Fuel Consumption and Emissions Models for Traffic

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Abstract

Calculating fuel consumption and emissions is a typical offline analysis step that uses the data previously obtained by simulations or observations. Depending on the aggregation level and level of detail, we distinguish several global, macroscopic, and microscopic approaches. The macroscopic modes takes as total vehicle mileage, average speed, traffic density and traffic volume as input .The output are fuel consumption or emissions in kg per meter . For the microscopic models, the inputs are speed and acceleration profiles (as obtained from microscopic simulations or real trajectory data) and the engine speed (as obtained from gear-shift schemes). The output of the model are instantaneous fuel consumption and emission rates (CO_2 and others) on a single-vehicle basis.

1 Introduction

Generally, models for fuel consumption and for emissions (CO_2, CO, NO_x, particulate matter, and others) have the same structure, so they can be discussed together. These models establish a relationship between the exogenous variables (traffic demand, properties of traffic flow, vehicle composition and infrastructure) to following one of two sets of endogenous variables:

- *Local emission factors* describe fuel consumption or emissions in kg per meter (or liters per meter).
- *Instantaneous emission factors* describe fuel consumption or emissions in terms of kg per second per vehicle (or in liters per second per vehicle).

Generally, two different types of models are available for fuel consumption and emissions, namely macroscopic and microscopic models. Depending on the aggregation level and level of detail, there are several model categories (Fig. 1).

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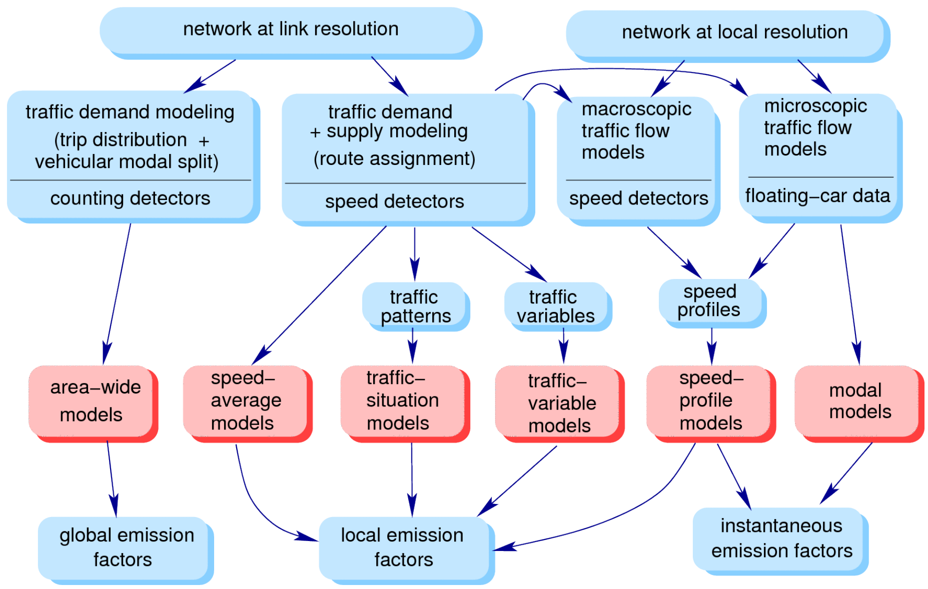

Figure 1: Overview of fuel consumption and emission models.

1.1 Macroscopic Models

1.1.1 Area-wide models

This model is simple and macroscopic approach. The model input is the total vehicle mileage (traffic volume integrated over the total link length of the network and over time) in the investigated region in terms of vehicle kilometers travelled (VKT). As output, these models deliver the global fuel consumption and emissions in the investigated area. This will be usually disaggregated at least with respect to passenger cars and heavy-duty vehicles (trucks). Each of these categories may be further disaggregated into several vehicle classes. The model input can be estimated by traffic demand models or by detector data since area-wide models are related to transportation planning rather than traffic flow modelling.

1.1.2 Average-speed models

The average-speed models use as input the average speed driven on a certain link of the considered network. In addition, some of these models include external factors such as the temperature. The standard tools to obtain the speed information obtained from the transportation planning models such as traffic demand and route assignment models. Other alternatives, one can directly measure speed and traffic volume by double-loop detectors or other stationary speed-detecting devices. The model output are local emission factors, i.e., volume or mass of consumed fuel or emitted pollutant per kilometer and per vehicle, on average. To date, the majority of fuel consumption and emission software use this model class, e.g., COPERT, MOBILE, MOVES or EMFAC. But this kind of model is more related to transportation planning than to traffic flow modeling and cannot determine the effect of jams.

1.1.3 Traffic-situation models

The input of this model input consists of several distinct *driving patterns*. Most traffic-situation models define the set of driving patterns as a combination of the set of traffic-flow patterns (e.g., free, congested, stop-and-go), and the set of driving facility (e.g., highway, rural road, arterial road, residential street). The traffic-flow situation may also be defined in terms of the *level of service* (LOS) assessing the traffic flow quality on an ordinal scale from 1 (best) to 6 (worst, i.e., completely congested). LOS is estimated based on average speed and ratio of volume/capacity of the particular link to be considered. But it is more tricky if stop-and-go traffic should be distinguished from stationary situations. Software implementing this class includes HBEFA, ARTEMIS, and some versions of MOBILE.

