category is motivated by a former study (Cedersund, 2006) on Swedish level crossings showing that crossings with and without crossbucks are equally risky. Hereafter, we call the crossings included in the fourth category unprotected crossings.

Information on accidents between 2009 and 2012 has been obtained from the Swedish Transport Administration where the accident record is included in the level crossing database ("plk-webb"). For earlier years the accident records has been gained from The Swedish Rail Agency (now The Swedish Transport Agency) in combination with information from the Swedish Transport Administration. Some detective work was required to be able to connect all the accidents to the exact crossing. For each accident the number of persons with different level of injuries, categorized as light injuries, severe injuries and fatalities, is also noted. Only level crossing accidents leading to personal injuries are included in the analyses and only accidents with road users are supposed to be included, i.e. in this analyses we have not taking into account personal injuries among the train crew.

To capture the influence from road traffic, information on the type of road that crosses the railway is used as a proxy variable for road traffic flow. In a previous Swedish study, Lindberg (2006) compared the results from a full sample model including this proxy variable and from a subsample including road traffic flow. He found that the same conclusions regarding rail traffic and protection devices could be drawn from both models and that the results regarding the road type reflected the expected road traffic volume. As in Jonsson (2011), the roads were categorized in three categories: national/regional, street/other roads, and private roads. Although the road type variable in the "plk-webb" consists of information that is not updated, previously analyses have shown that this variable is able to differentiate between accident risk in the same way as road traffic. As proxy variable for number of pedestrians/vulnerable road users passing the crossings, we use the number of persons living within 2 kilometres from the crossing. This variable has earlier been used by Isacson and Liss (2016) as proxy variable for traffic flow of vulnerable road users. In their study, they restricted the variable to only include individuals between 20 and 64 years old, whereas we in this paper include individuals of all ages. Data has been received from Statistics Sweden. The number of persons living in an area within 2 kilometres from the crossing is 2 188 persons on average (median = 348), range from 0 to 108 870 persons.

In Table 1, the number of crossings and accidents is presented for each of the years included in the study. The total number of crossings in the sample is 81 309, of which 79 709 crossings are used in the model on motor vehicle accidents (years 2000 to 2012) and 17 913 are used in the model on vulnerable road users (years 2010 to 2012). In the model on motor vehicles no footpath crossings are included. However, we include crossings where, according to an old categorization of the data, the railway is crossed by a road that are for pedestrians because we consider the possibility that also mopeds and other such motorized vehicles could pass. In the model of vulnerable road users all types of crossings are included. However, due to the fact that the Swedish Transport Administration earlier did not categorize accidents between vulnerable road users and trains as crossing accidents, we only have information about these accidents for years 2010 to 2012. The number of crossings included in the vulnerable road user model is

further limited by the fact that we do not have information about the number of persons living nearby each crossing.

The number of accidents between trains and motor vehicles for years 2000 to 2012 is 107 and the number of accidents between trains and vulnerable road users for years 2010 to 2012 is 32.

Table 1. No. of crossings in the sample 2000-2012

Year	Full barriers		Half barriers		Lights/sound		Unprotected		Footpaths		Total	
2000	1 016	(3)	926	-	561	-	4 439	(6)			6 942	(9)
2001	1 004	-	920	(1)	529	(1)	4 112	(4)			6 565	(6)
2002	1 067	-	946	-	633	(2)	4 216	(8)			6 862	(10)
2003	969	(2)	922	(1)	519	-	3 433	(2)			5 843	(5)
2004	1 008	(4)	946	(3)	516	(3)	3 468	(4)			5 938	(14)
2005	1 029	-	971	(4)	435	(2)	2 950	(6)			5 385	(12)
2006	1 040	-	967	(4)	426	-	2 774	(5)			5 207	(9)
2007	1 203	(1)	1 042	(1)	652	(2)	4 044	(7)			6 941	(11)
2008	1 216	(1)	1 038	-	638	(1)	3 957	(3)			6 849	(5)
2009	1 214	-	1 016	-	610	(1)	3 523	(1)			6 363	(2)
2010	1 180	(7)	958	(3)	554	(5)	3 133	(3)	534	-	6 359	(18)
2011	1 195	(8)	967	(2)	523	(1)	2 900	(1)	535	(1)	6 120	(13)
2012	1 183	(12)	964	-	500	(4)	2 760	(4)	528	(4)	5 935	(24)

Note. Number of accidents in parenthesis.

