Estimation of the marginal cost for road noise and rail noise

Jan-Erik Swärdh
Anders Genell
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Preface

This study is a sub project to the government commission to estimate the external marginal costs of the transport sector named Samkost 2, which is a sequel to the former Samkost project reported in Nilsson and Johansson (2014).

To know the marginal cost of external effects is essential in estimating the internalisation factor of taxes and charges for different types of traffic. Also, for efficient pricing outcomes, the marginal cost principle is the core component.

In this study, we estimate marginal costs of traffic noise in Sweden for the modes of road and rail. For air transports and maritime transports, we refer to other sub projects of Samkost.

Note that the methods used for road noise and for rail noise vary in some respects, this is due to differences in the research background. With regard to rail noise, we have an ongoing research project to estimate the marginal cost of railway noise based on the latest publication, which is a working paper (Ögren et al, 2011). Therefore, no adjustments are made to the noise calculations of that paper including differentiation of the Day-Evening-Night dimension, except the additional marginal cost of health outcomes. The main reason is that the calculation requirements would be resource demanding and we have not, within the scope of the current commission, devoted resources for these calculations.

Regarding road noise, on the other hand, a new noise calculation is made within this project. Thus we have the opportunity to differentiate across the Day-Evening-Night dimension regarding road noise.

The authors are grateful to Gunnel Bångman and Stefan Grudemo for comments to improve the report. We are also grateful to Mikael Ögren for validating the assumptions and method of the calculation for road noise. Regarding noise calculation data for rail noise, we thank Mikael Ögren for providing this.

Stockholm, October 2016

Jan-Erik Swärdh
Project leader
Quality review

Review seminar was carried out on 8 June 2016 where Gunnel Bångman reviewed and commented on the report. Jan-Erik Swärdh has made alterations to the final manuscript of the report. The research director Mattias Haraldsson examined and approved the report for publication on 29 September 2016. The conclusions and recommendations expressed are the authors’ and do not necessarily reflect VTI’s opinion as an authority.

Kvalitetsgranskning

Table of Content

Summary .................................................................................................................................7
Sammanfattning ......................................................................................................................9
1. Introduction ......................................................................................................................11
2. Data.................................................................................................................................13
  2.1. Noise calculations .....................................................................................................13
  2.1.1. Rail noise ..............................................................................................................14
  2.1.2. Road noise ...........................................................................................................14
  2.2. Disturbance costs .....................................................................................................15
  2.3. Health costs ............................................................................................................17
3. Calculation of estimated marginal costs .........................................................................19
4. Results ............................................................................................................................20
  4.1. Rail ..........................................................................................................................20
  4.2. Road ........................................................................................................................21
  4.3. Sensitivity analysis .................................................................................................22
  4.4. Comparison with previous studies .........................................................................24
  4.5. Discussion of the results .........................................................................................27
5. Conclusions .....................................................................................................................29
References ............................................................................................................................30
Summary

Estimation of the marginal cost for road noise and rail noise

by Jan-Erik Swärdh (VTI) and Anders Genell (VTI)

The purpose of this study is to estimate the marginal cost of road noise and rail noise in Sweden. We use the impact pathway approach (IPA) where traffic noise exposure implies an impact on individuals, which in turn is related to monetary valuation of these outcomes.

Our data consists of noise calculations and number of exposed individuals at different noise levels. We further use monetary valuations of noise disturbances based on property market differentials. Finally, impact functions of negative health outcomes due to noise exposure, and monetary valuations of these negative health outcomes, are used.

The empirical results show that the marginal costs of traffic noise are highly dependent on the number of exposed individuals and the vehicle type. The overall conclusion is thus that differentiation of the marginal costs is essential, as the noise exposure varies strongly with the population density, and that different vehicle types contribute very differently to the noise emissions. Furthermore, road noise marginal costs are positively influenced by the speed limit and the traffic volume. Nevertheless, the sensitivity with respect to traffic volume is not very substantial. For rail noise marginal costs, there is no effect of traffic volume on the estimated marginal cost.

In addition, the marginal costs for road noise are estimated separately for different times of the day. These results show that day times have the lowest marginal costs despite the largest traffic volume. Highest marginal costs are mostly estimated for evening but also in some calculations for night time. Sleep disturbances may not be captured in our analysis however, but a sensitivity analysis, including a separate function for sleep disturbance, shows that night time marginal costs are consistently the highest.

Compared to earlier studies, our estimates of road noise are lower than other relevant Swedish studies and official recommendations. On the other hand, our estimates are relatively close to recent EU-level recommendations. Keep in mind, though, that comparisons across studies are not straightforward as the vehicle type, time of the day, and type of agglomeration might vary. Our estimates of rail noise marginal costs are higher than the EU-level recommendation, which may be caused by different methods used, different valuation functions, and difficulties in comparing the results in a relevant way.

Finally, the most important policy implication is that the marginal costs of this study can provide a basis for efficient external cost pricing of rail and road traffic.
Sammanfattning

Skattning av marginalkostnader för väg- och järnvägsbuller
av Jan-Erik Swärdh (VTI) och Anders Genell (VTI)

Syftet med denna studie är att skatta marginalkostnaden för väg- och järnvägsbuller i Sverige. Vi använder effektkedjansatsen där trafikbullrets påverkan på exponerade individer kopplas till en monetär värdering av dessa utfall.

De data som används består av bullerberäkningar och antalet individer exponerade för olika bullernivåer. Vidare använder vi monetära värderingsfunktioner för bullerstörningar, vilka baseras på variationer i småhuspriser. Slutligen använder vi effektsamband för olika ohälsoeffekter till följd av bullerexponering samt monetära värderingar för dessa ohälsoeffekter.


Dessutom är variationen i marginalkostnaden över dygnet skattad för vägbuller. Dessa resultat visar att marginalkostnaden är lägst under dagtid trots att trafiken är som störst då. Högst marginalkostnad har oftast kvällstid och i några fall nattetid. Eventuellt är sömnstörningar inte infångat i dessa marginalkostnader varför vi i en känslighetsanalys inkluderar en separat funktion avsedd att ta hänsyn till sömnstörningar med resultatet att marginalkostnaden genomgående är högst nattetid.


Slutligen är den viktigaste policyimplikationen att en effektiv prissättning av externa väg- och järnvägsbullerkostnader kan baseras på våra skattningar.
1. Introduction

Transport activities lead to negative impacts on other people who are not compensated, which are known as external costs. For efficiency, such external costs should be priced at their marginal cost. Also, EU legislation postulates the marginal cost pricing principle (European Commission, 1998) and therefore, both in a theoretical and an empirical perspective, different external marginal costs in the transport sector have so far caused attendance among researchers (see e.g. Rouwendal and Verhoef, 2006; Sen et al, 2010; Cravioto et al, 2013; Musso and Rothengatter, 2013).

Traffic noise is one such external cost of the transportation system. Community noise is a common and still growing environmental problem. It has significant negative effects on human health and well-being, such as increased risk of cardiovascular diseases, primarily because of sleep disturbance from noise at night, as well as discomfort and annoyance. To estimate the cost of traffic noise we need to monetise these negative effects of health and disturbance.

In cost benefit analysis (CBA) all relevant benefits and costs from an investment or a measure should be included. Traffic noise is one example of such a cost. Note, however, that a measure can either increase the noise cost or decrease the noise cost. In the latter example the measure leads to a net benefit regarding the noise costs. Note also the important distinction between traffic noise and traffic noise exposure. A measure may decrease the traffic noise exposure despite increasing traffic noise. An example is a new road with a lot of high-speed traffic, but no individuals living proximate to the road, while a lot of the traffic is moved from another road where many more individuals live. In other words, as opposed to some other external costs of transportation e.g. CO2 emissions, traffic noise exposure is local in its nature meaning that the fact that individuals reside close to the traffic noise source is crucial for society costs. Where no people are exposed to the traffic noise, there is no impact of noise, which means that no society costs exist. Thus the number of exposed individuals is very important for the size of the negative effects; if the noise exposure occurs in an urban area the cost will be high, but if the noise exposure occurs in a rural area the cost will be low or even zero.

