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MANAGING THE ENVIRONMENTAL EXTERNALITIES OF TRAFFIC LOGISTICS: THE ISSUE OF EMISSIONS

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Abstract:

Companies are increasingly being held accountable for the life-cycle impact of their products and services. Transportation is frequently a major component of this life-cycle impact. Hence, to reduce total environmental impact, logistics managers will have to become more sophisticated in their understanding of how they can reduce the environmental impact of their transportation operations, without negatively affecting the cost or effectiveness of these operations. In line with this mandate, we quantify the dynamic impact of road vehicles on the environment. In most emission models, a constant speed is used depending only on the specific road type. Using such a model will lead to an under-estimation of the effective emissions. It turns out that the differences with a more realistic dynamic assessment model are significant. The analysis here suggests that the policy consequences of these differences for both public sector managers and private companies are potentially quite important.

Keywords:
traffic logistics, environmental impact, road traffic, queueing theory, life cycle management impact

1. Introduction

Companies are vigorously pursuing new strategies in supply chain networks and e-business. However, these important developments have some environmental effects, which will be on the agenda of the supply chain manager or the logistics manager in the future. One of the main effects, heavier reliance on road traffic, will be the subject of this paper. Supply and demand networks put an increased stress on road traffic. Much of the ultimate remaining inventory in the future will be 'on the road' fulfilling e-commerce objectives of short and timely deliveries without the use of excessive stocks. Increased traffic causes congestion and a general intensified impact on the environment. Consequently, total logistics cost will be affected as these negative environmental externalities become taxable or face other costly regulatory compliance requirements. Logistic managers will therefore face increasing pressures to manage their use of road traffic in such a way that its total impact, both in terms of cost and environmental effects, is rationalized. This requires a thorough understanding of the relationships between traffic flows and emissions, the basic thrust of this paper.

In the public sector, just as in the private sector, accurate modeling of operations and logistics functions is a necessary precondition to effective operational planning and control for society as a whole. Public sector managers play a key role in determining and regulating societal externalities and standards for environmental quality. Policy conclusions and regulatory policies based on inaccurate modeling affect the entire economy. Since policy has a fundamental impact on the costs of logistics activities of firms, the private sector will of course be affected as noted above. We argue that the same tools that have brought so many gains to the private sector, are equally critical in the public sector. Indeed, the consequences of inaccuracy or incomplete modeling in the public sector can be even more significant than in the private sector in that they not infrequently give rise to policy conclusions and regulatory policies that can affect an entire economy and not just a single firm. This is perhaps nowhere more evident than in the area of transportation policy where models of regional airsheds have led and continue to lead to significant policy pronouncements about everything from ozone precursors to vehicle routing

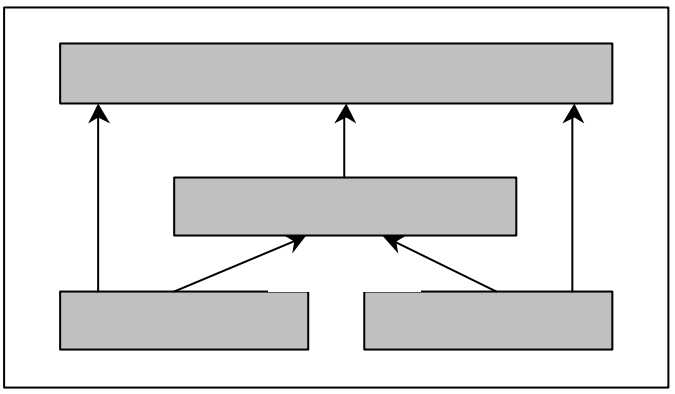
restrictions. In this paper, we illustrate this for the specific area of transportation science related to the impact of vehicle speed on air pollution. Setting the regulations right will encourage companies to take the right logistical decisions to balance the economic value of logistical activities against the broader societal costs of environmental externalities associated with these decisions.

