
On the trade-off between noise exposure cost and resource efficiency in traffic

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Achieving sustainable transport involves a trade-off between providing transportation while reducing traffic-related impact, such as improving resource efficiency and reducing the noise exposure. Previous studies showed that the trade-off between reducing the noise exposure cost and reducing the energy demand is dependent on other factors than the vehicle itself. Being part of traffic in a road network, the interactions between other vehicles will affect both the necessary mechanical work associated with the motion of the vehicle, the energy demand, and the resulting noise exposure cost due to the noise emissions from each vehicle in the traffic flow and the vehicles' locations with respect to the measurement points in the network at which the noise exposure is evaluated. While initial results of microscopic traffic simulations indicate that a vehicle's energy demand and noise exposure cost are positively correlated, it is also shown that the vehicle-specific noise exposure cost does not correlate with the increase in system-wide noise exposure costs under peak traffic conditions. For vehicles travelling in the network during peak hours, this means that a reduction in the vehicle-specific noise exposure cost may not necessarily correspond to a lower rate-of-change for the system-wide noise exposure cost. A different allocation strategy may improve the correlation between the vehicle-specific noise exposure cost and the system-wide effects. The study aims to analyse the correlation between different vehicle-specific effects and system-wide effects in a microscopic traffic simulation. It also aims to analyse how a weighting-based allocation strategy for the vehicle-specific noise exposure cost affects the correlation between the vehicle-specific noise exposure cost and the rate of change of the system-wide noise exposure cost, and how this allocation strategy in turn influences the correlation between the energy demand and the vehicle-specific noise exposure cost.

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1. Introduction

For transport to be sustainable, it is important not only to consider the provision of transportation but also to make sure it remains efficient and reduces the traffic-related effects, such as the health-related effects from traffic noise exposure. In a previous study [1], it was observed that a reduction in the vehicle-specific noise exposure cost, meaning the impact of noise exposure evaluated in monetary units for an individual vehicle, occurred under peak hour traffic conditions - under which the system-wide noise exposure cost increased the most. It was concluded that the preferred behaviour for the individual vehicles to reduce their individual noise exposure cost may not be the preferred

behaviour in terms of reducing the system-wide noise exposure cost. Another strategy in terms of the allocation of noise exposure cost from a system perspective down to each individual vehicle, based on their respective noise contribution, may reflect the system-wide effects during peak hours. An original allocation strategy, denoted here as the weighting-based allocation strategy, was then proposed [1]. The present study extends this work by analysing the correlation between the vehicle-specific noise exposure cost to the system-wide noise exposure cost increase and how this is affected by the weighting-based allocation strategy.

However, by changing the allocation strategy of the noise exposure cost to improve the correlation between the vehicle-specific- and the system-wide noise exposure cost, the relation between a vehicle's energy demand and duration to the vehicle-specific noise exposure cost will be changed as well. As the energy demand, the noise exposure cost and the duration in the network for a specific vehicle are all dependent on the driving behaviour, it means that a change in the behaviour to reduce the noise exposure cost will also result in a different energy demand. A change to the allocation strategy results in a different noise exposure cost and a different relation between the driving behaviour and the corresponding noise exposure cost. The preferred behaviour in terms of reduced noise exposure cost with this weighting-based allocation strategy may then be less beneficial in terms of lower energy demand or shorter duration. Therefore, this study also considers the correlation between the vehicle-specific noise exposure cost and the vehicle's energy demand and duration, which are used as proxies for the resource efficiency evaluation associated with individual vehicles and their specific driving behaviour.

2. Case study

The case study introduced here uses vehicle kinematics data obtained from the microscopic traffic simulation software SUMO [2] to calculate each individual vehicle's noise exposure cost, energy demand and duration in the network. The vehicle-specific noise exposure cost is a monetary impact assessment of the resulting noise exposure at measurement points in the network, evaluated by means of a willingness-to-pay model. The method of calculating the vehicle-specific noise exposure cost based on the actual behaviour was proposed in [1]. A vehicle's energy demand is a measure of the necessary mechanical work to overcome the work arising from frictional forces exerted on the vehicle during its motion in the network [3, 4].