The marginal cost and pricing of traffic noise has been widely studied (e.g. Rothengatter, 2003; de Vos, 2003; Andersson and Ögren, 2007; Andersson and Ögren, 2011; Andersson and Ögren, 2013; Nerhagen et al, 2015; Ricardo-AEA, 2014). Besides the number of exposed individuals, the type of vehicle is important for the noise emission, and thus important for the marginal cost. Also, the noise disturbances are dependent on the time of the day, where, given the traffic volume and the noise level, night time has a higher disturbance level than evening time, which in its turn has a higher disturbance level than day time.

In this study, we will estimate the marginal cost of both road noise and rail noise in Sweden. Here we differentiate our estimates with respect to vehicle type and number of exposed individuals. We chose to use detailed disaggregated calculations of railway noise from a former project (Ögren et al, 2011) where there was no time-of-day differentiated traffic data. For road, on the other hand, we also differentiate with respect to time of the day. We use data of the complete national rail network as well as data of all national roads within agglomerations. Both these networks are combined with traffic data and data of number of exposed individuals.

As mentioned above, estimation of the marginal cost requires the noise disturbances and the negative health effects to be expressed in monetary terms. In the literature, the main approach to monetising environmental external costs is the impact pathway approach (IPA). IPA was developed in the so called ExternE project and for a more detailed description we refer to Friedrich and Bickel (2001).

1 Note that e.g. Andersson and Ögren (2007) are estimating rail noise marginal costs which are differentiated with respect to time of day. This is, however, a case study of one municipality in Sweden, so imputing the shares of marginal costs of different times of day may likely lead to biases, as the traffic volume of different times of day varies substantially for different track sections.
Shortly described, IPA works through different steps. First, noise emission and its distribution are calculated. Second, the impact of noise exposure is estimated by impact functions. Finally, a monetary valuation, e.g. willingness to pay, for each impact is attached to calculate the monetised cost. In all these steps, established models and functions are required.

Importantly we point out that we in this study estimate the *marginal* cost of noise and not the *total* cost of noise. The total cost is all costs compared to a situation without traffic noise exposure at all. The marginal cost is the cost by one more vehicle causing a marginal (usually extremely small) additional noise emission, leading to a marginally higher noise cost. This is especially important for road, since using national roads only, i.e. no local roads, we would not be able to accurately estimate total costs of road noise. But as we are interested in the marginal road noise costs, we can use this data, as there is no reason to believe that national roads, given the noise level, speed, and exposure, should lead to marginal costs of road noise other than that of local roads. It is important that this difference is already clarified here in the introduction.

The report is disposed as follows. In Section 2, we present our data including noise calculations, impact functions, and monetary valuations for different impacts. The explicit formula for the calculation of marginal costs is presented and described in Section 3. Subsequently, in Section 4, the estimated marginal costs are presented including sensitivity analyses and comparisons with previous studies. The report is concluded in Section 5.
2. Data

Multiple data types are needed to estimate marginal costs of traffic noise by IPA. Firstly, as inputs for noise calculations we need traffic data, data of the road/rail network, and data of the population, to be able to estimate the number of exposed individuals.

Further, we need information about the impact functions and the individuals’ valuation of the different impacts. Regarding disturbance costs these two steps of the IPA are integrated, as the valuation is based on the noise-level differences in the housing market, i.e. relationships known as hedonic functions. All other things being equal, a higher noise exposure leads to a lower selling price of a private property, which can be used to estimate the willingness to pay for different noise levels.

Considering health costs, on the other hand, the impact functions and the valuations clearly comprise two separate steps. The sources for health impacts of noise are WHO (2011) and the ExternE project (Bickel and Friedrich, 2005). The costs of each health impact are mainly taken from a former project with a similar purpose to this study (Nerhagen et al, 2015) and originate from the Swedish Transport Administration (2014, chapter 9), Ricardo-AEA (2014), and Holland (2014). In Sections 2.2 and 2.3 below, disturbance costs and health costs respectively will be more thoroughly described. Note also that the official Swedish traffic noise values used by the Swedish Transport Administration (2016, chapter 10) are also based on similar sources to those used in this study.

2.1. Noise calculations

As stated in the introduction, community noise is a common and still growing environmental problem, which has significant negative effects on human health and well-being, as well as causing discomfort and annoyance. The most prominent metric for noise is the so-called A-weighted decibel, dB(A). The A-weighting refers to a compensation for the varying sensitivity to different pitches in human hearing, and the decibel is a logarithmic scale that accounts for the huge range of pressure variations the ear can handle. The most widespread source of community noise is road traffic, especially in urban areas.

For road noise the de-facto standard metric in Sweden is the A-weighted equivalent noise level, which is a form of mean value for the noise emitted along a road for 24 hours and is denoted $L_{Aeq,24h}$.

The Environmental Protection Agency (2011) recently commissioned a survey of the number of individuals who are exposed to noise. They conclude that 1.64 million people in Sweden are exposed to a noise level of $L_{eq,24h} > 55$ dB at the façade due to road traffic, representing about 17 percent of the population (valid for 2011). The survey is based on the Nord96 model for noise from road traffic. This mapping includes both the national and the local road network and, given that the majority of the population live in cities, the local road network dominates the exposure in the city.

$L_{DEN}$ is an alternative metric that is similar to $L_{Aeq,24h}$, but where noise during evening ($L_{Evening}$), or night time ($L_{Night}$), is weighted to contribute more to the average than noise during daytime ($L_{Day}$), e.g. to compensate for the greater risk of sleep disturbance during the night. The weighting factors are to punish noise during evenings by adding 5 dB and to punish noise during nights by adding 10 dB. $L_{DEN}$ will thus always be at least as large as $L_{Aeq,24h}$ and at most 10 dB higher than $L_{Aeq,24h}$, the latter in the extreme case when all traffic occurs during the night.

$L_{DEN}$ was adopted by the European Environment Agency in the beginning of this century, and is nowadays also the metric the European Commission requires all member states to use when reporting noise exposure in accordance with the European Noise Directive. Day time is defined as the time period from 07.00 to 19.00, evening time is from 19.00 to 23.00, and night time is from 23.00 to 07.00. The purpose of this punishment is to capture the higher disturbance resulting from the noise level in the evening compared to during the day, and even further the experienced disturbance, e.g. sleep disturbances, of noise exposure during the night.
Through a large number of epidemiological studies of noise effects on people, a noise level $L_{\text{Aeq,24h}}$ of 55 dB(A) has become the limit above which noise exposure can be considered detrimental to health and well-being. This limit applies to levels at the exposed dwelling façade, in order to avoid being dependent on information about the noise-reducing properties of the building.\(^2\)

### 2.1.1. Rail noise

In this sub section, the rail noise calculations are presented based on the description in Ögren et al (2011).

Based on the data of the Swedish national rail network and traffic, we need to calculate the noise level at all the exposed dwellings. The method used is a simplified version of the standardised noise calculation method, namely the Nordic method (Ringheim, 1996), which takes total traffic and speed of different trains into account. In this method information about terrain, noise barriers and buildings are used to calculate the noise level at various distances from the track. To apply this noise calculation model to the complete rail network would be too cumbersome, so instead a simplified model is applied. This simplified model is determined by the noise level of the complete noise calculation model 25 metres from the track, $L_{25m}$, and the distance in metres from the track, $d$, is estimated and predicted as the function:

$$L(d, L_{25m}) = 15.94 + L_{25m} - 15.74 \log(d).$$  \((1)\)

Further, the marginal noise level is calculated separately for each track section and calculated for ten different train types, although diesel trains are not used in our study due to some measuring errors when calibrating the noise model for that specific type of train.\(^3\)

Finally, we need data of the exposed individuals. Here we use the population of each square with sides measuring 250-metres, where at least one corner is located less than one kilometre from the railway. This data was provided by Statistics Sweden and is based on population data from the end of 2009.

### 2.1.2. Road noise

A number of models for how road traffic result in noise have been developed in the last 20 years. The model that is most utilised in Sweden is “Road Traffic Noise – Nordic Prediction Method” (Jonasson and Nielsen, 1996), revised 1996 (often abbreviated to Nord96). The model was developed based on noise measurements in a large number of locations at various distances from a number of different roads with different traffic flows. The result is a computational model that, given that the traffic is similar to when the noise level was measured, calculates noise levels corresponding to the measured noise, depending on the surrounding topography, buildings, and ground properties, etc. The output from the Nord96 model is given as $L_{\text{eq,24h}}$.