It should be clear that various decision makers are involved here. At the strategic level, it is the 'Strategic Regulator', who sets the various parameters (maximum allowed speeds, road capacity, car characteristics, emission and congestion taxes, etc.) in order to preserve the well-being of the society. His multicriteria objective has to do with the economic value of transportation activies, as well as with greenhouse gas reduction, congestion reduction and traffic regulation. On the more tactical or operational level, a 'Traffic Manager' controls the real time management of traffic systems, which is also increasingly conceived as a multicriteria decision problem. This operational problem has more to do with daily atmospheric ozone concentration reduction in summer months, instantaneous traffic management (temporary additional speed restrictions, batch driving, highway access management, etc.) and executing the differentiated financial contributions schemes. It should be clear that the decision making of both the Strategic Regulator and the Traffic Manager are highly interdependent. The resulting policies have rather fundamental impacts on the costs of manufacturing and logistics activities of private agents active in the regional airsheds under consideration. It is precisely for this complex problem that our modeling approach can be of value for the respective decision makers. We illustrate this for a very specific area of transportion science related to the impact of vehicle speed on air pollution.

In assessing the environmental impact of road traffic, infrastructure and vehicles have both a static and a dynamic impact on the total emissions and waste (Figure 1). The combination of infrastructure and vehicles results in traffic flows, resulting in a dynamic impact on the environment. Vehicles in use produce emissions (CO2, CO, NOx, and VOC). The static environmental impacts of roads (e.g. visual intrusion, damage to natural watercourses, threats to

the natural habitat of wildlife, etc.) and vehicles (e.g. consumption of natural resources, waste at the end of their life cycle, etc.) are not considered in this paper.

Figure 1: Static and dynamic impact of road traffic on emissions and waste



As traffic flows occupy a central position in the assessment of road traffic emissions, a robust traffic flow model is required. In this paper queueing models are used to describe traffic flows. Based on formulas obtained from general queueing models, the speed-flow-density diagrams are constructed analytically and speeds are calculated for a given flow (Vandaele, Van Woensel and Verbruggen, 2000), using the software implementation *TRAQ* (Van Woensel and Vandaele, 2000).

Both speed and flow are used as input for the emission model MEET (European Commission, 1999). Most emission models (FACTS (NEI, 1993), EMEP/ CORINAIR, MEET, etc.) calculate emissions using a time-dependent observed flow but a flow-independent speed (constant speed emissions models). Speed is set only dependent on the type of road (urban, rural or highway) and remains constant over time for this road type. Implicitly, the effect of congestion on speed and on the resulting emissions is neglected.

Emissions produced at low speeds, which is typical for a congested situation, increase exponentially. The use of a constant speed does not take into account this observation. Thus, neglecting the effect of congestion on speed, results in an under-estimation of the real environmental impact. In uncongested situations (free flow), speed is usually higher than then

speed set in the constant speed emissions model, again leading to an under-estimation of real emissions. The question is how significant are these mis-estimates of emissions.

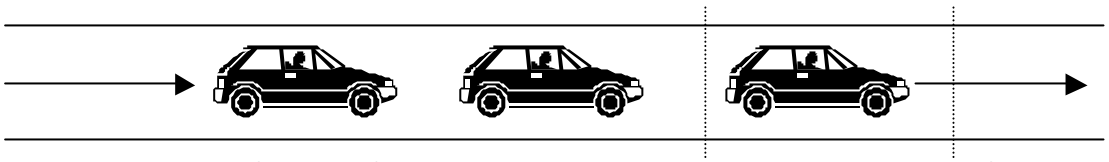
We will show that using a time-dependent speed, obtained from the queueing model *TRAQ* (section 2), combined with the emission model MEET (section 3), results in a more realistic estimation of road traffic emissions for various pollutants (section 4). We then consider the implications of these findings for public and private sector managers with responsibilities in the transportation sector (section 5) and we present our summary and conclusions in section 6.

2. A queueing approach to traffic flows

Traditionally, uninterrupted traffic flows are modeled empirically: speed and flow data are collected for a specific road and econometrically fitted into curves (Daganzo, 1997). This traditional approach is limited in terms of predictive power and sensitivity analysis. Queueing theory is almost exclusively used to describe traffic behavior at signalized and unsignalized intersections (Heidemann, 1991, 1994, 1997). However, Vandaele, Van Woensel and Verbruggen (2000) and Heidemann (1996), showed that queueing models can also be used to explain uninterrupted traffic flows.