Because several crossings have to be excluded from the analyses – due to missing data or other problems with the data – the numbers in Table 1 are smaller than the actual numbers of crossings. For example, according to official statistics (Trafikanalys, 2013a) there existed 7 380 level crossings in the Swedish rail network in 2012.

4 MODELLING THE ACCIDENT PROBABILITY AND THE MARGINAL COST

To estimate the marginal cost we first need to calculate the accident probability. Count regression models like the Poisson model or the negative binomial model are natural choices when modelling the number of events during a given time period. In situations with a high proportion of zeros, their zero-inflated counterparts, the ZIP and ZINB are also applicable. The theoretical motivation behind the zero-inflated models is a dual-state process which implies that, in this case crossings, exist in two states - safe and unsafe. As discussed in Lord (2005) the excess zeros in crash data often arise from low exposure or an inappropriate selection of time/space scales and not an underlying dual-state process where some locations are totally safe. Lord (2005) therefore instead suggests a more careful selection of time/space scale for the analysis, improvements in the selection of explanatory variables, including unobserved heterogeneity effects into count regression models or applying small-area statistical methods to model motor vehicle crashes with datasets with a preponderance of zeros. Another choice of accident model is presented in Oh (2005) who models accidents at railway-highway crossings in Korea using a gamma probability count model that can deal with underdispersion as well as overdispersion.

But looking at our dataset, no accident at all occurs at most crossings during the 13 years covered by our data and only one crossing has more than one accident during the period. Instead of using a count model to model the number of accidents we model the probability that one (or several) accident(s) will occur at a given crossing during a certain time period, in this case a year, using the logit model.

$$P(y = 1|X) = \frac{e^{X'\beta}}{1+e^{X'\beta}} = \Lambda(X'\beta) \quad (5)$$

where y is the number of (personal injury) accidents, X is the independent variable(s), β is the parameter(s) that will be estimated, and $\Lambda(X'\beta)$ indicates the logistic cumulative distribution function. The probability that an accident occurs at a crossing during a year is a function of the number of passing trains, number of crossing road users, and crossing characteristics like protection device, sight distance, number of tracks, the crossing angle etc. Our dataset lacks many of those variables that should be included in a complete model, but at least we have access to information on protection device, train passages, and road type/road administrator.

For each year from 2000 to 2012 we observe whether or not an accident occurs at an existing crossing. Our dependent variable is dichotomous, accident or no accident, and we have information on the type of protection device that the crossing is equipped with, the type of road that crosses the railway and the number of passing trains.

The fact that our dataset on crossings is a panel opens up for estimation methods that use the variation in accident risk, traffic and crossing characteristics within the same crossing over time to estimate the effect of traffic on the accident risk. The fixed effects estimator uses a time-invariant individual specific constant to get unbiased and consistent estimates even in the case of unobserved effects that are correlated with the regressors. The downside with the fixed effects estimator is that time-constant variables cannot be included and that the within-variation, the variation within the same crossing over time, is the only source behind the estimation of the effect of train traffic on the accident risk. In cases where the variation over time within the same crossing is very small compared to the variation between crossings the fixed effects estimator is not a suitable alternative. The random effects estimator uses both the variation within a crossing and the variation between crossings and is a good choice if it can be assumed that unobserved individual specific effects are uncorrelated with the regressors. If the variation within a crossing over time is very small the random effects estimator approaches the pooled estimator.