The model used in our study is instead a simplified variant of the recently developed Cnossos-EU calculation model (Kephalopoulos et al, 2012). The Cnossos-EU model differs from Nord96 by accurately describing the noise created by a single vehicle and then applying the characteristics of the environment that affect the level, such as distance from the source, the presence of absorbing surfaces, mainly soft ground, the presence of reflective surfaces, particularly hard ground and buildings, prevailing weather conditions etc. One advantage of using this model is that it can discriminate between vehicles with and without studded tyres as well as different types of road surfaces. The output of Cnossos-EU is given as $L_{\text{DEN}}$, so here there is a difference between our noise calculations for road traffic and rail traffic.

\(^2\)Throughout our study we use the A-weighted noise as the noise measure and for simplicity this is not stated explicitly in the following.

\(^3\)Note that diesel trains are not that common in Sweden.
In the calculations in our study, a detailed description of the vehicle noise characteristics has been used, based on speed, acceleration, temperature and vehicle type. In addition, a much simplified propagation model has been reverse engineered from Nord96, using exposure data from the studies included in the project REBUS (see e.g. Andersson et al, 2013a). A number of assumptions have been made in our noise exposure model. The two most important are that the population of each locality is uniformly distributed throughout the urban area, and that the propagation of noise from roads in urban areas can be described by one of the three functions, depending on dwelling density, which are only dependent on the perpendicular distance from the road.

First, the source strength of the noise source, i.e. traffic, is calculated based on the annual average daily traffic (AADT) in combination with estimates of the distribution of vehicles over a day, evening and night, the posted speed limit and estimates of differentiation between heavy, medium heavy and light vehicles. The proportion of vehicles with studded tyres is estimated to 70 percent of light vehicles during a third of the year.

Second, the level decrease with distance from the road is calculated by applying one of the three distribution functions, depending on residential density. The number of exposed individuals is then calculated by mapping between what distances from the road a certain noise level prevails, and combining that with the length of the stretch of road being studied, and finally simply multiplying by the population density of the area.

Since the source strength is dependent on vehicle speed, there might be a reduction in noise level due to congestion, but as Sweden has very limited congestion the effect has been excluded from the calculations.

We cover only the parts of the national road network that are found in agglomerations and thus represent a smaller portion of the total exposure to noise from road traffic in the country. About 280,000 individuals are exposed to noise levels of \(L_{eq,24h} > 55\) dB in the included 7,147 kilometre road data set. As noted earlier, since our study concerns marginal cost, the total exposure is of lesser interest, however. The interesting features are how traffic flow and population density affect how much of a contribution one extra vehicle means to the noise exposure.

2.2. Disturbance costs

The disturbance costs in our study are short-term costs based on recent Swedish hedonic valuations of traffic noise with separate studies for rail noise (Swärdh et al, 2012), and road noise (Andersson et al, 2013b), respectively. According to these studies, the hedonic functions for road noise and rail noise are different and we thus use separate functions for rail and road. Both these Swedish valuation studies estimate the full demand for noise abatement by using both estimation steps of the hedonic pricing approach (see e.g. Day et al, 2007).

Further, to be experienced as disturbing (in fact influencing property prices), traffic noise needs to exceed a certain value expressed as the 24-hour equivalent level \(L_{eq,24h}\). This noise level was found to be different for rail noise and road noise in the recent hedonic price studies of Sweden, namely 49.1 dB \(L_{eq,24h}\) for rail noise (Swärdh et al, 2012) and 53 dB \(L_{eq,24h}\) for road noise (Andersson et al, 2013b).

As stated earlier, in this study, for road noise but not rail noise, we use the common international practice to differentiate the marginal costs with respect to day, evening, and night. The purpose of this is to capture the higher disturbance from a given noise level in the evening compared to during the day, and the even further experienced disturbance of noise exposure during the night.

Our original hedonic valuation functions are based on the 24-hour equivalent level. When we now calculate the marginal costs for road noise in the day-evening-night dimension, we first adjust the valuation according to the rule-of-thumb formula from WHO (2011), which is \(L_{DEN} \approx L_{eq,24h} + 2\). This further means that we have to adjust the hedonic valuations of this formula and the day-time noise
level is reduced by 2 dB, the evening-time noise level is increased by 3 dB, and the night-time noise level is increased by 8 dB.

In Table 1, the valuation functions used for rail noise disturbances during the complete 24-hour period, and for road noise separately for day, evening, and night, are presented. The hedonic function is estimated for noise levels up to 75 dB. In our noise calculations, however, there are a few individuals exposed to higher levels, especially when the evening or night punishment is implemented. Thus we extrapolate the valuation of these higher noise levels, and the functions given in Table 1 are also adjusted to be correct in terms of this punishment.

We will also calculate a separate night-time marginal cost where we include a sleep disturbance function for road noise according to WHO (2011, p. 59). The reason is that the night-time punishment may not capture the sleep disturbance costs when the noise level is low, meaning that the disturbance costs according to the hedonic valuation function will also be low. Further we conservatively assume that the disability weight is 0.04 and that the DALY (Disability-Adjusted Life Year) is worth the same as a VOLY (see Section 2.3 about VOLY).

**Table 1. Valuations of traffic noise disturbance. In SEK price year 2014.**

<table>
<thead>
<tr>
<th>Traffic noise disturbance</th>
<th>Unit</th>
<th>Valuation in SEK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disturbance rail</td>
<td>SEK per exposed individual per year</td>
<td>Hedonic valuation function, marginal willingness to pay $WTP = 1675 - 64.6(75 - L_{eq,24h})$</td>
</tr>
<tr>
<td>Disturbance road, day</td>
<td>SEK per exposed individual per year</td>
<td>Hedonic valuation function, marginal willingness to pay $WTP = 4309 - 193(77 - L_{eq,24h})$</td>
</tr>
<tr>
<td>Disturbance road, evening</td>
<td>SEK per exposed individual per year</td>
<td>Hedonic valuation function, marginal willingness to pay $WTP = 4309 - 193(72 - L_{eq,24h})$</td>
</tr>
<tr>
<td>Disturbance road, night</td>
<td>SEK per exposed individual per year</td>
<td>Hedonic valuation function, marginal willingness to pay $WTP = 4309 - 193(67 - L_{eq,24h})$</td>
</tr>
<tr>
<td>Sleep disturbance</td>
<td>Sleep disturbed individuals as a percentage of total exposed individuals (% HSD)</td>
<td>Is assumed to be included in the hedonic valuation functions and its night punishment. As a sensitivity analysis given as: % HSD = 20.8 - 1.05(L_{Night}) + 0.01486(L_{Night})^2</td>
</tr>
</tbody>
</table>

In Ögren et al (2011) the marginal cost of rail noise was estimated per track section based on the same hedonic valuation function as given in Table 1. The marginal cost for rail noise disturbances was estimated to an average 3.46 SEK for a 500-metre freight train. The overwhelming conclusions from Ögren et al (2011) is that there is a large difference in marginal cost across train types as well as across track sections. The difference with respect to train types depends mostly on differences in noise emissions but also train length and speed. Regarding the differences across track sections, the different number of exposed individuals is almost the sole explanation.

As the study of Ögren et al (2011) is state of the art for differentiated rail marginal costs in the dimension of disturbance costs, we will in this study add health costs to the marginal costs already estimated by Ögren et al (2011). Swärdh (2014) is an earlier version of the rail part of this study given in Swedish.

What we are not able to capture for rail but for road, is the differentiation of marginal costs across the time of day. The reason is that we do not have any reliable imputable data on how the rail traffic is
distributed during a 24-hour period. The tradition of traffic noise calculation in Sweden is to measure the noise in a 24-hour equivalent level, and not in the day-evening-night (DEN) dimension as in most other parts of Europe (see also the previous discussion in Section 2.1.2).

