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A study of the interaction between vehicle exterior noise emissions and vehicle energy demands for different drive cycles

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Abstract

This initial study investigates the interaction between vehicle noise emissions and the energy required to move the vehicles along different drive cycles. There is a trade-off between reducing noise emissions and at the same time reducing other environmental impacts. A vehicle's energy demand associated with a specific drive cycle may be affected when a different route is chosen between two locations to reduce the noise exposure at certain observer points. The methodology of the study was to use the existing IMAGINE traffic noise model as a source model, and to evaluate the sound exposure level (SEL) at observer points as a function of instantaneous sound pressure level estimates as the source moved from one location to another via two different routes. A noise impact estimate with a linear dependence on the difference between the SEL and a threshold level was proposed. Also, the energy demand for each route was calculated. The results indicated that there is a difference between the two routes if the aim is to reduce the noise exposure or the energy demand. Suggested future research is to further improve the noise impact evaluations in the context of very short durations of exposure.

Keywords: Vehicle noise emissions, Energy demand, Drive cycles.

1 INTRODUCTION

Noise emissions from transport persists as one of the greatest environmental issues in modern day. The social cost for road traffic noise in Europe was estimated to €40 billion per year in 2007, where passenger vehicles and trucks were responsible for 90% of the annual cost (1). While most of the health effects due to traffic noise are measured using long-term averaged noise indicators, effects such as sleep disturbance in the form of awakenings can also be caused by noise events with transient behaviour which might not be resolved using the long-term averaged noise indicators. In this context, a time-dependent measure, potentially capturing these short-time noise events, may be needed in order to provide estimations of the impact of noise emissions from individual vehicles.

There is often a trade-off between noise emissions and other environmental impacts such as energy use. For example, the energy demand for moving from one point to another may change when taking different routes between the two points. The level of impact related to noise emissions is measured with respect to one or several observer points, whereas the energy demand is related to the specific vehicle and the drive cycle. However, they are not necessarily independent from one another. When an attempt is made to minimize either the impact of noise or the energy demand, one does not necessarily keep the other unchanged. For example, one driving strategy to minimize the impact of noise is to make sure that the route from one location to another remains as far away from the observer points as possible, which might lead to a longer route than what would be taken if the only goal was to minimize the energy required to move between the two locations.

The aim of this study is to investigate how a choice of route between two locations affects the resulting impact due to noise emissions as well as the energy demand and how these two environmental impacts interact on

a system level. An initial study will be performed on a simplified model of a road network with two routes between two different locations. The total sound exposure level (SEL) is suggested as a noise indicator, estimated over the duration of driving along each route. The energy demand required to move along a route is also calculated.

2 BACKGROUND

There has been extensive research in the field of long-term averaged traffic noise estimations and long-term health effects regarding road traffic. Andersson and Ögren (2) investigated a pricing model for road and railway noise using short-run marginal cost from changes in the SEL over 24 h. The World Health Organization (WHO) (3) recently published new guidelines and recommendations on community noise and a review of research providing evidence on health outcome related to noise exposure measured using noise indicators such as averaged night-time noise levels (L_{night}) or averaged day-evening-night noise levels (L_{den}).

Traffic noise models can then be used to calculate estimations of these noise indicators. A common noise assessment method (CNOSSOS-EU) was developed for the EU in 2010-2012 (4), and is currently being used to harmonize the estimation of L_{den} in European countries. CNOSSOS-EU is a model on a macroscopic level of traffic behaviour, and is one of several existing traffic noise models. Another traffic noise model developed by the EU is the IMAGINE traffic noise model (5), which is based on a microscopic level of traffic behaviour instead. The IMAGINE model provides representative source models for vehicles of a certain category, and these are defined as one or two point sources at different heights. The sound power level for each source is given in 1/3-octave bands and is speed and acceleration-dependent. Correction terms for vertical directivity are provided in the model, but for a more detailed formulation of the directivity, including horizontal directivity, one can use the correction terms found in (6).

However, long-term averaged traffic noise estimations do not provide information on the temporal structure of the noise. De Coensel *et. al.* (7) implemented the IMAGINE traffic noise model in a microscopic traffic simulation to estimate the instantaneous sound pressure levels produced by individual vehicles. This enables an exposure analysis that includes the duration of the exposure and the time history of the sound pressure level.