In our dataset the variation over time within the same crossing when it comes to train passages is very small. The fixed-effects estimator is therefore not an appropriate choice. The estimation of a random effects logit model shows that the within-variation is insignificant, i.e. the variation over time within the same crossing is so small that it cannot help explain the variation in accident probability. Due to this fact the models in the paper are estimated with a pooled logit with clustered robust standard errors where each cluster consists of one crossing.

The (external) marginal cost per train passage can be calculated as the marginal effect on the probability multiplied by the expected accident cost, here estimated by the average cost per accident in the sample (C):

$$MC = dP/dQ \times C \quad (6)$$

Since the marginal effect is crossing specific the marginal cost will also vary depending on traffic volume, protection device and type of road.

5 RESULTS

5.1 Model specification

The focus of our study lies in estimating the effect of train traffic on the accident risk. This effect might vary depending on other crossing characteristics like type of protection and it might also vary depending on the existing traffic volume. A hypothesis is that more frequent traffic increases the probability of an accident by increasing the number of occasions when a train can collide with a road vehicle. In other words, the exposure will increase with the traffic volume of both trains and road vehicles. The speed of both the trains and the road vehicles also influences the accident risk. At the same time, a crossing with more frequent train traffic will induce safer behaviour from the road users that reduces the probability of an accident. This latter effect due to changed behaviour among the road users could in some traffic situations override the effect from more collision occasions. In that case the accident probability would fall with the number of passing trains and the marginal cost would be negative. But safer behaviour is not without cost. This risk-reducing behaviour in the form of speed reduction or the extra anxiety that the road user feels when passing a crossing that is perceived as unsafe should be included in a full measure of the accident cost. Unfortunately, it is impossible or at least very hard to observe this risk-reducing behaviour and our measure of the accident externality from train traffic therefore only includes the estimated effect on the accident probability and not the increase in accident avoidance costs for the road users. A level crossing accident may also lead to costs in the form of time delays for both train users and road users. This cost is not included in our estimates.

Theory gives us no direct guidance when it comes to model specification. Three natural choices are to estimate the accident probability as a:

i, linear function of train passages (Q)

$$P(y = 1|X, Q) = \Lambda(X'\beta + \delta Q), \quad (7)$$

ii, function including a quadratic term to capture increasing/decreasing effects

$$P(y = 1|X, Q) = \Lambda(X'\beta + \delta Q + \gamma Q^2) \quad (8)$$

iii, function of the natural logarithm of train passages

$$P(y = 1|X, Q) = \Lambda(X'\beta + \eta \ln(Q)) \quad (9)$$

The fact that the distribution of train passages is extremely skewed (see Figure 1) complicates the analysis. By taking the natural logarithm of train passages the variable becomes more symmetric as can be seen in Figure 2.