2.3. Health costs

Negative health impacts caused by traffic noise are mainly based on the impact functions of WHO (2011), although impacts other than myocardial infarctions, i.e. angina pectoris and high blood pressure, are from the earlier ExternE project (Bickel and Friedrich, 2005). The impact functions of WHO (2011) are considered as state of the art for health effects of noise exposure, so it is only when impact functions are missing from that source that we use the impact functions of ExternE based on Table 6.6 in Bickel and Friedrich (2005). Note that traffic noise exposure may also cause a higher risk of stroke but according to WHO (2011) there are no established impact functions for this risk. We measure the outcome of these health impacts in lost life years, number of non-fatal cases, days of hospitalisation, days of work absence, and days of illness. The health impacts and their respective marginal effects are summarised in Table 2.

Table 2. Impact functions for health costs of noise exposure.

<table>
<thead>
<tr>
<th>Impact and unit</th>
<th>Source</th>
<th>Marginal effect per 1,000 exposed adults over 70 dB $L_{DEN}$</th>
<th>Marginal effect per 1,000 exposed individuals over 55 dB $L_{Day}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myocardial infarction, years of lost life</td>
<td>WHO</td>
<td></td>
<td>13.2 $\times$ 0.721 $\times ME_L$</td>
</tr>
<tr>
<td>Myocardial infarction, days of hospitalisation</td>
<td>WHO</td>
<td></td>
<td>18 $\times$ 2.079 $\times ME_L$</td>
</tr>
<tr>
<td>Myocardial infarction, days of work absence</td>
<td>WHO</td>
<td></td>
<td>320 $\times$ 2.079 $\times ME_L$</td>
</tr>
<tr>
<td>Myocardial infarction, no of non-fatal cases</td>
<td>WHO</td>
<td></td>
<td>2.079 $\times ME_L$</td>
</tr>
<tr>
<td>Angina pectoris, days of hospitalisation</td>
<td>ExternE</td>
<td></td>
<td>0.168</td>
</tr>
<tr>
<td>Angina pectoris, days of work absence</td>
<td>ExternE</td>
<td></td>
<td>0.684</td>
</tr>
<tr>
<td>Days of work absence, days of illness</td>
<td>ExternE</td>
<td></td>
<td>0.240</td>
</tr>
<tr>
<td>High blood pressure, days of hospitalisation</td>
<td>ExternE</td>
<td></td>
<td>0.063</td>
</tr>
</tbody>
</table>

To explain the impact functions given in Table 2 we start with myocardial infarctions based on WHO (2011). The impact functions are not linearly dependent on the noise level, which implies that the marginal impact functions are also dependent on the noise level. For each integer of noise exposure, we use the marginal effect of Appendix 1 in WHO (2011, p. 43), and relate to the number of individuals exposed to these noise levels at the different road sections in our data. This marginal effect is given as $ME_L$ in Table 2. Here we also use $L_{eq,24h}$ as an approximate of $L_{Day}$.

Regarding rail noise, we have data on the total number of exposed individuals above 55 dB $L_{eq,24h}$, so we need an approximation of how these exposed individuals are distributed at different noise levels above 55 dB $L_{eq,24h}$. Here we use information based on the hedonic pricing study of Swärdh et al (2012), where we calculate the number of exposed individuals for each integer noise level as a share of all exposed individuals above 55 dB $L_{eq,24h}$. This method means that $ME_L$ given in Table 2 for rail noise is constant.

The marginal effect, $ME_L$, is a relative risk and we thus need to relate this to the base risk of myocardial infarction. For 2014 this base risk in Sweden was 2.079 non-fatal cases per 1,000 individuals calculated from $(27,295-7,031)/9,747,355$, where 27,295 is the total number of myocardial infarctions in Sweden 2014 whereof 7,031 were fatal (Socialstyrelsen, 2015) and 9,747,355 was the
Swedish population in 2014 (Statistics Sweden, 2016a). In the same way, the base risk of a fatal myocardial infarction is 0.721 cases per 1,000 individuals calculated as 7,031/9,747,355.

The number of lost life years per fatal myocardial infarction is assumed to 13.2, which is based on the calculation example of WHO (2011, p. 25). A useable average number of hospitalisation days and work absence days are not found in WHO (2011). Instead we use the relations in ExternE, which is 18 days of hospitalisation and 320 days of work absence for each non-fatal case of myocardial infarction.

Regarding the impact functions of ExternE, these are not dependent on the noise level except the threshold value of 70 dB $L_{DEN}$. Also here we set $L_{day}$ as an approximate of $L_{Aeq,24h}$ and use the rule of thumb of WHO (2011) that $L_{DEN} \approx L_{eq,24h} + 2$. In other words, our threshold level is 68 dB $L_{Day}$.

Further, regarding the impact functions taken from ExternE, is the fact that these are given per 1,000 of exposed adults. Thus we adjust these functions with the factor 0.796 calculated as the share of all Swedish individuals in 2014 that were 18 years and older (9,747,355 in total population whereof 7,762,073 were adults, see Statistics Sweden (2016b)).

All impact functions of health costs are given in $L_{DEN}$ or $L_{Day}$, as these are considered long-term effects and therefore do not change at different times of the day. Thus we do not differentiate with respect to day, evening, and night for the health impacts. Instead all long-term health impacts are based on the noise exposure during day time.

To end up with a monetary estimate of the marginal effects of traffic noise, i.e. the marginal cost estimates, we need to attach a monetary value to each of the health outcomes of Table 2. Here we use the valuations meticulously produced in the former marginal cost project of traffic noise, see Table 21 and Section 5 of Nerhagen et al (2015). These valuations are presented in Table 3, updated to the price year of 2014 using an index based on consumer price index and real income per capita.

A brief explanation of the background to these valuations is as follows. VOLY is based on the value of a statistical life (VSL) in official Swedish CBA of road traffic safety, discounted by assuming a discount rate of 0.035, and an average of 40 lost life years per road traffic accident death. For symptoms of myocardial infarction, symptoms of angina pectoris, work absence, and hospitalisation days we use recent valuations from Ricardo-AEA (2014) or Holland (2014).

Table 3. Valuations of traffic noise health effects. In SEK price year 2014.

<table>
<thead>
<tr>
<th>Traffic noise effect</th>
<th>Unit</th>
<th>Valuation in SEK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Premature deaths</td>
<td>Per lost life year (VOLY)</td>
<td>1,125,000</td>
</tr>
<tr>
<td>Symptom myocardial infarction</td>
<td>Per non-fatal case</td>
<td>235,000</td>
</tr>
<tr>
<td>Symptom angina pectoris</td>
<td>Per day of illness</td>
<td>17,070</td>
</tr>
<tr>
<td>Work absence</td>
<td>Per day</td>
<td>1,361</td>
</tr>
<tr>
<td>Health care costs</td>
<td>Per hospitalised day</td>
<td>2,900</td>
</tr>
</tbody>
</table>
3. Calculation of estimated marginal costs

In this Section we formalise how the impact functions and valuations of traffic noise are used to calculate the estimates of the marginal costs.

The estimated marginal cost, $MC$, of traffic noise per vehicle kilometre for a given vehicle type, and for a track/road section, $i$, is calculated as:

$$MC_{i,k} = \sum_{L=58}^{78} \Delta N_i^L \times HF_k \times D_i^{-1} \times 365^{-1} + \sum_{j=1}^{178} \sum_{L=58}^{73} ME_{jL} \times \Delta N_i^L \times V_j \times D_i^{-1} \times 365^{-1},$$ (2)

where the first term captures the disturbance costs and the second part captures the health costs. $L$ is the noise level in dB $L_{eq,24h}$ with a “bar” denoting that the noise level is adjusted to capture differences in $k$; $k$ denotes the different times of a day, i.e. day, evening, or night; $\Delta N$ is the change in the number of exposed individuals when traffic is increased by one vehicle; $HF$ is the hedonic price function presented in Table 1; $D$ is the length in kilometres of the track/road section; $j$ is the different health impacts outlined in Table 2; $ME_{jL}$ is the marginal effect of health impacts; and $V$ is the monetary valuation of health outcomes presented in Table 3. Finally, we need to adjust the marginal calculations with number of days, otherwise the result will be the marginal cost for a vehicle kilometre driven each of the 365 days per year.