The present contribution extends the work performed in [1], and the same configurations in terms of road network, vehicle type and traffic demand are used here. In addition, the present study introduces a stochastic behaviour and studies how the observed variation in energy demand, noise exposure cost and duration correlate with each other for each individual vehicle over 100 simulations, each with a total simulation time of 24 hours. Including a stochastic behaviour enables the analysis of the performance of the weighting-based allocation strategy and how it impacts the correlation between the vehicle-specific noise exposure cost and the noise exposure cost evaluated at a system level. Using a weighting-based allocation strategy may also impact the correlation between the vehicle-specific noise exposure cost and energy demand, which will be investigated as well.

2.1 Road network

The layout of the road network affects how the vehicles are able to move from their starting position to their destination. In the present study, a road network consisting of a total of 2 two-lane roads is implemented, see Fig. 1. The two roads intersect at two locations, resulting in a three-way junction at each intersection where one route will have a lower priority as they will have to make a left turn. This results in a total of 4 possible routes in the network between two points. In addition, 24 measurement points are located along each road, totalling to 48 measurement points in the network. It is at these points that the noise exposure is evaluated, and an associated noise exposure cost is calculated.

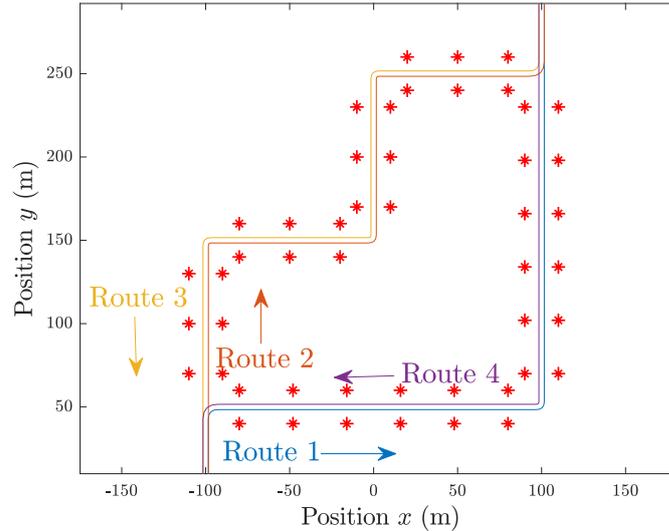


Figure 1: A map of the road network including the measurement points, marked as $*$, used for evaluating the impact of the noise exposure.

2.2 Traffic demand and vehicle properties

The traffic demand defines the amount of traffic on the network. It is represented here as how often a vehicle is entering the network. It is set up in such a way that there are two periods of high traffic demand, corresponding to peak traffic conditions where a large amount of vehicles are entering the network, with periods of low traffic demand in between with fewer vehicles entering the network per unit time. For more details on the specific traffic demand, see [1].

A vehicle's motion is modelled in SUMO using a vehicle follower model. The vehicle aims to drive at the speed of the lane it is currently driving on while keeping a certain safe distance to the leading vehicle in order to avoid collisions. In SUMO, a vehicle type is defined by certain parameters, see Table 1. The actual speed a particular vehicle will drive at will depend on the resulting speed factor, which is a normally distributed parameter defined by a mean, `speedFactor`, and a standard deviation, `speedDev`. Provided this target speed is below the maximum capable speed of that vehicle type, `maxSpeed`, the vehicle will try to maintain the target speed. A resulting speed factor value above 1 provides a target speed above the speed limit of the lane, meaning that the vehicle will inherently attempt to exceed the speed limit of the lane. In contrast, a value below 1 provides a target speed below the speed limit of the lane instead. Over the 100 simulations performed, the resulting speed factor of each vehicle will be a different value in each simulation.