3 METHODOLOGY

As the aim of this initial study is to analyze both the effects of noise and energy demand along different routes, the noise and energy models should be simple enough for calculation purposes but complex enough to capture a variation in vehicle behaviour. The approach is to use the existing representative source model for a category 1 vehicle in the IMAGINE traffic noise model. This category corresponds to light motor vehicles. The source model will be used to estimate the instantaneous sound pressure level at a certain time step produced by an individual vehicle, and then evaluate it over time as the vehicle moves. Any acoustic effects due to source motion are assumed here to be negligible. The time delay related to the sound propagation between source and observer will be omitted. This initial study only considers one vehicle at a time, and a time shift corresponding to the time delay would in this case only delay the same noise that will eventually be observed. Also, the two point sources that the vehicle model is comprised of are very close to each other. Thus, one can assume the distances between the point sources and the observer are similar. Correction terms for horizontal and vertical source directivity will be used in accordance to the documentation of acoustic source modelling of nordic road vehicles (6). These correction terms are tabulated in 1/3-octave bands and depend on source height and horizontal as well as vertical angles between observer and source direction. The sources are assumed to be in a free field with standard temperature and pressure, and the sound propagation is therefore simplified to a function of distance $r(t)$ between an observer and the source at height h, given by

$$L_{p,h}(t) = L_{W,h}(t) - 10\log\left(4\pi r(t)^2\right), \tag{1}$$

where $L_{W,h}(t)$ is the sound power level provided by the IMAGINE traffic noise model. The sound exposure level (SEL) L_E will be used as noise indicator

$$L_E = \int_0^T 10^{L_p(t)/10} dt, \tag{2}$$

where $L_p(t) = \sum_h \exp\left(L_{p,h}(t)/10\right)$ is the total instantaneous sound pressure level at time t and the integration is evaluated over a total time of T. The sound exposure level takes into account both the sound pressure level of the exposure as well as its duration. An exposure to a lower equivalent sound pressure level over a longer time may have the same SEL as a higher equivalent sound pressure level over a shorter time. The impact I given the SEL L_E estimated over a number of observation points will then be calculated with an evaluation proposed here to be such that

$$I = K \sum_{n=1}^{N} \max\left(L_E - L_{E,threshold}, 0\right), \tag{3}$$

where K relates the impact to a difference in SEL with respect to some threshold level $L_{E,threshold}$. K here is assumed to be independent of the total SEL L_E. It is therefore assumed that the impact is linearly dependent on the difference between the current SEL and the threshold level, and that there is no measurable impact related to SEL below the threshold level. The impact estimate does not resemble an actual cost or health effect estimate in the current state. However, it should aim to resemble such an estimate.

The noise exposure will be compared with the energy demand for each route. The energy demand is considered as the energy needed to overcome the aerodynamic, inertial and rolling resistance for a specific drive cycle. For more details on the calculations, see references (8, 9). It translates into the total necessary mechanical work, and is calculated as

$$W_T = W_R + W_a + W_L, \tag{4}$$

where W_T is the total energy required, W_R is the energy required to overcome rolling resistance, W_a is the energy to overcome the inertial resistance due to acceleration, and W_L is the energy to overcome the aerodynamic drag. They are calculated as

$$\begin{aligned} W_R &= (1-r) g f_R C_{WR} \\ W_a &= m C_{Wa} \\ W_L &= 0.5 \rho c_D A C_{WL} \end{aligned} \tag{5}$$

where r is the fraction of kinetic energy regained during deceleration, g is the gravitation constant, f_R is the rolling resistance coefficient, m is the mass of the vehicle, ρ is the density of air, c_D is the drag coefficient, and A is the frontal area of the vehicle. The coefficients C_{WR}, C_{Wa} and C_{WL} are characteristic values that only depend on the drive cycle. They are sums over discrete segments of Δs over the length of the drive cycle, as $C_{WR} = \sum \Delta s$, $C_{Wa} = \sum a_i \Delta s_i$, and $C_{WL} = \sum v_i^2 \Delta s_i$ where a_i and v_i are the incremental acceleration and velocity, respectively.

Lastly, the vehicle parameters will be defined for a typical passenger vehicle similar to the representative vehicle of category 1 in the IMAGINE traffic noise model.