Note from the equation above that $ME_{jL}$ is zero for noise levels below 58 dB, which follows from WHO (2011, Appendix 1).
4. Results

In this Section our estimated marginal costs are presented, separately for rail and road traffic. In subsequent sections, we present sensitivity analyses and then a comparison with other studies. We also, finally, discuss the implication of our results.

4.1. Rail

As we stated earlier, the basis for our rail marginal cost estimations is the study by Ögren et al (2011), where we have now added health costs according to impact functions presented in Section 2.3. In Table 4, the estimated marginal costs are presented for four different heterogeneous track sections, as well as the nation-wide average, and all estimates are for a freight train of 500 metres in length. One can see that the marginal cost per train kilometre varies enormously, as the track sections are extremely different with respect to traffic and the number of exposed individuals. The nation-wide average is slightly more than SEK 4 per train kilometre. Close estimates are found for track sections 637 and 919 although these two differ in their features. Track section 637 has many more exposed individuals than track section 919 but, on the other hand, much less traffic density.

Table 4. Estimated marginal costs for rail noise for chosen track sections and national average for a 500-metre freight train. SEK per train kilometre, price year 2014.

<table>
<thead>
<tr>
<th>Track section</th>
<th>Number of exposed individuals &gt; 55 dB $L_{eq24h}$</th>
<th>Number of trains per 24-hour period</th>
<th>Marginal cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>327</td>
<td>6</td>
<td>7</td>
<td>0.96</td>
</tr>
<tr>
<td>401</td>
<td>10,695</td>
<td>444</td>
<td>143</td>
</tr>
<tr>
<td>637</td>
<td>789</td>
<td>27</td>
<td>4.06</td>
</tr>
<tr>
<td>919</td>
<td>95</td>
<td>161</td>
<td>3.15</td>
</tr>
<tr>
<td>All track sections</td>
<td>123,766</td>
<td>-</td>
<td>4.22</td>
</tr>
</tbody>
</table>

In Table 5, we present the differentiation with respect to train types. The factors for transferring marginal costs across train types and speed are based on Ögren et al (2011, Table 3 p. 7). The results show that the marginal cost varies greatly across different train types, from SEK 4.06 for freight trains to SEK 0.05 for the small passenger train Y31. As can be seen, some of the differences across train types are caused by different standard lengths used in the noise calculation model.

Table 5. Estimated marginal costs for different train types on track section 637. SEK per train kilometre, price year 2014.

<table>
<thead>
<tr>
<th>Train type</th>
<th>Train length in metre</th>
<th>Speed in km/h</th>
<th>Marginal cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freight train</td>
<td>500</td>
<td>90</td>
<td>4.06</td>
</tr>
<tr>
<td>RC passenger train</td>
<td>230</td>
<td>120</td>
<td>2.53</td>
</tr>
<tr>
<td>X2</td>
<td>165</td>
<td>120</td>
<td>0.62</td>
</tr>
<tr>
<td>X60</td>
<td>107</td>
<td>120</td>
<td>0.10</td>
</tr>
<tr>
<td>Y31</td>
<td>39</td>
<td>120</td>
<td>0.05</td>
</tr>
<tr>
<td>X52</td>
<td>54</td>
<td>120</td>
<td>0.17</td>
</tr>
<tr>
<td>X31</td>
<td>79</td>
<td>120</td>
<td>0.25</td>
</tr>
<tr>
<td>X40</td>
<td>75</td>
<td>120</td>
<td>0.28</td>
</tr>
<tr>
<td>X10</td>
<td>50</td>
<td>120</td>
<td>0.25</td>
</tr>
<tr>
<td>Freight train with k-block brakes</td>
<td>500</td>
<td>90</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Another important result to point out is the difference between the marginal cost of a freight train with conventional brakes, compared to a freight train with k-block brakes. The latter brake types maintain
the circularity of the train wheels which causes much less noise emission. The reduction of the marginal cost with this change of brakes would amount to about 85 percent (1 – 0.62/4.06). To change brakes to k-blocks on all freight trains is efficient for society but not efficient for the train operators (Ögren et al, 2011), whereas a pricing scheme would induce the incentive to change brakes.

4.2. Road

The marginal costs for road noise are differentiated in three dimensions, namely exposed individuals through the density of the agglomeration, day-evening-night, and vehicle type. Marginal costs including all these differentiations are presented in Table 6.

Table 6. Estimated marginal costs for road noise, differentiated with respect to exposure level, time of day, and vehicle type. SEK per vehicle kilometre, price year 2014.

<table>
<thead>
<tr>
<th></th>
<th>High-dense agglomeration</th>
<th>Medium-dense agglomeration</th>
<th>Low-dense agglomeration</th>
<th>Very low-dense agglomeration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day</td>
<td>Evening</td>
<td>Night</td>
<td>Day</td>
</tr>
<tr>
<td>Car</td>
<td>0.126</td>
<td>0.248</td>
<td>0.341</td>
<td>0.073</td>
</tr>
<tr>
<td>Car with studded tyres</td>
<td>0.140</td>
<td>0.260</td>
<td>0.349</td>
<td>0.082</td>
</tr>
<tr>
<td>Truck without trailer</td>
<td>0.652</td>
<td>1.04</td>
<td>1.37</td>
<td>0.351</td>
</tr>
<tr>
<td>Truck with trailer</td>
<td>1.58</td>
<td>3.22</td>
<td>3.27</td>
<td>0.934</td>
</tr>
</tbody>
</table>

Notes: High-dense agglomerations have an average population density above 2000 inhabitants per square kilometre, medium-dense agglomerations have an average population density between 1000 and 2000 inhabitants per square kilometre, low-dense agglomerations have an average population density between 400 and 1000 inhabitants per square kilometre, and very low-dense agglomerations have an average population density below 400 inhabitants per square kilometre.

We can see that the estimated marginal cost varies, as expected, with the number of exposed individuals and vehicle type. For high-dense agglomerations the marginal cost is about 30 times larger than the marginal cost for very low-dense agglomerations. Further, the vehicle-type dimension is very important. Large heavy vehicles, i.e. trucks with trailer, have a marginal cost that is about 10 times larger than the marginal cost for cars. In addition, we differentiate between cars with and without studded tyres, as the latter is common in Sweden during the winter. As can be seen the studded tyres imply an increase in the marginal cost of about 10 percent.

Considering the differentiation across day, evening, and night, some more unexpected patterns are shown. Here, the difference occurs in two dimensions. First, the disturbance functions of evening and night are both punished with a higher disturbance cost, which would lead to an increased marginal cost, compared to day time, during evenings and an even further increased marginal cost during night time. On the other hand, there is a lower traffic flow during evenings and nights, which may offset the increase in the marginal costs. As has been concluded earlier, the marginal costs of traffic noise are not as sensitive to different traffic flows and noise levels, so the mechanism is instead that the much lower traffic flow during the night means that many road sections during night time have too low noise level to be considered as disturbing at all, i.e. the noise level is below the disturbing threshold.

With this feature in consideration, we can see that for some groups of vehicles and agglomerations, night times have the largest marginal costs, whereas for other groups of vehicles and agglomerations the largest marginal costs are estimated for evenings. In addition, we can see that for low-dense and very low-dense agglomerations, the marginal cost is consistently highest for evening time.
Note that all these marginal cost estimates in Table 6 are for traffic in agglomerations. For traffic in rural areas, where almost no individuals are exposed, the marginal costs will be so small that we can set this to approximately zero. In Nerhagen et al (2015) it was noted that there are also noise-exposed individuals in rural areas, but compared to agglomerations these numbers will be negligibly small. There is, of course, the possibility to approximate the marginal cost for a road section in a rural area if you know the number of exposed individuals per vehicle kilometre, which can be useful for measures in rural areas. Nevertheless, compared to the exposure in agglomeration, we have decided not to prioritise complete noise calculations for rural areas. Still, as a brief calculation exercise, the average population density in very low-dense agglomerations is 298 inhabitants per square kilometre. This implies an average marginal cost of SEK 0.0009 per vehicle kilometre per inhabitant for trucks with trailer in the evening, which is an extremely low value, highlighting the irrelevance of estimating the marginal cost of noise where almost no people live.