Queues occur whenever instantaneous demand exceeds the capacity to provide a service. Queueing theory involves the mathematical study of these waiting lines. Using a large number of alternative mathematical models, queueing theory provides various characteristics of the waiting line, like waiting time or length of the queue. In a queueing approach to traffic flow analysis, roads are subdivided into segments, with length equal to the minimal space needed by one vehicle on that road (Figure 2). Each road segment can be considered as a service station, in which vehicles arrive at a certain rate l and get served at rate m (Vandaele, Van Woensel and Verbruggen, 2000).

Figure 2: Queueing representation of traffic flows



Using well-known formulas from queueing theory, we reconstruct the speed-flow-density diagrams. Vandaele, Van Woensel and Verbruggen (2000) developed four different queueing models: a M/M/1, a M/G/1, a G/G/1 and a state dependent G/G/1 model.

The M/M/1 model (exponential arrival and service rates) is considered as a base case, but, due to its specific assumptions regarding the arrival and service processes, it is not useful to describe real-life situations. Relaxing the specifications for the service process of the M/M/1 model, leads to the M/G/1 model (generally distributed service rates). Relaxing both assumptions for the arrival and service processes leads the G/G/1 model. Finally, a special case of the G/G/1 model can be used: a state dependent G/G/1 model, which assumes the service rate as a (linear, exponential,…) function of the traffic flow. In this case vehicles are served at a certain rate, which depends upon the number of vehicles already on the road. The (state dependent) G/G/1 model is considered as the most useful model to describe the traffic flows, because its more general nature can be applied to a greater variety of situations (Vandaele, Van Woensel and Verbruggen, 2000).

In the G/G/1 model, arrival times are generally distributed with expected arrival time $1/l$ (l equals the product of traffic density E and nominal speed SN) and standard deviation s_a. In an analog way, service times follow a general distribution with mean $1/m$ (m equals the product of nominal speed SN with maximum traffic density C) and standard deviation s_s. The speed formulas are then obtained by combining Little's theorem and the Kraemer-Lagenbach-Belz approximations (Kraemer and Lagenbach-Belz, 1976). For a detailed explanation of the parameters used in the queueing models, see Table 1.

Table 1: Parameters in the Queueing Models

Parameter	Description
E	Traffic density (veh/km)
C	Maximum traffic density (veh/km)
s	Effective speed (km/h)
SN	Nominal speed (km/h)
q	Observed traffic flow (veh/h)
l	Arrival rate (veh/h)
m	Service rate (veh/h)
r	Traffic intensity = l / m
W	Total time in system (h)
q_{max}^h	Maximum historical flow observed
q_{max}^d	Maximum observed flow of the considered day

For the G/G/1 model, we obtain the following effective speed formulas:

$$s = \frac{2 * SN * (1 - r)}{2 * (1 - r) + r * (c_a^2 + c_s^2) * e^{\frac{-2*(1-r)*(1-c_a^2)^2}{3*r*(c_a^2+c_s^2)}}} \qquad c_a \leq 1$$