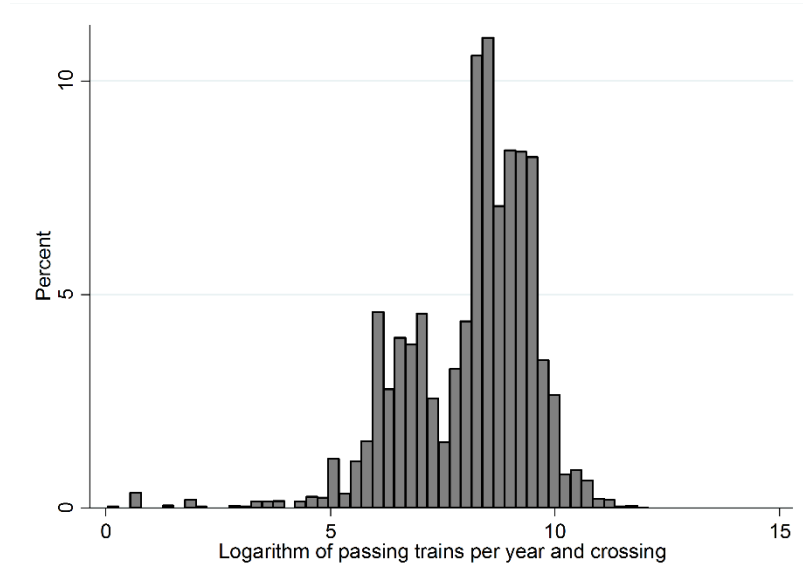


Figure 2. Logarithm of traffic volume distribution

In a logit model the marginal effect (dP/dQ) varies depending on the values of all independent variables. A general marginal effect has therefore been calculated by taking the mean of the crossing specific marginal effect. For comparison also the median is shown since the distribution of the marginal effect is skewed. In Table 2 it can be seen that the marginal effect varies substantially depending both on functional form and between the mean and the median. The main purpose with the table is to illustrate the differences between the different specifications. In the calculations of the marginal cost estimations we use the individual marginal effects, i.e., we do not use either the mean nor the median.

Table 2. Marginal effect – different specifications

	Linear Q	Incl. Q^2	Log Q
$dP/dQ \times \text{mean}$	$2.20 \cdot 10^{-8}$	$1.31 \cdot 10^{-7}$	$2.78 \cdot 10^{-7}$
$dP/dQ \times \text{median}$	$1.41 \cdot 10^{-8}$	$6.84 \cdot 10^{-8}$	$9.90 \cdot 10^{-8}$
AIC	1561.08	1539.87	1532.52
BIC	1626.08	1614.16	1597.52
N	79 709	79 709	79 709

Both the Akaike Information Criteria (AIC) and the Bayes Information Criteria (BIC) point towards using the model with the logarithm of train passages compared to the model with train passages directly.

The formulas for the marginal effects based on each of the three functions are

$$ME(Q) = \frac{\exp(\beta_0 + \beta_Q Q_b + \beta_{RT1} RT_{i1} + \beta_{RT2} RT_{i2} + \beta_{PR1} PR_{i1} + \beta_{PR2} PR_{i2} + \beta_{PR3} PR_{i3})}{\{1 + \exp(\beta_0 + \beta_Q Q_b + \beta_{RT1} RT_{i1} + \beta_{RT2} RT_{i2} + \beta_{PR1} PR_{i1} + \beta_{PR2} PR_{i2} + \beta_{PR3} PR_{i3})\}^2 \times \beta_Q} \quad (10)$$

$$ME(Q^2) = \frac{\exp(\beta_0 + \beta_Q Q_b + \beta_{Q^2} Q_b^2 + \beta_{RT1} RT_{i1} + \beta_{RT2} RT_{i2} + \beta_{PR1} PR_{i1} + \beta_{PR2} PR_{i2} + \beta_{PR3} PR_{i3})}{\{1 + \exp(\beta_0 + \beta_Q Q_b + \beta_{RT1} RT_{i1} + \beta_{RT2} RT_{i2} + \beta_{PR1} PR_{i1} + \beta_{PR2} PR_{i2} + \beta_{PR3} PR_{i3})\}^2 \times (\beta_Q + 2\beta_{Q^2} Q_b)} \quad (11)$$

$$ME(\ln Q) = \frac{\exp(\beta_0 + \beta_{\ln Q} \ln Q_b + \beta_{RT1} RT_{i1} + \beta_{RT2} RT_{i2} + \beta_{PR1} PR_{i1} + \beta_{PR2} PR_{i2} + \beta_{PR3} PR_{i3})}{\{1 + \exp(\beta_0 + \beta_Q Q_b + \beta_{RT1} RT_{i1} + \beta_{RT2} RT_{i2} + \beta_{PR1} PR_{i1} + \beta_{PR2} PR_{i2} + \beta_{PR3} PR_{i3})\}^2 \times \left(\frac{\beta_{\ln Q}}{Q_b}\right)} \quad (12)$$