In Table 7, we present the marginal costs per vehicle kilometre for the three most densely populated agglomerations in Sweden. Here we can see that the marginal cost is somewhat larger in these cities than for high-dense agglomerations in general. Furthermore, the marginal cost of noise seems to be highest in Malmö, especially regarding trucks with trailer.

Table 7. Estimated average marginal costs for road noise for the most densely populated agglomerations. SEK per vehicle kilometre, price year 2014.

<table>
<thead>
<tr>
<th></th>
<th>Malmo, population density 3650/km²</th>
<th>Stockholm, population density 3597/km²</th>
<th>Lund, population density 3216/km²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day</td>
<td>Evening</td>
<td>Night</td>
</tr>
<tr>
<td>Car</td>
<td>0.252</td>
<td>0.505</td>
<td>0.589</td>
</tr>
<tr>
<td>Car with studded tyres</td>
<td>0.280</td>
<td>0.519</td>
<td>0.599</td>
</tr>
<tr>
<td>Truck without trailer</td>
<td>1.17</td>
<td>3.44</td>
<td>2.34</td>
</tr>
<tr>
<td>Truck with trailer</td>
<td>2.57</td>
<td>7.61</td>
<td>9.72</td>
</tr>
</tbody>
</table>

4.3. Sensitivity analysis

To analyse how variations in the underlying data influence the marginal cost, we have conducted sensitivity analyses in different dimensions. For road noise, we have chosen to, in the same OLS regression, analyse change in traffic flow, speed limit, and the number of exposed individuals. The estimated, and thus model-based, marginal cost observed per road section is the dependent variable. Traffic flow and number of exposed individuals are expressed in natural logarithms to facilitate the percentage interpretation. Each road section is one observation in the OLS model and we estimate how the calculated marginal cost is influenced by traffic flow, speed limit, and population density. In Table 8 these results are presented as changes of the marginal costs in SEK for the example of a truck with trailer during day time.

As is shown in Table 8, the marginal cost of road noise is sensitive to all of these variables but most sensitive to a speed limit increase. Note, however, that a 10 km/h increase is not the same as a 10 percent increase. Also, all of these estimates are strongly statistically significant.

These sensitivity analyses coincide fairly well with the empirical finding of other studies, e.g. Andersson and Ögren (2013), that the marginal cost for road noise is relatively robust to traffic increases but sensitive to the number of exposed individuals. This fact also illustrates one of the essential facts about traffic noise costs, namely that with no exposed individuals there will be no external costs.
Table 8. Sensitivity analysis of estimated marginal costs of road noise. 99,396 road sections are the observation unit

<table>
<thead>
<tr>
<th>Variable and change in percent</th>
<th>Change of marginal cost in SEK for truck with trailer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic flow, increase 10 %</td>
<td>0.02</td>
</tr>
<tr>
<td>Speed limit, increase 10 km/h</td>
<td>0.12</td>
</tr>
<tr>
<td>Number of exposed, increase of density 10 %</td>
<td>0.05</td>
</tr>
<tr>
<td>$R^2$-square</td>
<td>0.39</td>
</tr>
</tbody>
</table>

For rail noise, we have estimated a similar OLS regression to analyse how changes in traffic flow, speed limit, and the number of exposed individuals, influence the estimated marginal cost. These results are found in Table 9 for the example of a freight train. Note that the model approach is not as straightforward for rail as for road. The reasons are that traffic flow has a more discrete pattern and may consist of very different train types on different train sections. Moreover, the speed limit used is the highest speed limit on a train section which is often not allowed for a freight train.

Table 9. Sensitivity analysis of estimated marginal costs of rail noise. 135 rail sections are the observation unit

<table>
<thead>
<tr>
<th>Variable and change in percent</th>
<th>Change of marginal cost in SEK for a freight train</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic flow, increase 10 %</td>
<td>0.02 (insignificant)</td>
</tr>
<tr>
<td>Speed limit, increase 10 km/h</td>
<td>-2.38</td>
</tr>
<tr>
<td>Number of exposed, increase of 10 %</td>
<td>0.86</td>
</tr>
<tr>
<td>$R^2$-square</td>
<td>0.44</td>
</tr>
</tbody>
</table>

The sensitivity analysis of the rail noise marginal costs shows that the traffic flow in this case is not influencing the marginal cost in a statistically significant way. The variable of exposed individuals is positively influencing the marginal cost, which is as expected. Regarding speed limit, on the other hand, we have a non-expected negative sign of the effect. Nonetheless, this is nothing we believe in, and instead we refer to the engineering-based tabulated results of Ögren et al (2011, Table 3 p. 7), for how speed for a given train type influences marginal costs of rail noise. Also, note that a given speed is already included in the calculated marginal cost used as the dependent variable. However, we still believe that the speed-limit variable plays an important role as a control variable in the regression above, as it may increase the coefficient precision of the other variables. As an example, we do not distinguish between different types of train in the traffic flow, which may be strongly correlated with the speed limit.

Regarding rail noise, with separate calculations for each rail section, we are not in need of a prediction model. Regarding road noise, on the other hand, such a prediction model would be a useful tool for calculating marginal costs based on traffic flow, speed limit and number of exposed individuals as inputs.

The result that marginal costs of traffic noise are relatively robust to traffic increases, depends on two forces moving in different directions. First, high traffic intensity means higher noise levels and thus
high noise costs, but then one more vehicle implies an extremely small marginal effect of the noise level. Second, low traffic intensity means lower noise levels and thus low noise costs, but here one more vehicle implies a much larger (but still small) marginal effect of the noise level. Thus, the two parts of the marginal cost of traffic noise, i.e. the noise valuation and the marginal noise contribution, move in opposite directions with the result that marginal costs of traffic noise are relatively robust to changes in traffic intensity.

Also, which is not shown in Tables 8 and 9, the underlying valuation functions of the marginal cost estimations strongly influence the marginal costs. This is as expected, since the only things in the equation of Section 3 that will change when the valuation is changed, are the variables HF and V, and no other variable offsets this change as is the fact with a traffic increase. Thus new established impact functions, e.g. for sleep disturbances or the risk of myocardial infarctions, will potentially have a substantial influence on the level of the external marginal costs of traffic noise.

Since the marginal costs in low-dense agglomerations are found to be lower during the night than during the evening, one can question whether sleep disturbances are actually captured in the noise valuations. Therefore, as a calculation exercise we include the sleep disturbance function in the marginal cost estimates of night time for the two types of truck vehicles. In Table 10 we present these estimates and compare them with the previous estimates. We can see that the marginal costs during night time increase substantially when this sleep disturbance cost is added to the previously calculated marginal cost. The increase in percentage is highest for very low-dense agglomerations, probably as the marginal cost is now zero for far fewer road sections. Also, when direct sleep disturbance costs are included, the marginal cost is consistently highest during night time. To include these sleep disturbance costs may thus be important for the correct estimation of marginal cost for traffic during night time. More discussion about this is provided in Section 4.5.

Table 10. Estimated marginal costs for night time including sleep disturbances. SEK per vehicle kilometre, price year 2014.

<table>
<thead>
<tr>
<th></th>
<th>High-dense agglomeration</th>
<th>Medium-dense agglomeration</th>
<th>Low-dense agglomeration</th>
<th>Very low-dense agglomeration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Night–including sleep disturbances</td>
<td>Night–including sleep disturbances</td>
<td>Night–including sleep disturbances</td>
<td>Night–including sleep disturbances</td>
</tr>
<tr>
<td>Truck without trailer</td>
<td>1.37</td>
<td>1.81</td>
<td>0.944</td>
<td>1.50</td>
</tr>
<tr>
<td>Truck with trailer</td>
<td>3.27</td>
<td>4.33</td>
<td>2.65</td>
<td>4.23</td>
</tr>
</tbody>
</table>

4.4. Comparison with previous studies

In Table 11 we present a comparison of our estimated results with other previous estimates of the marginal costs of road traffic noise during day time. Regarding rail noise marginal costs, we cannot easily compare our study with other studies. The reason is that the marginal cost in our study is calculated for rail sections separately and not for different types of agglomerations. Still we make a simplified comparison and this result is found in Table 12.