In addition to the normal speed distributions, the vehicle's behaviour is altered by a driving imperfection parameter σ , which is a value between 0 and 1. For $\sigma = 0$, all vehicles of that type drive perfectly, whereas for $\sigma > 0$ the driving quality will decay in the sense that they will have to continuously adjust their speed to keep distance to leading vehicles – and to maintain their current target speed.

Table 1: Parameters defining the vehicle type in SUMO.

Parameter	Description	Value
length	Length of the vehicle	5.0 m
maxSpeed	Maximum capable speed	50.0 m/s
speedFactor	Mean of the normal speed factor distribution	1
speedDev	Standard deviation of the normal speed factor distribution	0.1
accel	Maximum acceleration	2.6 m/s ²
decel	Maximum deceleration	4.5 m/s ²
sigma	Driving imperfection parameter	0.5

In order to calculate a vehicle's energy demand, additional parameters related to the vehicle need to be defined, see [1, 3, 4]. The vehicle-related parameters, the rolling resistance, vehicle mass, drag coefficient and frontal area, that are used in the present study are defined in Table 2.

Table 2: Parameters used to define a typical light road vehicle.

Parameter	Description	Value
f_R	Rolling resistance	0.01
m	Vehicle mass	1500 kg
c_D	Drag coefficient	0.3
A	Frontal area	2 m ²

Apart from the vehicle parameters in SUMO and to calculate the energy demand, the vehicle type is also defined in terms of its noise source characteristics. The noise source model IMAGINE [5] is used to model the noise emissions from each vehicle, together with an included correction factor for the source directivity from [6].

3. Methodology

3.1 Calculating the noise exposure cost and resource efficiency

The noise exposure cost is based on a model by Andersson *et al.* of the willingness-to-pay associated with a certain noise exposure [7]. The resulting noise exposure cost C associated with a change in the noise exposure from L_1 to L_2 , given in A-weighted equivalent noise levels over a time T , is given by

$$C = \frac{T}{T_{1yr}} \frac{\max(L_2, L_{A,threshold}) - \max(L_1, L_{A,threshold})}{2} (\Pi(L_1) + \Pi(L_2)), \quad (1)$$

where T/T_{1yr} is the fraction of time T with respect to one year, and $L_{A,threshold}$ is the A-weighted equivalent noise level threshold for the demand function $\Pi(L)$, given by

$$\Pi(L) = \begin{cases} 3859 - 173.4(75 - L), & L \geq L_{A,threshold} = 52.8 \text{ dB(A)}, \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

In [1], the resulting calculation of the vehicle-specific noise exposure cost $C_{R,V_{ID}}(t_i)$, at time t_i for vehicle V_{ID} associated with the measured noise exposure at measurement point R , uses the information of the individual vehicle's contribution to the noise, its estimated instantaneous mean-square pressure contribution $\tilde{p}_{R,V_{ID}}^2(t_i)$, and the information of the total traffic noise contribution,

$\tilde{p}_{R,traffic}^2(t_i)$. The proposed weighting-based allocation strategy, shown in Eq. (3), uses weighting functions $K(x)$ of the form $K(x) = A_m x^m$. The term A_m is used to normalize the results so that the sum of the vehicle-specific noise exposure costs over all time T and all vehicles is equal to the total traffic-related noise exposure cost $C_{R,traffic}$. In the present study, the vehicle-specific noise exposure cost was calculated with a linear weighting function for $K_{VID}(x)$, with $m = 1$, and $K_{traffic}(x)$ was allowed to be either linear ($m = 1$) or quadratic ($m = 2$).

$$C_{R,VID}(t_i) = K_{VID} \left(\frac{\tilde{p}_{R,VID}^2(t_i)}{\tilde{p}_{R,traffic}^2(t_i)} \right) K_{traffic} \left(\frac{\tilde{p}_{R,traffic}^2(t_i)}{\sum_{t=0}^T \tilde{p}_{R,traffic}^2(t)} \right) C_{R,traffic}. \quad (3)$$

