Impact of Traffic Congestions on Energy Consumption and Emissions

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Abstract:
Road traffic contributes a major share of emissions and energy consumption. A shift to other transportation modes is often seen as an approach to combat the emissions. A shift is not always possible in some regions where other transportation modes are not sufficiently developed due to low population density or other reasons. This paper discusses possibility of combating emissions and energy consumption by optimization of traffic management. Traffic microsimulation models were used to obtain vehicle trajectories for calculation of emissions. It has been shown that traffic volume and management have significant impact on vehicle emissions. A possibility of application of an emissions model and of vehicle specific power (VSP) model was used in a case study. The VSP has several benefits over conventional emission models in cases where vehicles are powered by alternative drive-trains.

Keywords:
traffic volume, energy, vehicle emissions, congestions, traffic management

1. Introduction

The European Union focuses a great deal on policies for energy efficiency and to decrease emissions in transport [1]. Transport sector is contributing nearly a third of CO\textsubscript{2} emissions and energy consumption within the EU [2]. Most efforts to combat this problem are directed towards traffic mode shift, use of energy-efficient vehicles and alternative fuels [3]. As a result there was a decline of overall emissions by 3% in 2012 and by 2014 average light vehicle emissions were below the targets set for 2015. These values were obtained in part as the EU requires member states to record data on registering new vehicles [4]. Similar policies are being practiced elsewhere in the world, such as in the USA and China [5,6]. Such transport policies also focus on limiting road traffic in cities, increasing use of public transport and on shifting from road to other modes of transport. Such approaches work well in densely populated areas, but in sparsely populated areas road traffic is still, necessarily, the transportation mode of choice. An example of a study of reducing emissions in a densely populated area is the article [7], where a case study from London is described. An alternative to such approaches can be better traffic management that could result in less congestion and lower emissions.

When roads are preferred and necessary, some focus should be put on relation between greenhouse emissions and traffic management. Traffic simulation and emissions models are a tools that can be applied for such analysis. This paper will include a review of traffic simulation models that may be used for microscopic emissions model which can be used to calculate emissions.
1.1 Traffic simulation models

Traffic simulation models can be divided into microscopic, mesoscopic and macroscopic models. Microscopic models are models that simulate highest level of detail, individual vehicles. On the other hand least detailed models are macroscopic that simulate traffic conditions by representing road network with pipe equations. Microscopic models consist of vehicle following and lane-changing models. Among most popular are Fritzschke [8], Wiedemann [9], IDM (Intelligent Driver Model) [10–12] and Gipps [13] models. It is common among them that they consider speed, acceleration and longitudinal distance to be continuous variables and lateral position (lane) is a discrete variable. Nearly all of the microscopic vehicle following models output acceleration which needs to be integrated to obtain speed and longitudinal position. The only exception is Gipps model that outputs speed directly, therefore it is less suitable for emission analysis as they are significantly affected by the acceleration.

Most of the traffic microsimulation software use single vehicle following model, for example VISSIM uses Wiedemann model, Paramics uses Fritzschke model etc… In the area of research SUMO (Simulation of Urban Mobility) tool is becoming increasingly popular as it is open source and allows modifications to be made to any part of the code. Even without modifications of the code, it provides many configuration options not usually found in other packages such as choice of a vehicle following, lane changing and emissions models. It uses the Krauss vehicle following model by default [14].

1.2 Overview of emission models

Traffic microsimulation models need to be coupled with emission models in order to obtain individual and aggregated vehicle emissions. Vehicle emission models can also be divided into microscopic and macroscopic. Macroscopic emission models are used to estimate emissions based on traffic volume and average speed, ignoring instantaneous accelerations. More detailed are the microscopic emission models that rely on inputs such as speed, acceleration, vehicle weight and road grade.