4 SETUP OF ROUTES AND MEASUREMENT POINTS

The setup allows for an evaluation of noise exposure at set measurement points with respect to two similar, yet different, routes.

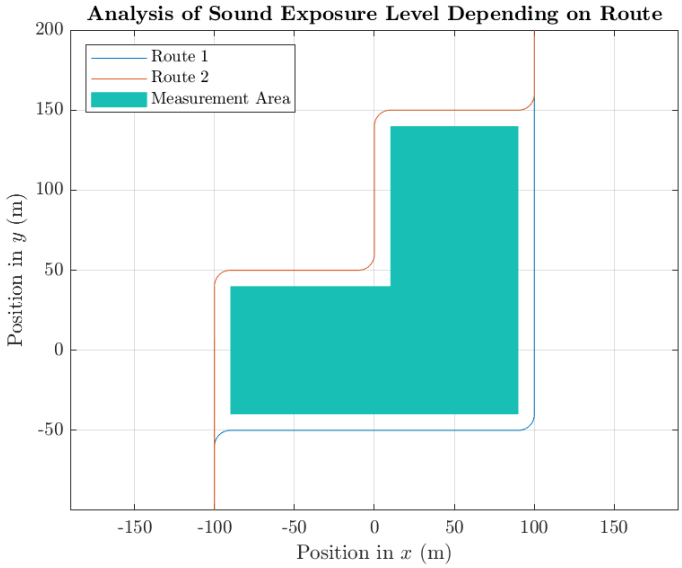

Figure 1. Setup of the analysis.

The two routes in the setup shown in Figure 1 have the same locations for departure and arrival, respectively. The measurement area located at a height of 2 m consists of 5600 measurement points distributed over the area. The routes are flat and follow the same set of simple rules regarding speed and acceleration/braking, shown in Table 1.

Table 1. Rules for the speed of the source.

v_s	50 km/h
v_t	40 km/h
$t_{a/b}$	3 s

The source will move at a constant speed of v_s on the straight road sections. It will then brake for a time length of $t_{a/b}$ with a constant deceleration just before it enters a turn, which it will drive in at a constant speed of v_t. All the turns for both routes have the same radius of curvature of $r_{turn} = 10\,\text{m}$. Right after the turn the source will then accelerate up to v_s by accelerating with a constant acceleration for a time length of $t_{a/b}$. The distance travelled along each route and the time it takes for the source to go from the start point to the end point are shown in Table 2.

Table 2. Distance travelled and time it takes to travel along each route given the rules in Table 1.

	Distance	Time
Route 1	491.4 m	37.2 s
Route 2	482.9 m	38.3 s

The choice of vehicle parameters will have an impact on the resulting energy demand for each route. The proposed vehicle parameters are chosen to be consistent with a vehicle of the same category as in the IMAGINE

traffic noise model.

Table 3. Vehicle parameters.

Description	Param.	Value
Weight	m	1500 kg
Air drag coefficient	c_D	0.3
Frontal area	A	$2\,\mathrm{m}^2$
Rolling resistance coefficient	f_R	0.01

In addition to the vehicle parameters in Table 3, the air density was set to $\rho = 1.2\,\mathrm{kg/m^3}$.

5 RESULTS

The following sections will present the results of the noise level calculations as well as the energy demands corresponding to each route.

5.1 Noise impact

The resulting total SEL over the measurement area differs when driving on either route.