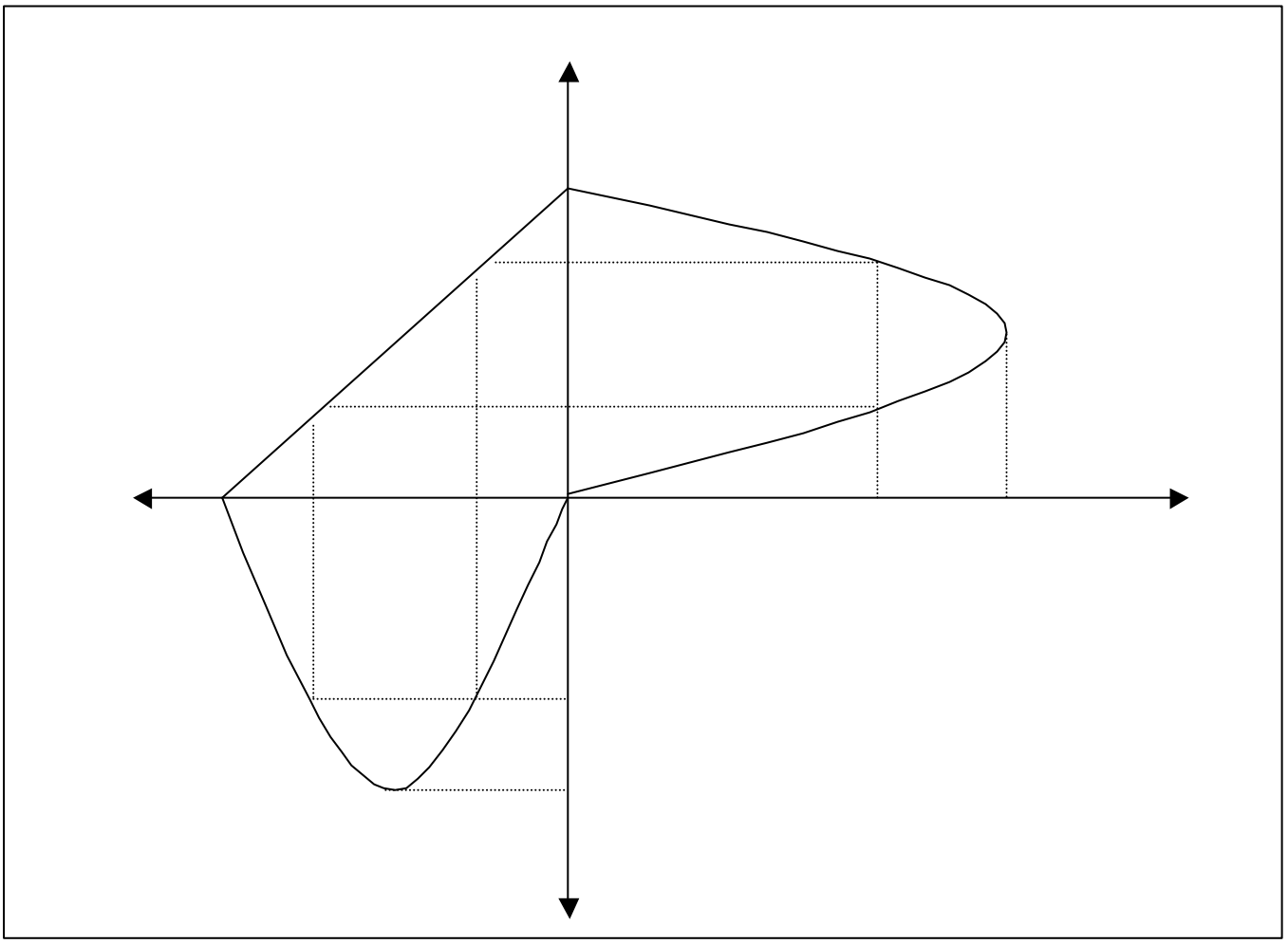
$$s = \frac{2 * SN * (1 - r)}{2 * (1 - r) + r * (c_a^2 + c_s^2) * e^{\frac{-(1-r)*(c_a^2-1)^2}{(1+r)*(c_a^2+10c_s^2)}}} \qquad c_a \geq 1 \qquad (1)$$

with c_a^2 representing the squared coefficient of variation of inter-arrival times and c_s^2 the squared coefficient of variation of service times. Depending upon the specific value of the squared coefficient of variation of inter-arrival times (larger or smaller than 1), the speed is calculated using (1). The higher c_a^2 and c_s^2, the higher the uncertainty. Higher values imply worse traffic conditions on the road. Note that the speed formulas depend on these coefficients of variation for both service times and inter-arrival times (Vandaele, Van Woensel and Verbruggen, 2000).