As can be seen from Table 11, comparisons across studies are not straightforward as the categories may not coincide well. Regarding trucks, the main problem is the different classes of heavy vehicles, which may be denoted differently in different studies. Furthermore, the classification of agglomeration...
Density is even more problematic as country-specific characteristics are important. Sweden is a very low-dense populated country with large rural parts, but also where the agglomerations are relatively low-dense populated. This means that we have calculated road noise marginal costs for agglomerations only, and assume the cost to be approximately zero in rural areas. Thus we do not compare our results with the rural classification of Ricardo-AEA (2014) and the rural parts of the road sections analysed in Andersson and Ögren (2011).

Table 11. Estimated road noise marginal costs from different studies. Day time, SEK per vehicle kilometre, price year 2014.

<table>
<thead>
<tr>
<th>Agglomeration and/or vehicle type</th>
<th>Current study (day time)</th>
<th>SAMKOST 1 (Nerhagen et al, 2015)</th>
<th>ASEK (Swedish Transport Administration, 2016)</th>
<th>Andersson and Ögren (2011) (day time)</th>
<th>EU handbook (Ricardo-AEA, 2014) (day time) (EUR 10 = SEK 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-dense agglomeration (Urban)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>0.126</td>
<td>0.138</td>
<td>0.29</td>
<td>-</td>
<td>0.150</td>
</tr>
<tr>
<td>Truck without trailer</td>
<td>0.652</td>
<td>0.945</td>
<td>2.06</td>
<td>-</td>
<td>0.751</td>
</tr>
<tr>
<td>Truck with trailer</td>
<td>1.58</td>
<td>4.70</td>
<td>-</td>
<td>1.38</td>
<td></td>
</tr>
<tr>
<td>Medium-dense agglomeration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>0.073</td>
<td>0.083</td>
<td>0.27</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Truck without trailer</td>
<td>0.351</td>
<td>0.599</td>
<td>1.86</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Truck with trailer</td>
<td>0.934</td>
<td>4.26</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Low-dense agglomeration (Suburban)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>0.016</td>
<td>0.019</td>
<td>0.24</td>
<td>0.028</td>
<td>0.010</td>
</tr>
<tr>
<td>Truck without trailer</td>
<td>0.080</td>
<td>0.131</td>
<td>1.69</td>
<td>0.113</td>
<td>0.047</td>
</tr>
<tr>
<td>Truck with trailer</td>
<td>0.210</td>
<td>3.86</td>
<td>0.326</td>
<td>0.086</td>
<td></td>
</tr>
<tr>
<td>Very low-dense agglomeration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>0.004</td>
<td>0.005</td>
<td>0.04</td>
<td>0.005</td>
<td>-</td>
</tr>
<tr>
<td>Truck without trailer</td>
<td>0.021</td>
<td>0.034</td>
<td>0.26</td>
<td>0.018</td>
<td>-</td>
</tr>
<tr>
<td>Truck with trailer</td>
<td>0.052</td>
<td>0.59</td>
<td>0.053</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Notes: Studies other than the current are updated to the price level of 2014 by Swedish consumer price index and real income per capita. – means that no estimate corresponds to the given category. For Andersson and Ögren we define E20 through Partille as low-dense agglomeration and E20 through Lerum as very low-dense agglomeration. Truck without trailer corresponds to “medium heavy trucks, 2 axles (6 wheels)” and truck with trailer corresponds to “heavy trucks at least 6 axles” in Andersson and Ögren. For the EU Handbook we have calculated an average with respect to traffic type, truck without trailer corresponds to LCV, and truck with trailer corresponds to HGV.

Comparing the different studies listed in Table 11, we can see that the studies based on Swedish contexts (all except the EU Handbook) in fact differ substantially. ASEK, which is the Swedish Transport Administration’s official recommendations, consistently suggests the highest marginal costs. Our present study, on the other hand, and Andersson and Ögren (2011) have similar marginal costs in all comparisons, especially for very low-dense agglomerations. This is not the result of the use of the same models and calculations, as the official Swedish valuation functions have been somewhat upward-shifting since the study of Andersson and Ögren (2011).

We need to provide a caveat regarding the comparison across different studies regarding the time of day. We have presented day time in the present study and in Andersson and Ögren (2011), while ASEK does not differentiate with respect to time of day. If we use the implicit formula of Andersson...
and Ögren (2011, Table 2) that marginal costs of day time are some 2.4 times lower than marginal costs calculated based on the 24-hour equivalent noise level, the ASEK values still exceed our estimates, with the exception of cars in high-dense agglomerations where they are of the same size.

Comparing with the EU Handbook (Ricardo-AEA, 2014), the estimated marginal costs of our study coincide well with its estimates. In fact, the estimates are extremely similar for high-dense agglomerations but less so, although still similar, regarding low-dense agglomerations, with our estimates the highest. Note that the marginal cost in the EU Handbook differentiates between dense and thin traffic, and in our comparison of Table 11 an average between these two has been used. Note also that the traffic volumes used in the EU Handbook are much higher than the average in our data. The lowest traffic volume in the EU Handbook (Ricardo-AEA, 2014, Table D2) of 800 vehicles per hour, means 19,200 vehicles per 24-hour. The average in our data is 4,200 vehicles per 24-hour only, with less than five percent of the road sections having a traffic volume above 19,200 vehicles per 24-hour.

Finally, the ASEK estimates stand out in one important aspect compared to all other comparison studies, namely that the difference of marginal costs with respect to the density of agglomerations is extremely small in ASEK. In fact, the marginal cost for road noise in a low-dense agglomeration is about 82 percent of the marginal cost for road noise in a high-dense agglomeration. Unfortunately, no description of how these different types of agglomeration are defined, is provided in their report. Our definition is more than 2000 inhabitants per square kilometer for high-dense agglomerations, and 400-1000 inhabitants per square kilometre for low-dense agglomerations.

The relatively large differences of marginal costs compared to ASEK need to be briefly discussed. As far as we know, if not completely equal, at least similar valuation functions are the basis of both calculations. In fact, we use a valuation function for road noise that implies high valuations of road noise in an international perspective. For example, the valuations used by the EU Handbook (Ricardo-AEA, 2014) are lower than the ones used in our study. Instead we suggest that the differences are caused by different methods for the noise exposure, and the correlation between density of the population and the number of noise-exposed individuals. There are difficulties in following the basis for the marginal cost calculations of ASEK, and we thus leave no further discussion on their estimates and especially the reason why the different types of agglomerations have these similar marginal costs. We are confident that our method is showing a marginal cost of noise that is strongly dependent on the population density in agglomerations.

Considering rail noise marginal costs, the comparison presented in Table 12 shows that our estimates are slightly higher compared to a previous Swedish study (Andersson and Ögren, 2013), and the reason may be that we have included health costs separately and have used an updated, and higher, valuation function for noise exposure. Compared to the EU-level recommendation (Ricardo-AEA, 2014), on the other hand, our estimates are much higher. Recall, however, that the methods differ in several aspects, meaning that we cannot easily compare estimates. For example, the valuation function for noise disturbances differ. In addition, we have a disaggregated marginal cost for each track section, including the actual exposed number of individuals living there. Also, we are not calculating the marginal cost for agglomeration categories based on population density. Thus, we use the nation-wide average of marginal costs, which has no reflective category in the EU Handbook. We have chosen to compare with day time, thin traffic, and rural areas in the EU Handbook, as Sweden is a relatively sparsely populated country on average. Other comparisons may be relevant instead however.
Table 12. Estimated rail noise marginal costs from different studies. SEK per train kilometre, price year 2014.

<table>
<thead>
<tr>
<th>Train type</th>
<th>Current study (no time-of-day differentiation)</th>
<th>Andersson and Ögren (2013)</th>
<th>EU handbook (Ricardo-AEA, 2014) (EUR 1 = SEK 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freight train, 90 km/h</td>
<td>4.22</td>
<td>3.47</td>
<td>0.61</td>
</tr>
<tr>
<td>X2 high speed train, 120 km/h</td>
<td>0.64</td>
<td>0.36</td>
<td>-</td>
</tr>
<tr>
<td>Passenger train, 120 km/h</td>
<td>2.38</td>
<td>-</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Notes: Studies other than the current are updated to the price level of 2014 by Swedish consumer price index and real income per capita. For the EU Handbook we have used day time, thin traffic and rural area as the most relevant comparison with Swedish rail network averages.