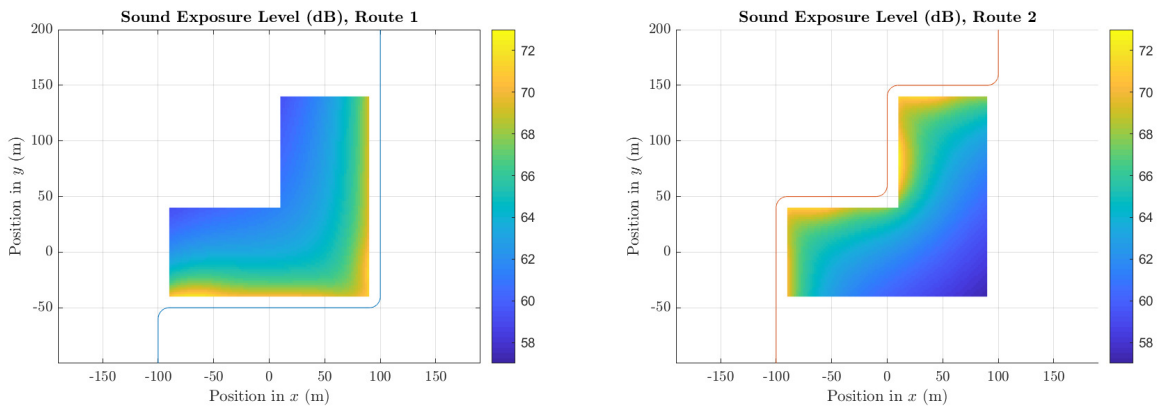

Figure 2. Total sound exposure level on the measurement area when driving along route 1 (left) and route 2 (right).

A higher SEL was observed close to where the source was accelerating after each turn in Figure 2. A histogram of the results is used for comparison of the distribution of the exposure level over the measurement area, see Figure 3.

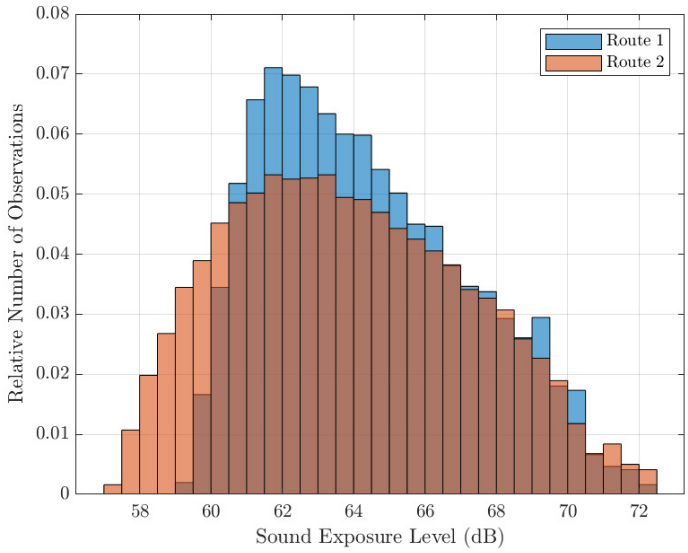

Figure 3. A histogram comparing the total sound exposure level when driving along route 1 and 2.

The histogram is normalized with respect to the total number of observation points over the measurement area. A larger portion of the measurement area has a lower SEL when the source moved along route 2 compared to route 1, as the relative number of observations are larger for lower SEL for route 2 compared to route 1 in Figure 3. However, there is a small difference at very high SEL where route 2 has slightly more observations compared to route 1. The results of the impact estimate given in Equation 3 is shown in 4.

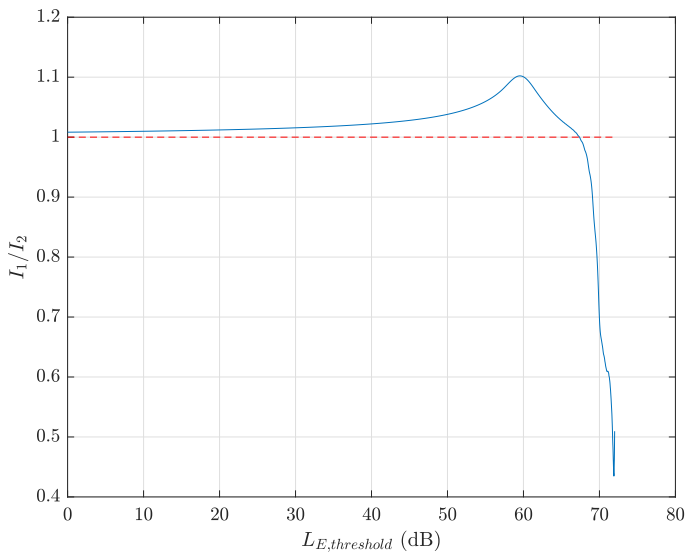

Figure 4. Ratio of impact estimates as function of the threshold level.

The impact of route 1 appears to be slightly higher than the impact of route 2 for almost all choices of the

threshold level. At almost 60 dB there is a maximum related to the shape of the distributions in the histogram. If the threshold level is set to 60 dB it means that the observations at low exposure levels are omitted, and the larger difference between the exposure levels from the routes at 61 to 67 dB results in this peak. As the threshold level is increased there are fewer data points in the ratio estimate, and there are no data points for either route with a measured SEL above 72.5 dB.