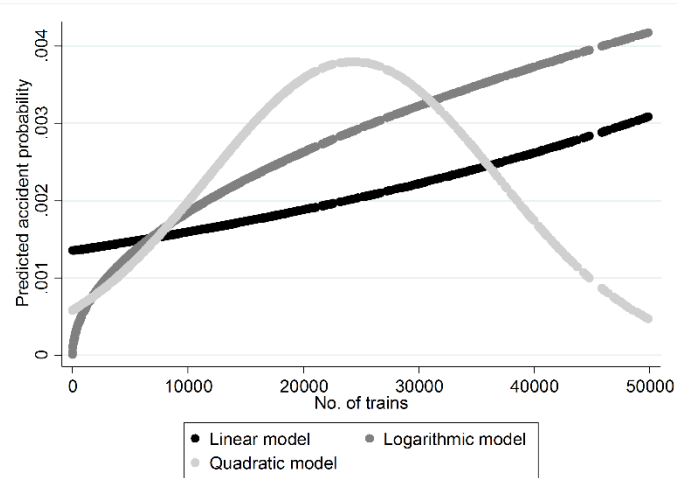
The choice of functional form influences how the predicted accident probabilities as well as the marginal effect vary over the traffic interval. In Figure 3 and 4 we show the predicted accident probabilities and marginal effects for crossings with full barriers crossing a national/regional road and unprotected crossings crossing a private road for all three models. To make the graphs easier to read only predicted probabilities and marginal effects for traffic up to 50 000 passages/year are shown, thereby reducing the dataset by less than 1%. We have also omitted nine observations in Figure 4a that had a marginal effect larger than 3.0×10^{-6} , and 14 observations in Figure 4b that had a marginal effect larger than 2.0×10^{-6} .

The marginal effect of train passages on the accident probability varies in different ways over the traffic interval depending on functional form. Since the marginal cost is a direct function of the marginal effect this will have a large impact on the accident charge if the charge should vary depending on traffic volume.

The model including a quadratic term gives a decreasing accident probability for high train volumes and thereby a negative marginal effect for crossings with high train volumes, something that is problematic from the view of charging the marginal cost to the train operators. For the model with logarithmic traffic the marginal effect as a function of train traffic is continuously decreasing but positive, as seen in Figure 3 and 4, which is reassuring given that the train volume influences the behaviour of the road users. The pattern is similar for both these examples of combinations of protection and road type we have chosen to show here, although the predicted accident probabilities and the marginal effects are of different magnitudes. Also the other combinations of protection and road type show approximately a similar pattern, with the exception of the combination national/regional roads with only lights/sounds as protection where the accident probability tended to increase with increasing traffic for all functional forms.