The energy demand is a measure of a vehicle's total necessary mechanical work W_T , to move as described by the vehicle kinematics data provided by the microscopic traffic simulation. The total work W_T is comprised of contributions related to the work to overcome rolling resistance W_R , inertial resistance W_a , and aerodynamic drag W_L , see Eq. (4). For more details on the calculations of the different contributions to the total necessary mechanical work, see [1, 3, 4].

$$W_T = W_R + W_a + W_L. \quad (4)$$

3.2 Correlation coefficient

To analyse how the observed fluctuations in noise exposure cost, energy demand and duration for each vehicle between the 100 simulations co-variate or correlate, the linear Pearson correlation coefficient r_{xy} is used. It may be considered a function of the covariance of the samples $\{x_i\}$ and $\{y_i\}$ of two stochastic variables X and Y , divided by the estimated standard deviation of each respective variable from the samples, and is given by

$$r_{xy} = \frac{\sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^N (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^N (y_i - \bar{y})^2}}. \quad (5)$$

The correlation coefficient r_{xy} is a value between -1 and 1. A value of 1 (-1) means that the observed data have a strong positive (negative) linear correlation. On the other hand, a value of 0 means that the variables appear not to be linearly correlated with each other in the data.

4. Results and analysis

The correlation analysis was performed on a subset of the vehicles. The correlation coefficients were calculated for all vehicles along routes 1 and 4 in Fig. 1. The correlation coefficient between the vehicle-specific noise exposure cost and the average rate of change of the system-wide noise exposure cost for all measurement points along the same road as the vehicle is presented in Fig. 2. The average rate of change of the system-wide noise exposure cost is estimated over the duration of each individual vehicle as the total noise exposure cost increase while the vehicle was in the system, divided by the duration of the vehicle. Each point in the figure represents an individual vehicle, entering the network at a given departure time.

A non-linear weighting function in the allocation strategy improves the correlation between vehicle-specific noise exposure costs and the system-wide increase of the noise exposure cost. However, the observed effects depend on the specific route that the vehicle drove on, indicating a system-dependency in the resulting effects of the non-linear allocation strategy. As can be seen in Fig. 2, the correlation coefficient for vehicles driving along route 4 during peak hours (departure times between 8h and 11h) is increased to slightly more positive when going from a linear allocation strategy, see a), to a non-linear allocation strategy, see b).