5.2 Energy Demands

The resulting energy demands are a function of the drive cycle along each route and the vehicle parameters. The characteristic values for each route are shown in Table 4.

Table 4. Characteristic values.

	C_{WR} (m)	C_{WL} (m^3/s^2)	C_{Wa} (m^2/s^2)
Route 1	491.4	8.7E4	69.5
Route 2	482.9	7.8E4	138.9

The ratio of the energy demands between route 1 and route 2 were calculated with Equation 4 to be $W_1/W_2 \approx 0.69$, meaning that the energy demand for route 1 was approximately 70 % of the energy demand needed to move along route 2.

6 ANALYSIS

Given this specific scenario there appears to be a conflict in reducing noise exposure as well as the required energy to move along a route at the same time. While route 1 seems to have a higher impact in terms of noise exposure, it does also seem to require less overall energy associated with its drive cycle when compared to the corresponding estimates associated with route 2. The difference in energy demand between the two routes was largely as a result of the greater C_{Wa} for route 2 because of the additional cornering. As expected, the results for noise levels and energy demand were dependent on how the source was moving along each route and where the observer points were located with respect to the source.

However, the noise impact estimate needs to be further improved in order to determine the total impact, in particular the coefficient K. It is not ideal for K to be assumed constant, as this coefficient can be related to an individual cost as a function of a change in the SEL. Reviewing other studies on cost analysis of noise one realizes that a difference in noise levels relates to different costs depending on the current noise level, as presented by Andersson and Ögren (2). The same difference in noise levels will result in a higher cost if the current noise level is higher compared to a lower current noise level. Also, other studies investigating cost measures of noise often use the averaged day-evening-night noise level L_{den} or the A-weighted 24 h equivalent sound level $L_{Aeq,24h}$, which make it non-trivial to relate these to the estimation of the impact of noise events with very short durations ($T \ll 1$ h). Given that both energy demand and a cost estimate based on noise exposure could be comparable quantities, it is of interest to further investigate the derivation of suitable indicators in contribution of the steps presented with this contribution.

7 CONCLUSIONS

There is a trade-off between noise exposure and energy demand for the specific scenario presented here and the associated drive cycles. It was possible to show that one route might be preferred with respect to one environmental impact, whereas the other route would be preferred with respect to another environmental impact. Continued research is needed to provide a comparison of the total environmental impact from noise exposure and energy demand using a common value of impact for very short durations of exposure as presented in this initial study.

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REFERENCES

[1] European Environment Agency (EEA), Noise in Europe 2014, EEA Report No 10. ISSN 1977-8449.

[2] Andersson, H.; Ögren, M. Charging the Polluters: A Pricing Model for Road and Railway Noise. Journal of Transport Economics and Policy (JTEP), Vol 47 (3), 2013, pp 313-333.

[3] World Health Organization (WHO), Environmental Noise Guidelines for the European Region, 2018. ISBN 978-92-890-5356-3.

[4] European Commission (EC), Common Noise Assessment Methods in Europe (CNOSSOS-EU), 2012. ISBN 978-92-79-25281-5.

[5] Peeters, B.; van Blokland, G. J. The Noise Emission Model For European Road Traffic. Improved Methods for the Assessment of the Generic Impact of Noise in the Environment (IMAGINE). Deliverable 11 of the IMAGINE project, 2007.

[6] Jonasson, H. Acoustic Source Modelling of Nordic Road Vehicles, SP Rapport 2006:12, final revision, Borås (SE), 2006.

[7] De Coensel, B.; Brown, A.L.; Tomerini, D. A road traffic noise pattern simulation model that includes distributions of vehicle sound power levels. Applied Acoustics, Vol 111 (C), 2016, pp 170–8.

[8] Koffler, C.; Rohde-Brandenburger, K. On the calculation of fuel savings through lightweight design in automotive life cycle assessments. The International Journal of Life Cycle Assessment, Vol 15 (1), 2010, pp 128-135.

[9] O'Reilly, C. J.; et. al. Life cycle energy optimisation: A proposed methodology for integrating environmental considerations early in the vehicle engineering design process. Journal of Cleaner Production, Vol 135 (C), 2016, pp 750-759.