Figure 3. Predicted accidents probabilities

a) Full barriers – National/Regional road



b) Unprotected crossing – Private road

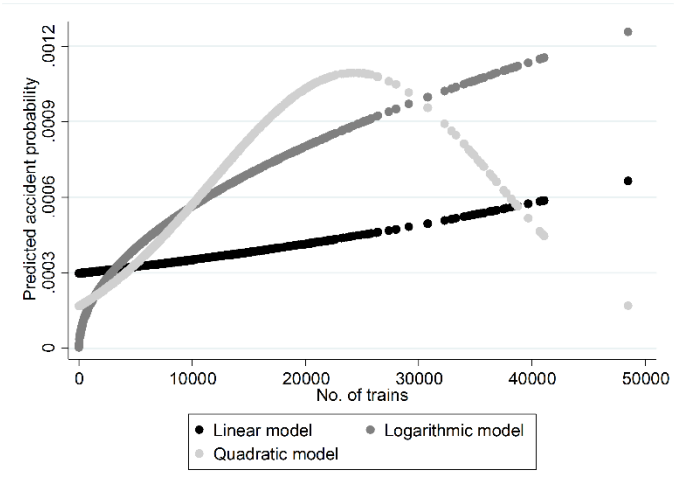
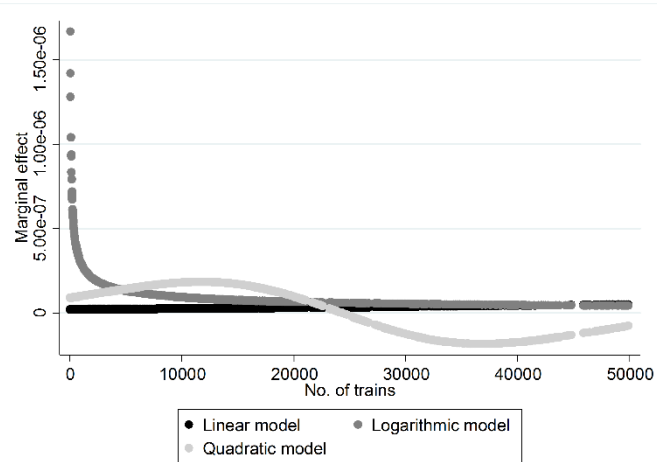
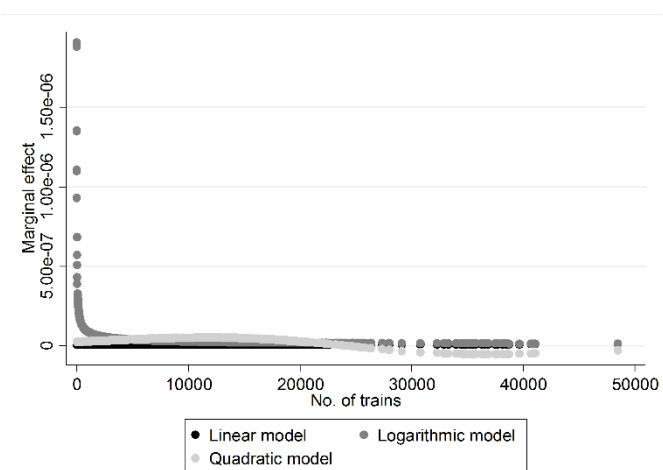


Figure 4. Marginal effects

a) Full barriers – National/Regional road



b) Unprotected crossing – Private road



Based on both the AIC/BIC results and the shape of the marginal effect the model with logarithmic traffic volume is used in the rest of the analysis. Regression results from this model are shown in Table 3. The logarithm of train passages ($\ln(Q)$) significantly increases the accident probability. The road type variables are significant and with the expected signs where crossings with streets/other roads and private roads have a significant lower accident probability than the reference category national/regional roads. Crossings with full and half barriers have a significant lower accident probability than the reference category crossings with lights/sound while the unprotected crossings do not differ from the reference category. Train speed probably also influences the accident probability and one way of capturing train speed is to distinguish between freight trains and passenger trains where freight trains in general are slower than passenger trains. However, we did not found any separate effect from different train types in the estimation.

Table 3. Regression results from the logarithmic model, motor vehicle accidents

	b	S.E.
Constant	-9.13***	.71
Ln(Q)	.51***	.08
National/regional roads	reference	
Street/other road	-.97***	.28
Private road	-2.93***	.47
Lights/sound	reference	
Full barrier	-1.83***	.36
Half barrier	-1.65***	.32
Unprotected	-.09	.27
AIC	1532.52	
BIC	1597.52	
N	79 709	

Note. Standard errors are corrected for clustering on crossing.

* $p < .05$, ** $p < .01$, *** $p < .001$

In Table 4, the regression results from the model on accidents involving vulnerable road users are presented⁵.

Table 4. Regression results from the model on vulnerable road user

	b	S.E.
Constant	-19.45***	1.70
Ln(Q)	.88***	.23
Number of persons living nearby (ln)	.68***	.13
AIC	353.82	
BIC	377.20	
N	17 913	

Note. Standard errors are corrected for clustering on crossing.

* $p < .05$, ** $p < .01$, *** $p < .001$

⁵ In 106 observations, the number of persons living within 2 kilometres from the crossing was zero. Because we use the logarithm of this variable in the model, we choose to replace these values with the value 1 to not lose these observations. A comparison between a model with and without these observations show that the values of the coefficients were exactly the same.