Regardless if the model is microscopic or macroscopic, most models provide no direct physical model of fuel consumption, rather tables or functions that are based on statistical analysis of different variables that have an impact on emissions [15,16]. One example of a macroscopic model is the ARTEMIS study that involves CO₂ and NOₓ emissions dependent on vehicle speed and driving cycles [17,18]. A statistical analysis of the dependence of truck fuel consumption on speed and road grade was conducted in an experimental study by [19] conducted on highways in realistic traffic conditions. Fuel volume flow was measured using the vehicles’ CAN (Controller Area Network) bus interface. Such results can be used for comparative purposes and for model tuning but not for direct estimation of instantaneous fuel consumption for different types of vehicles that is required for microsimulation. For general energy demand forecasting models with lower level of detail are used. In [20], where a long-term forecasting was simulated, a simple model based on mileage travelled and average fuel economy was used.

Notable microsimulation models are Versit+, PHEM, CMEM and VT-Micro. Versit+ is a model that is based on a vehicle type, velocity and acceleration [21] that was developed by the TNO from Netherlands. It has interface with AIMSUN traffic microsimulation software. The AIMSUN is based on the Gipps model therefore velocity must be differentiated to obtain acceleration [22]. PHEM is an emissions model that was developed by the University of Graz and has interface for the SUMO microscopic traffic simulator [23,24]. CMEM and VT are models that were development in the USA. The CMEM was developed during the 90s and was afterwards, while the VT (Virginia
Tech) is a newer model. Both of them are based on velocity, acceleration and factors that depend on vehicle types.

1.3 VSP (Vehicle Specific Power) model

Since new fuels and electric vehicles are becoming increasingly popular, calculating energy impact of traffic can be difficult. A lot more straight-forward approach would be to rely on the energy required by the vehicle directly. Among all approaches, the VSP (vehicle specific power) model was the only one that was directly based on power required by the vehicle [25,26]. Vehicle specific power is based on energy conversions, changes of potential and kinetic energy. Power needed for acceleration results in a change of kinetic energy and is therefore affected by congestion; road grade, too, has an impact on potential energy change. Apart from the energies, air and rolling resistances are also modelled. There are two frequently mentioned formulas for VSP in the literature. The first was developed by Jimenez and is based directly on changes of energy, and further derived to include drag and rolling resistance coefficients and accelerations [25]. Another formula was developed by Zhai; this also introduces several coefficients [26]. The main difference between the two is that Jimenez uses wind velocity as an independent variable, which is the reason this formula is preferred; in case of unidirectional tunnels the air velocity is usually in the direction of travel, which results in lower air resistance as opposed to the open road.

The downside of the VSP model is that it does not account for engine idling, which can be significant in case of congested traffic. According to [27] and [28], fuel consumption during engine idling is between 0.5 and 1.5 l/h for light vehicles and a bit over 3 l/h for heavy vehicles. The VSP is also suitable for adaptation to analysis of alternative drivetrains as it is based on energy consumption with a clear physical background. It is not a regressive model of fuel use. It merely estimates power at the wheels. The power at the engine should be higher as transmission and engine efficiencies should be considered as well. A relationship between the vehicle specific power and fuel consumption rate (flow) was conducted by [29,30].

An exhaustive study involving vehicle efficiency defines separate ratios for powertrain, vehicle and primary energy efficiency [31]. It can be deduced that due to many different fuels that are being used, it is more feasible to have a model that is based on energy and then to calculate primary energy use from the energy at the wheels.

2. Road geometry data sources

To analyze the energy footprint of the vehicles that pass along a road network, geometrical and traffic data must be obtained. Road geometry can be obtained from road management companies or any map provider. Useful map data with worldwide coverage is available free of charge from OpenStreetMap [32]. However most traffic maps do not provide elevation data, which has to be obtained elsewhere. High-resolution elevation data measured by remote sensing from satellites are available from USGS Earth Explorer [33]. It is possible to use it to estimate road gradient that affects fuel consumption.