1.1.4 Traffic-variable models

In contrast to the traffic-situation models depends on a finite set of qualitative (categorically scaled) traffic patterns, this model class takes as input quantitative (i.e., metrically scaled) macroscopic factors related to traffic flow such as traffic density, traffic volume relative to capacity, queue length, and speed. These variables depends on the road category, design speed, signal cycles, link length, number of lanes, and type of intersection, etc. The models from transportation planning are no longer sufficient to provide this input but they have to be complemented by microscopic or macroscopic traffic flow models. The output of this model are local emission factors, usually related to a single vehicle. Representatives of this class include TEE (Traffic Emissions and Energetics) and the queue-based Matzoros Model.

1.2 Microscopic Models

The microscopic consumption and emission models need speed profiles of single vehicles at a high temporal resolution (of a few seconds or less) which can only provided by microscopic traffic flow models or by floating-car or trajectory data. As output, these models deliver local or instantaneous emission factors of single vehicles of a certain vehicle class. While traffic-situation and traffic-variable models evaluate coarse assessment affect to which degree congestions influence consumptions/emissions, only microscopic consumption/emission models allow us to answer questions related to individual vehicles and drivers such as :

- How much fuel/emissions can be saved by a fuel-efficient driving style? How does this saving potential depend on different traffic conditions? Is it possible to implement a fuel-efficient behavior into driver-assistance systems for the longitudinal driving task (adaptive cruise control)?

- What saves more fuel/emissions: Avoiding high accelerations/decelerations or driving at low engine speeds?
- Are roundabouts or signalized intersections more fuel-efficient? Does it depend on the type of roundabout, or on the origin-destination (OD) matrix characterizing traffic demand and the topology of the intersection?
- Is the savings potential and/or the optimal driving style different when switching from traditional combustion engines to modern developments such as hybrid or all-electric cars?
- What is the savings potential of recent ITS (Intelligent Transportation Systems) such as vehicle-to-vehicle or infrastructure-to-vehicle communication (e.g., a traffic light communicating its switching times to equipped cars)? How do the effects depend on the penetration rate of such ITS implementations?

The microscopic consumption/emission models are strongly related to traffic flow models and traffic flow dynamics in general, and principally, they classify as two classes.

1.2.1 Speed-Profile Emission Models

This model class does not use the instantaneous information provided by the simulated or measured trajectories directly. Rather, it is aggregated to several speed profile factors of a driving cycle which, in turn, determine the instantaneous consumption and emission factors.

speed profiles of single vehicles at a high temporal resolution which are obtained by floating-car data, trajectory data, or by a microscopic traffic flow simulation. At this level of detail, less road geometry data is needed since the speed profiles implicitly contain most of this information (except in road gradients). The outputs of speed-profile models are either local or instantaneous emission factors which are related to a single vehicle. Most models of this class (e.g. MEASURE or PKE) assume a linear multivariate mapping between the speed profile factors $\mathbf{x}$ and the estimates e of the instantaneous emission factors:

$$e = \mathbf{L} \cdot \mathbf{x}. \tag{1}$$

Here, the components of the instantaneous emissions vector e may contain the CO_2, CO, HC, NO_x, PM (particulate matter), and others emission rate.The $n \times m$ matrix $\mathbf{L}$ represents the linear relations between the m speed profile factors and the n components of the instantaneous emissions vector.

Table 1 displays typical speed profile factors that are used by many models of this class and their influence on consumption and emission varying from strongly negative (– –) to strongly positive (++) with respect to the reference.The coefficient of this factors are estimated by a multivariate linear regression.

Table 1: A selection of common speed profile factors and their effect on CO_2 emissions ($--$ ⇔ strongly negative, $-$ ⇔ negative, $+$ ⇔ positive, $++$ ⇔ strongly positive)

Factor	Effect on CO_2 emissions
Constant of value 1	reference ($+++$)
Fraction of time in speed range 0-25 km/h	$++$
Fraction of time in speed range 50-75 km/h	$--$
Fraction of time in speed range 75-100 km/h	$-$
Fraction of time in speed range > 125 km/h	$++$
Standard deviation of speed	$+$
Average and standard deviation of acceleration	$+$
Average and standard deviation of deceleration	$-$
Frequency of acceleration-deceleration cycles	$+$
Fraction of time the vehicle is standing	$+$
Fraction of time the vehicle needs power near its maximum power	$++$
Fraction of road gradients greater than 5 %	$+$
Engine speed (crankshaft revolution rate) 1 000 - 2 000 rpm	$--$
Engine speed (crankshaft revolution rate) > 3 500 rpm	$++$

1.2.2 Modal Emission Models

Modal emission models use the instantaneous information directly from the trajectory information (of floating-car data or microscopic simulations)(cf. Fig. 1). At any moment, modal models calculate the vector $e(t)$ of instantaneous emission factors as a function of the instantaneous "mode" of vehicle operation, essentially speed $v(t)$ and acceleration $\dot{v}(t)$.

In the more advanced modal models, the vehicle operation mode is expressed by engine speed $f(t)$ (including the idling mode), power demand (or torque), and possibly other history-related factors such as engine age and temperature. At this microscopic level, the only road geometry related information that is used directly are road gradients and possibly the road surface quality. Depending on the situation and model complexity, further input is also included such as local road-related variables (e.g., uphill grade ϕ), external variables (e.g., altitude, air temperature), and variables related to the engine history (e.g., engine temperature).

Models of this class are perfectly suited to be used in conjunction with time continuous microscopic traffic flow models. The models are linked such that the endogenous variables of the traffic flow models (speed, acceleration) are exactly the main exogenous variables of the modal emission models. The modal models gave have the potential to give the most precise description, but they have the highest demand on data for calibration, and validation. Particularly, it is extremely difficult to measure the instantaneous emission rates on a continuous basis at a time resolution of seconds.

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