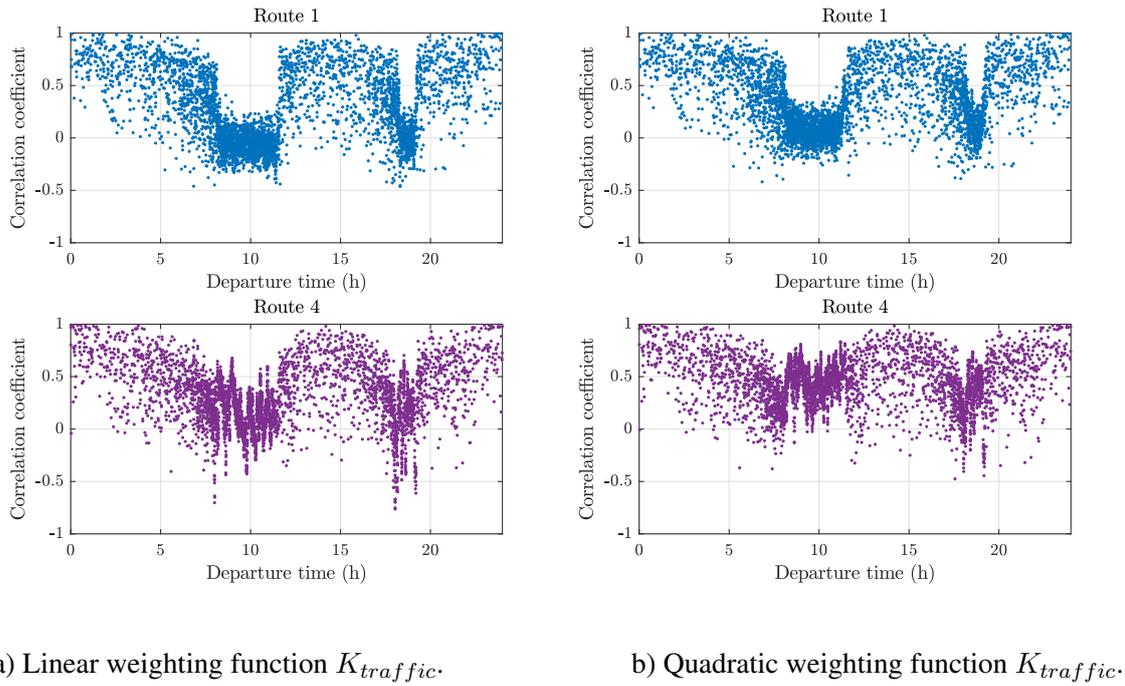


Figure 2: Correlation coefficient between linearly (a), or non-linearly (b), allocated vehicle-specific noise exposure cost and the average cost increase per second for the measurement points along the same road.

However, vehicles along route 1 do not observe as great an impact on the correlation coefficient during the same time period. The correlation coefficients for vehicles entering the network during peak hours are distributed around $r_{xy} = 0$, indicating a weak linear correlation or no linear correlation.

A change in the allocation strategy for the noise exposure cost also impacts the relation between observed variations in noise exposure cost and that of the duration and energy demand. Figure 3 presents the calculated correlation coefficient between each individual vehicle's noise exposure cost and duration in the network, for vehicles along routes 1 and 4.

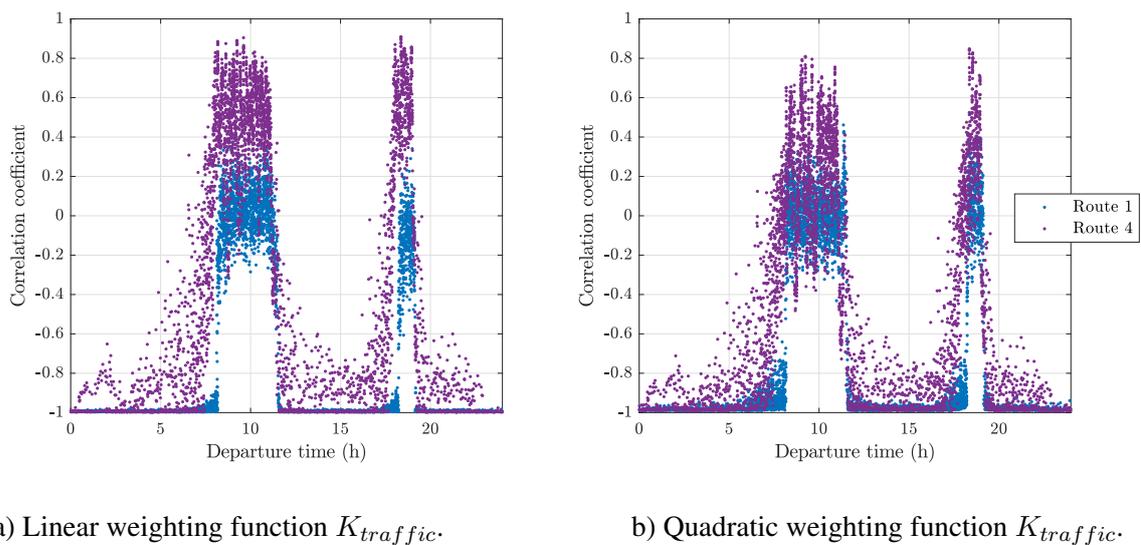
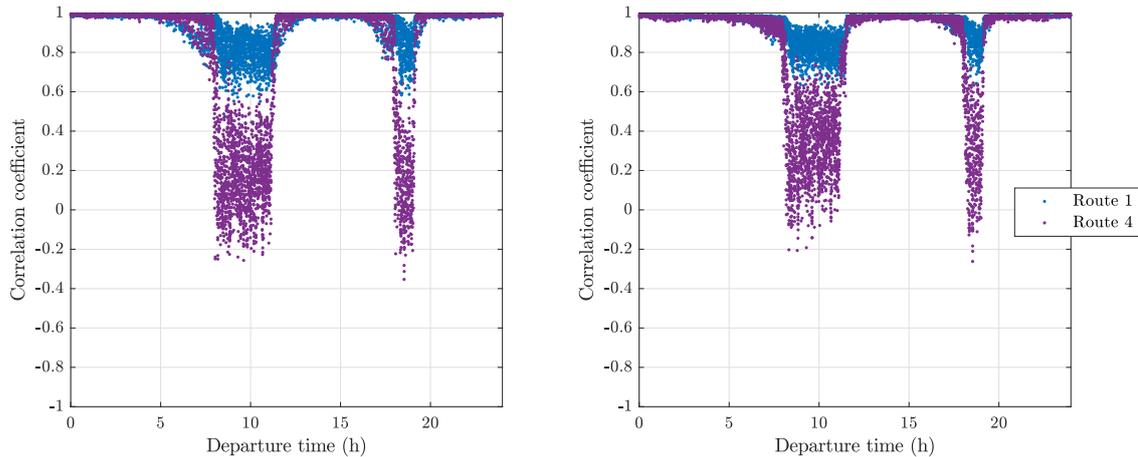