Using the above relations (1), the typical speed-flow-density diagrams are constructed. These diagrams incorporate the interdependence of traffic flow (q), density (E) and speed (s). Figure 3 illustrates that, although every speed s corresponds with one traffic flow q, the reverse is not true. There are two speeds for every traffic flow: an upper branch (s_2) where speed decreases as flow increases and a lower branch (s_1) where speed increases. Intuitively it is clear that, as the flow moves from 0 (at speed SN) to q_{max}, congestion increases but the flow rises because the decline in speed is offset by the higher volume. If traffic continues to grow past q_{max}, flow falls because the decline in speed more than offsets the additional vehicle numbers, further increasing congestion

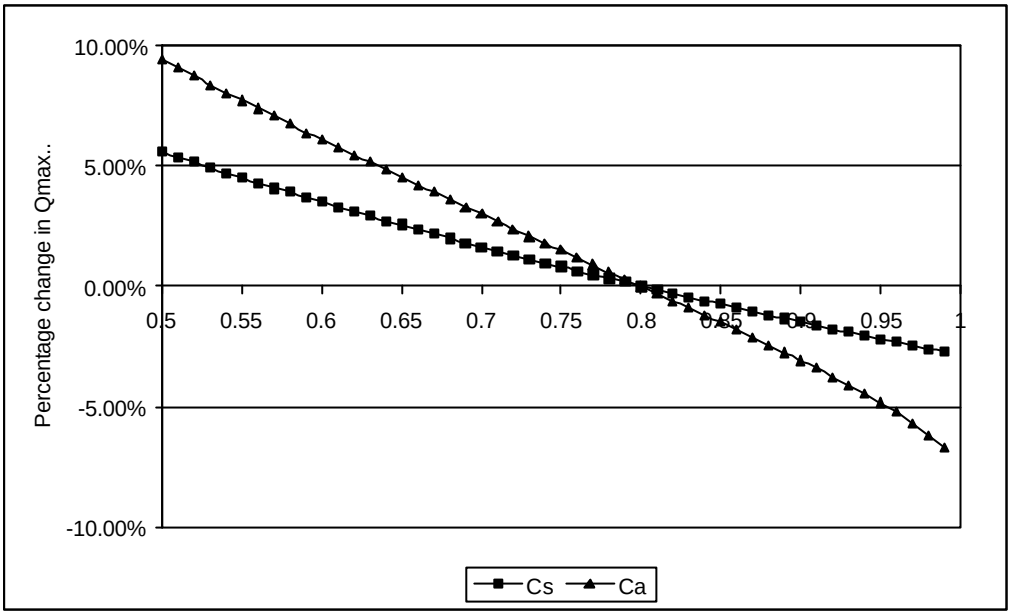
(Daganzo, 1997). The flow-density diagram and the speed-density diagrams are an equivalent representation and can be interpreted in the same way. The exact shape of the speed-flow-density diagrams depends upon the queueing model chosen and thus on the parameters used for the model.

Figure 3: Speed-flow-density diagrams



TRAQ (Traffic flows and Queueing) is the translation of this queueing model into operational software (Van Woensel and Vandaele, 2000). It can be used for what-if scenarios and sensitivity analysis for traffic management, congestion control, traffic design, etc. *TRAQ* can also be linked with existing emission models to assess the environmental impact of road traffic. Figure 4, produced using *TRAQ*, shows the effects that occur when the coefficients of variation of arrival and service times on the maximum flow (q_{max}) are changed (starting from c_a and c_s both equal to *0.8*).

Figure 4: Effect of a change in the coefficients of variation of arrival and service times on maximum flow



It is clear that the arrival process has a much larger impact on the maximum flow than the service process. Reducing the uncertainty in the service process by lowering c_s to *0.5*, increases the maximum possible flow by *5.8%*. On the other hand, lowering the variation in the arrival process (bringing c_a down to *0.5*), increases the maximum possible flow by *9.8%* (Vandaele, Van Woensel and Verbruggen, 2000). Government trying to improve traffic flow should primarily focus on the arrival rate variability or adjust the way cars are entering the highway (on ramps,…).

Finally, *TRAQ* can also be used as a real-time traffic management tool. For each time interval, (e.g. a minute) real-time measurements (speed and flow), can be used to calculate the optimal speed-flow combination. Using for example Dynamic Route Information Panel Systems (DRIPS), this information can be brought to the attention of road users and traffic management services. Based on this information, drivers are expected to change their speed or change their route to avoid congestion

.