3. Traffic and emission models in SUMO

The SUMO uses Krauss vehicle following model by default [34]. It is based on maximum safe speed, \( v_{safe} \), that a following vehicle can maintain considering gap to the leading vehicle, in front and its speed. Every vehicle sets its desired speed \( v_d \) to

\[
v_d = \min (v_{safe}(t), v(t - 1) + aT, v_{max})
\]
where $v_{\text{max}}$ is maximum allowed or possible speed on a road section, $T$ is time step and reaction
time and maximum safe speed, $v_{\text{safe}}$, is calculated as

$$v_{\text{safe}}(t) = v_l(t) + \frac{g(t) - v_l(t)T}{(v_l + v) / b + T},$$ \hspace{1cm} (2)

where $v_l$ is leading vehicle speed, $g$ is gap and $b$ is desired maximum deceleration.

The emission model in SUMO can be either HBEFA which is basically a macroscopic emission
model that does not consider instantaneous acceleration directly and is therefore a function of

$$CO_2 = f(v, m, k),$$ \hspace{1cm} (3)

where $v$ is vehicle velocity, $m$ vehicle mass and $k$ road grade.

### 3.1 Modification of VSP for use in SUMO

The VSP model that was developed by Jimenez [25], was slightly modified to consider not only
vehicle power while vehicles are moving, but to penalize idling as well. It was estimated from

$$VSP = 2 + 1.1va + gkv + 0.213v + 0.000305(v + v_w)^2v,$$ \hspace{1cm} (4)

where $v$ is vehicle speed, $a$ is acceleration, $g$ gravity and $v_w$ wind velocity. The constant power of 2
kw per tonne is an additional term to consider energy lost during idling as well. The estimate is
based on data from [27,28].

The vehicle trajectories were exported from SUMO and later processed for calculation of the VSP
that has to be integrated to obtain the energy consumed by certain vehicle

$$E_v = m_v \int_0^T VSP(t) dt$$ \hspace{1cm} (5)

### 4. Traffic model design for a testing intersection

This work proposes a methodology to assess the energy impact of road networks operation on the
energy used by the traversing vehicles. Traffic conditions are simulated on a model that is based
upon traffic network imported from the OpenStreetMap into a SUMO network simulator. Importing
a map into SUMO can be done using a Netconvert tool that can as the name suggests, convert maps
between different formats. Since many maps do not provide exact data about allowed turns on
junctions, it can guess automatically. After the conversion, automatic guessing has to be inspected
using a map editor in order to allow realistic traffic flow as guessed usually do not resemble real
situation.

As it can be seen in the Fig. 1, road consists of edges (sections) that can have multiple lanes. Edges
are bordered by the junctions that can have priority rules and traffic lights defined.

Several parameters in the traffic model significantly influence the emissions:

- traffic light control
- junction rules (priorities)
- lane changing rules
- speed limits
5. Simulations of scenarios

An example simulation case will be presented to assess an impact of semaphore control on emissions and to compare HBEFA model results with the energy calculated from the VSP. Traffic model for the simulation is an intersection imported from the OpenStreetMap and slightly modified to provide realistic behavior at junctions. Only turns that are allowed on real road are allowed. The traffic conditions are random generated and are the same during all runs.

The simulated intersection (junction) is controlled with a semaphore using 8 cycles. The first experiment will show total emissions with different cycle durations. The semaphore cycles are shown in the table 2. Semaphore states are defined for each traffic light phase using letter codes: G (green), r (red) and y (yellow).

Table 1. Simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation time</td>
<td>1500 s</td>
</tr>
<tr>
<td>Vehicle generator</td>
<td>Random, Poisson approximated with binomial p=0.4</td>
</tr>
<tr>
<td>Average vehicle generator period</td>
<td>0.8 seconds/vehicle</td>
</tr>
<tr>
<td>Vehicle following model</td>
<td>Krauss</td>
</tr>
<tr>
<td>Emissions model</td>
<td>HBEFA 3.1</td>
</tr>
<tr>
<td>Energy consumption model</td>
<td>Modified VSP</td>
</tr>
</tbody>
</table>
Table 2. Semaphore phases.