Figure 3: Correlation coefficient between linearly (a), or non-linearly (b), allocated vehicle-specific noise exposure cost and the duration.

By comparing the resulting correlation coefficient between the duration and the noise exposure

cost with either a linear- or non-linear allocation strategy, shown in Fig. 3, it is observed that the correlation is slightly weaker for vehicles along route 4 when a non-linear weighting function is used. The correlation coefficient is also more spread just before the peak hour traffic with a non-linear weighting function, indicating again a weaker correlation.

The different allocation strategies have a different effect on the correlation between energy demand and noise exposure cost. In Fig. 4, showing the correlation coefficient between energy demand and vehicle-specific noise exposure cost for vehicles along routes 1 and 4 at their departure time, the correlation coefficient for vehicles along route 4 is slightly increased in b) when using a non-linear weighting function compared to a).



a) Linear weighting function $K_{traffic}$.

b) Quadratic weighting function $K_{traffic}$.

Figure 4: Correlation coefficient between linearly (a), or non-linearly (b), allocated vehicle-specific noise exposure cost and the energy demand.

There is a slight increased variation in the calculated correlation coefficient at off-peak traffic conditions when the noise exposure cost is calculated with the non-linear weighting function in b) compared to the linear weighting function in a).

5. Conclusions

The results are dependent on the road network, as it impacts the vehicle behaviour and dependencies. Analysing a microscopic traffic simulation and allocating the noise exposure cost down to individual vehicles is a computationally costly process. A city-scale network model would require more efficient modelling techniques, as developed in [8].

Allocating the noise exposure cost down to individual vehicles using non-linear weighting functions may improve the correlation between the observed variations in the vehicle-specific noise exposure cost and the overall increase in noise exposure cost in the system. However, by using a different allocation strategy the relation between the noise exposure cost and aspects of resource efficiency will be impacted as well. The allocation strategy therefore affects the trade-off between reducing noise exposure and achieving resource efficient transport, and should not be chosen in isolation. There may be an allocation strategy for the noise exposure cost that is less ideal in terms of noise exposure alone, but allows for a better comparison between the noise exposure cost and resource efficiency under different traffic conditions.

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