The logarithm of train passages significantly increases the accident probability also in this model. We also find a significant effect of the number of persons living within 2 kilometres from the crossing.

5.2 Marginal effects and crossing characteristics

The marginal effect varies depending on crossing characteristics as well as the traffic volume. Table 5 shows calculated marginal effects from the model using the logarithm of train traffic for crossing with different protection devices and road types. The marginal effects are calculated as a by train traffic weighted average marginal effect over all train passages in year 2012 for each crossing type.

In that way, crossings with larger traffic volume have a larger impact on the marginal effect than crossings with smaller traffic volume. Because of different number of train passages in each cell, for each combination of protection devices and road types, comparisons between them can not be done.

Table 5. Marginal effect for different crossings – weighted average traffic

	Full barrier	Half barrier	Light/sound	Unprotected
National/regional	7.03×10^{-8}	9.99×10^{-8}	1.12×10^{-6}	-
Street/other road	2.95×10^{-8}	3.90×10^{-8}	2.67×10^{-7}	2.43×10^{-7}
Private road	3.48×10^{-9}	4.44×10^{-9}	2.68×10^{-8}	3.97×10^{-8}

Some crossing types are more common than others as can be seen in Table 6. There is a clear tendency that barriers are more common on crossings with road types with larger traffic volumes. The difference between road types in protection devices is also supported by a Chi-square test ($\chi^2(6)=2.3 \times 10^3$, $p<.001$).

Table 6. No. of crossings in the model on motor vehicles year 2012

	Full barrier	Half barrier	Light/sound	Unprotected	Total
National/regional	428	410	109	0	947
Street/other road	736	543	325	1 293	2 897
Private road	19	11	66	1 466	1 562
Total	1 183	964	500	2 760	5 406

The average marginal effect in the vulnerable road user model is 1.44×10^{-7} .

5.3 Marginal cost

The accident cost relevant for the accident charge is the cost that without a charge will be external to the train operators. We have taken this cost to equal the cost that is due to injuries and fatalities among the road users involved in the accidents. For each crossing, we have information on the number of fatalities, severe injuries and light injuries among the road users involved. The values for the injuries come from the official Swedish values used in cost benefit analysis and cover both material costs in the form of lost income and health care and risk

valuation, i.e. the willingness to pay to avoid an accident. These values are 25 400 000 SEK⁶ for fatality, 4 700 000 SEK for a severe injury, and 230 000 SEK for a light injury (Trafikverket, 2016).

The 107 accidents between trains and motor vehicles that are included in the study resulted in 59 fatalities, 28 severe injuries, and 51 light injuries, leading to an average accident cost for the accidents of SEK 15 819 907. Table 7 shows weighted average marginal cost estimates per passage for each combination of road type and protection device where crossings with many passages have a higher weight than crossings with few passages. Because the marginal effect decreases with the number of passages, the differences between the crossings increases when weighting by the number of passages than when taking an unweighted average across the crossings. The differences between crossings reflect both differences in protection device, road type, and number of train passages.

Table 7. Marginal cost per train passage for different combinations of road type and protection device – based on weighted average traffic and motor vehicle accidents, year 2012 (SEK)

	Full barrier	Half barrier	Light/sound	Unprotected
National/regional	1.11	1.58	17.65	-
Street/other road	0.47	0.62	4.22	3.85
Private road	0.06	0.07	0.42	0.63

Note. SEK 1 ≈ EUR 0.1

A uniform charge per km can be calculated using the crossing specific calculated marginal cost weighted by the train traffic. Such a calculation gives an average marginal cost per train passage at SEK 1.50 for motor vehicles in 2012.