<table>
<thead>
<tr>
<th>Phase Nr.</th>
<th>Duration [s]</th>
<th>Semaphore states</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>GGrrGgrrr</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>yyrrygrrr</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>rrrrrGrrr</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>rrrrryrrr</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>rrGgrrGGg</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>rrygrryyg</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>rrrGrrrrG</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>rrryyyyy</td>
</tr>
</tbody>
</table>

In the experiment length of phases 1 and 5 will be changed and total emissions and travelled distance for all the vehicles will be simulated.

Table 3. Simulation results and comparison of VSP and emissions.

<table>
<thead>
<tr>
<th>Run</th>
<th>Cycle 1 &amp; 5 duration [s]</th>
<th>Total CO2 emissions [t]</th>
<th>Total vehicle km</th>
<th>Average trip duration [s]</th>
<th>Total energy [MJ]</th>
<th>Energy increase [%]</th>
<th>CO2 emissions increase [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>74,4</td>
<td>251</td>
<td>243</td>
<td>666,2</td>
<td>6,2</td>
<td>5,4</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>74,2</td>
<td>251</td>
<td>217</td>
<td>648,6</td>
<td>3,4</td>
<td>5,0</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>70,6</td>
<td>251</td>
<td>128</td>
<td>637,0</td>
<td>1,6</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>45</td>
<td>73,5</td>
<td>251</td>
<td>192</td>
<td>627,0</td>
<td>0</td>
<td>4,1</td>
</tr>
</tbody>
</table>

As it can be observed from the table 3 semaphore cycles have significant impact on overall emissions. The aggregated CO2 emissions data in the tables are calculated from individual trip data by the vehicles that finished its route. This was achieved with extending the simulation time long enough for all vehicles to reach their destinations.

Even though we observe significant difference in emissions per vehicle km, even bigger differences are observed with the VSP model that better describes impact of accelerations during stop and got traffic that is a consequence of suboptimal traffic light control. It should also be noted that there is no trivial relationship between cycle lengths and emissions due to complex nature of road traffic and that simulation is the optimum way of solving this problem as longer cycle in one direction affects all the other directions as well.

An interesting result is that even though the longest semaphore cycle (run 4) resulted in lowest energy consumption due to less accelerating, travel time was shortest in run 3. Therefore optimization of travel time not necessarily results in lower emissions. It should be mentioned that the energy consumption model considered vehicle idling.

A relationship between travel time and the CO2 emissions can be seen in the Fig. 2. There is a strong correlation between them and the $R^2$ value is 0,945. As expected, in the Fig. 3, can be seen
that there is no significant correlation between the energy consumption and the CO\textsubscript{2} emissions from macroscopic HBEFA model. The reason for this is due the nature of the HBEFA model that is not based on acceleration. Therefore it is less suitable for analysis of congested traffic.

\textit{Fig. 2: Average travel time vs. CO\textsubscript{2} emissions.}

\textit{Fig. 3: Energy consumption from VSP vs. CO\textsubscript{2} emissions.}
6. Conclusions

Use of a traffic microsimulation for analysis of how vehicle emissions are affected by different traffic management regimes was presented. Analysis was carried out on a simple case of traffic light cycle adjustment. The purpose of this simulation is to test if the approach could be used for optimization of vehicle emissions. When using a relatively simple HBEFA emissions model, obtained results show no trivial connection between emissions and traffic light cycle lengths. However when comparing HBEFA model with the VSP we can see that it shows less sensitivity to accelerations which can be observed during long cycle lengths. When cycles are long vehicles in the queues at the traffic lights have to stop and go fewer times and therefore waste less energy. In such case the VSP model as an advantage as it is based directly on changes of energy.

In the future a calculation more research regarding accuracy of the VSP model should be carried out as it is better suited to assess the energy used by the vehicles powered by the electricity and other emerging drive-trains. It is afterward possible to calculate emissions based on the energy obtained from the VSP for different drive-train types.

Other emission models that are better suited to estimating the impact of a stop and go traffic, such as PHEMLight, should also be evaluated as well.

References


[19] Franzese, O., and Davidson, D., 2011, Effect of weight and roadway grade on the fuel economy of class-8 freight trucks, Oak Ridge National Laboratory, Tennessee, USA.