4.5. Discussion of the results

As has been concluded earlier, our study shows that the marginal cost of traffic noise is hugely varied across different circumstances, with the number of exposed individuals and vehicle type as the outstanding factors. More contra-intuitive, the differentiations with respect to time of day show lower marginal costs during night time than evening time for low-dense agglomerations.

The latter result addresses the issue with regard to taking sleep disturbances into account. The punishment of the hedonic pricing function that is supposed to capture greater disturbances during the night, will not work sufficiently if the traffic during the night is so low that the noise level, despite the punishment, is lower than the threshold level for noise disturbances.

When we incorporate a function for sleep disturbances in the calculations, we find that the night time marginal cost is the highest in all vehicle and agglomeration categories. This result raises the question – what is captured in hedonic pricing? Since there are effects capitalised into the housing market that are captured in hedonic pricing, these are afflicted with uncertainty. As researchers, we cannot know which effects are known by, and taken into account by, house buyers. Long-running health costs are naturally such an uncertainty, but so may sleep disturbances caused by night-time traffic be, as very few house buyers are likely to visit their prospective house during night time before the purchase takes place. There is thus a risk of double counting, as long-running health effects may, to some extent, also be captured by the hedonic pricing. On the other hand, there is also a risk that all relevant noise disturbances, e.g. sleep disturbances, are not captured by these valuations. Besides sleep disturbances, other effects that are difficult to observe for house buyers could be considered, for example high noise levels during week-day rush-hours as houses are usually shown to buyers during evenings and weekends.

Another important issue which affects the result is the used impact function. Connected to sleep disturbances, the hedonic function during night time is punished with 10 dB compared to day time. However, traffic intensity is lower during night time, so there is a risk that noise exposure of the sleep-disturbed individuals is too low to be considered as disturbing during night time. This further motivates the use of a sensitivity analysis by including the separate and additive valuation function for sleep disturbances. Furthermore, there is uncertainty about the health impact functions used in this study. The threshold noise level for myocardial infarctions is 58 dB $L_{Day}$, and in Sweden, many of the noise exposed individuals are below this level. This means that a lower threshold value for myocardial infarctions will have an influence on higher marginal costs. On the other hand, if such impact functions are to be established in the future, it will be fairly straight-forward to update the estimated marginal costs of our study.

There might be selection effects regarding what type of roads and traffic belong to each agglomeration type. This is likely the reason for the marginal cost per inhabitant and square kilometre to be higher in certain areas, as is the case for Malmö, which can be seen in Table 7. This type of selection effect
cannot however explain any differences between day, evening, and night as these estimates are based on the same road sections.

In this study, we have not incorporated different types of building environments in the noise calculation. Here, there can be a difference which is not captured in our study. Furthermore, given agglomerations are also heterogeneous in their density of population. We have used the average for all road sections within an agglomeration which means that the marginal costs of a specific road section can be both overestimated and underestimated, depending on the actual population density in the proximity of the road. One can likely presume that the national roads included in our study are in fact systematically located, where less people than the average level of agglomeration density actually live. If that is the case, our marginal cost estimates may be somewhat overestimated for national roads. For local roads, on the other hand, the population density might be higher, leading to somewhat higher marginal cost. However, one offsetting effect in this aspect is that the local roads are likely to have a lower speed limit, implying a lower marginal cost as shown in Table 8. To finalise this particular discussion, we want to remind you that not including local roads is not a systematic reason for underestimated marginal costs of road noise, as there is no reason to believe that national roads, given noise level, speed, and number of exposed individuals, should lead to other marginal costs of road noise compared to local roads.

Finally, we need to discuss the fact that the impact pathway approach (IPA) used in our study has uncertainties in all of its steps. Besides the impact functions described above, this holds also for the noise calculations and the monetary valuations. The different assumptions made, i.e. noise exposure, the value of a lost life year, and the number of lost life years from a fatal myocardial infarction, may all have considerable impact on the estimated marginal costs. Still, the approach used is based on the most recent available research and, as far as we know, there is no alternative method that is more frequently used for estimating marginal costs of environmental impacts than the impact pathway approach.
5. Conclusions

In this paper we have estimated external marginal costs for road noise and rail noise. The results show that the marginal costs of traffic noise are highly dependent on the number of exposed individuals and the vehicle type. As an example of the former, the marginal cost per train kilometre for a freight train is SEK 143 for a track section in a very high-dense urban area, whereas the marginal cost is SEK 0.96 for another track section where almost no individuals are exposed to the rail noise. For road noise, the same pattern occurs, as the marginal cost per vehicle kilometre for a truck with trailer during day time is SEK 1.58 in high-dense agglomerations, and SEK 0.052 in low-dense agglomerations (but still an agglomeration). As an example of the vehicle-type difference, the nationwide average marginal cost per train kilometre is SEK 4.06 for a freight train, and SEK 0.05 for a small passenger train (type Y31). Considering road noise marginal cost in high-dense agglomerations during day time, the cost per vehicle kilometre is SEK 1.58 for a truck with a trailer, and SEK 0.126 for a car.

The overall conclusion is thus that differentiation of the marginal costs is essential, as the noise exposure varies tremendously with the population density, and that different vehicle types contribute very differently to the noise emissions. Furthermore, for road noise the estimated marginal costs are somewhat sensitive to the speed limit and the traffic volume. Higher speed and larger traffic volume both lead to higher marginal costs, all else being equal. Nevertheless, the sensitivity with respect to traffic volume is not very substantial for road noise and, importantly, non-existent regarding rail noise.

Our estimates of road noise marginal costs are lower compared to other relevant Swedish studies, as well as much lower than official Swedish recommendations. On the other hand, our estimates are relatively close to recent EU-level recommendations (Ricardo-AEA, 2014). One reason might be that we use the recent EU noise calculation model (Crossos) in our study. Keep in mind though, that comparisons across studies are not straightforward as the vehicle type, time of the day, and type of agglomeration might vary.

Considering rail noise marginal costs, our estimates are higher compared to the EU-level recommendation (Ricardo-AEA, 2014). Recall, however, that the methods are somewhat different as we have a disaggregated marginal cost for each track section, taking into account the actual residential-based exposed number of individuals, and not calculating the marginal cost for agglomeration categories based on population density.

Moreover, the marginal costs for road noise is estimated separately for different times of day. These results show that day time has the lowest marginal costs despite the largest traffic volume. The reason is that the day-evening-night dimension punishes the disturbance costs with a level corresponding to 5 dB during evening time, and 10 dB during night time. The highest marginal costs are mostly estimated for evening but also, for some high-dense agglomeration categories, for night time. Sleep disturbances may be difficult to capture in our analysis though, as the punishment used for the disturbance costs during night time will have no effect, if the total night-time traffic is lower than the threshold noise level for disturbance costs. A calculation exercise including a separate function for sleep disturbance shows that night time marginal costs are consistently the highest.

Finally, the result of this study is useful in at least three different ways. First, the marginal costs can be used to calculate internalisation rates of rail and road traffic of different types. Second, the marginal costs can be a basis for efficient external cost pricing of rail and road traffic. Third, when policy measures have relatively small effects on the noise emission level, the marginal cost can be used to calculate the noise benefit or cost from that specific policy measure.
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HEAD OFFICE
LINKÖPING
SE-581 95 LINKÖPING
PHONE +46 (0)13-20 40 00

STOCKHOLM
Box 55685
SE-102 15 STOCKHOLM
PHONE +46 (0)8-555 770 20

GOTHENBURG
Box 8072
SE-402 78 GOTHENBURG
PHONE +46 (0)31-750 26 00

BORLÄNGE
Box 920
SE-781 29 BORLÄNGE
PHONE +46 (0)243-44 68 60

LUND
Medicon Village AB
SE-223 81 LUND
PHONE +46 (0)46-540 75 00