The 32 accidents between trains and vulnerable road users in the study (year 2010 to 2012) resulted in 32 fatalities, 3 severe injuries, and 1 light injury, leading to an average accident cost for these accidents of SEK 25 847 813. Based on this average accident cost, the average marginal cost per train passage for accidents between trains and vulnerable road users is calculated to SEK 5.02 in 2012.

According to official statistics (Trafikanalys, 2013a) the whole Swedish rail network with traffic consisted of 11 136 route km and 7 380 level crossings, including footpath crossings, in 2012. There is no official statistics of how many the footpath crossings are, but according to the dataset used in this paper, there were 528 such crossings 2012. Using this as an approximation of actual number of footpath crossings and deduct these from the official numbers gives 0.62 level crossings per km and an accident charge per km at SEK 0.92, for motor vehicle accidents. The same calculation including the footpath crossings gives 0.66 crossings per km and an accident charge per km at SEK 3.32 for accidents with vulnerable road users. This numbers include suicides. We also estimate a model without suicides, based on 13 accidents, resulting in 10 fatalities, 3 severe injuries, and 1 light injury. The average marginal effect in this model is 1.04×10^{-7} , the

⁶ Price level of 2014. SEK 1 ≈ EUR 0.1.

average accident cost SEK 20 640 769, the average marginal cost per train passage SEK 0.73 year 2012, and the accident charge per km SEK 0.49.

6 DISCUSSION

In this paper, we have estimated accident probability models for level crossing accidents both for motor vehicles and for vulnerable road users (pedestrians and bicyclists) and, based on that models, estimated marginal effects and marginal costs. The results show that the marginal effects and, as a consequence, also the marginal costs, not only increase as train traffic volume increases, they also differ between different road types and between different protection devices. The marginal effects and costs also increase as the number of persons living nearby the crossings increases.

The accident charge today in Sweden due to level crossing accidents is set to 0.34 – 0.80 SEK/train km (Trafikanalys, 2014) based on an earlier study using accident records for 2000-2008 (Jonsson, 2011). The accident charge per km in the present study was estimated to SEK 0.92 for accidents between trains and motor vehicles and SEK 3.32 for accidents involving vulnerable road users. In the earlier study, the average marginal cost per train passage was estimated to a value of SEK 1.13 in 2008, compared to SEK 1.50 in 2012 in the present study. Besides including vulnerable road users in the present paper, we have enlarged the data set, which now also includes the years 2009 to 2012. We also base the estimation on other data regarding traffic volume, which now includes station areas. The values for the injuries are also updated according to the official Swedish values which can explain the difference in average marginal cost between the two studies.

It is logical that the marginal cost for accidents involving vulnerable road users is much larger than the marginal cost for accidents between trains and motor vehicles because almost all of the former accidents leads to fatalities. And therefore, the average accidents cost for the accidents included in the models is almost twice as large for vulnerable road users than for motor vehicles. However, this is a first attempt to model level crossing accidents involving vulnerable road users and calculate marginal costs for those accidents and further research is needed to replicate these values. Regarding the question if the two marginal costs are addable or not, we consider they are. The crossings in the two models are indeed overlapping, but the accidents and the accidents costs are unique in each model. However, we recommend that more variants of models for vulnerable road users are performed before these values are implemented.

The size of the marginal cost is not only influenced by the variables included in the model, there are also a lot of estimation specifications influencing the size of the cost. For example, in this paper we prefer an accident probability model based on logarithmic train traffic volume, which results in other marginal effects/costs compared to a quadratic model or a linear model. We also prefer to calculate weighted average marginal effects and marginal costs. In that way, crossings with

larger traffic volume have a larger impact on the marginal effects/costs than crossings with smaller traffic which we see as an advantage. The reason why we choose to calculate the weights over train passages year 2012 was that this is the year in our data set that consists of most updated information.

Other things that could have influenced the value of the marginal effects and marginal costs are the missing data or that we in this paper exclude accidents resulting in non-injured persons or the ways we approximate the exposure of the motor vehicles and vulnerable road users. Future research should try to emphasize these questions.

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