3. An emissions model

As real emissions are almost impossible to measure for a complete traffic network, several models are available to estimate these traffic emissions, e.g.: FACTS (Forecasting Air pollution by Car Traffic Simulation, Nederlands Economisch Instituut, 1993), EMEP/CORINAIR, COPERT (Computer Programme for estimating Emissions from Road Transport, European Environment Agency, 1999). We opted to work with MEET (Methodologies for estimating air pollutant emissions from transport, 1999), a procedure developed by the European Environment Agency (EEA) for the European Commission. The MEET project has been undertaken in order to provide a uniform, Europe-wide procedure for evaluating the impact of transport on air pollution. The model brings together the most comprehensive and up-to-date European information on emission rates and activity statistics which, taken together, make it possible to estimate the emissions resulting from almost any transport operation.

In our analysis, we only take into account highway traffic and one single category of vehicles at a time. The total emissions produced by road vehicles are the sum of hot emissions, cold emissions and evaporation emissions. Hot emissions are produced when the engine is hot, while a cold engine generates cold emissions. The emissions by evaporation are the losses while refueling, diurnal-breathing losses, hot soak losses and running losses. In order to quantify the emissions produced while driving on a highway, we only consider the hot emissions.

Hot emissions are calculated as a function of vehicle speed. Depending on the vehicle type, a number of corrections can be made to allow for the effects of road gradient, vehicle load, vehicle mileage, and ambient temperature. In our illustration, as Flanders is flat, the road gradient correction is not applicable here. Secondly, only emissions produced by heavy-duty vehicles are corrected for their load. Thirdly, the mileage correction, which gives older vehicles a higher emission function, is necessary to model the emissions of the country's total vehicle fleet. Finally, we also neglect the temperature correction. It should be clear that by omitting these corrections we do not limit the applicability of our results.

These simplifications lead to the following equation for the hot emissions:

$$E_k = f(s)_k = \sum_{i=1}^{I} n_i * l_i * \sum_{j=1}^{J} p_{i,j} * e_{i,j,k}(s) \qquad (2)$$

where:

k	identifies the pollutant
i	identifies the vehicle category (i the number of categories)
j	identifies the road type (the number of road types)
n_i	is the number of cars in category i
l_i	is the average annual distance traveled by the vehicles of category i
$p_{i,j}$	is the percentage of the annual distance traveled on road type j by vehicle type i
$e_{i,j,k}(s)$	is the emission function of pollutant k corresponding to the average speed on road type j, for vehicle category i

We redefine this formula as follows:

$$E_k' = n * d * e_k(s) \qquad (3)$$

where:

n	is the number of cars counted on the highway
d	is the representative length of the counting station on the highway
$e_k(s)$	is the emission function of pollutant k

We do not specify the vehicle category since we consider each type of car separately. We separately model the emissions produced by gasoline passenger cars and diesel cars both with a cylinder capacity of *1,4* to *2,0* cc in conformity with the EURO-1 regulation (MEET, 1999). Neither do we have to identify the road type as we only take into account the traffic on a highway. We redefine the distance traveled as the representative length of the counting station (d). We estimate the emissions of the following four relevant pollutants: nitrogen oxides (NO_x), carbon-monoxide (CO), carbon dioxide (CO_2) and volatile organic compounds (VOC). According to the defined vehicle specifications we have the following speed dependent emission functions ($e_k(s)$):

Table 2: MEET emission functions for gasoline and diesel (1.4 cc – 2.0 cc, EURO-1)

Pollutant	Emission function Gasoline (g/km)	Emission function Diesel (g/km)
NO_x	$0{,}526 - 0{,}0085\, s + 8{,}54*10^{-5} s^2$	$1.4435 - 0.026\, s + 1.785*10^{-4} s^2$
CO	$9{,}617 - 0{,}245\, s + 0{,}001729\, s^2$	$1.4497 - 0.03385\, s + 2.1*10^{-4} s^2$
CO_2	$231 - 3{,}62\, s + 0{,}0263\, s^2 + 2526/s$	$286 - 4.07 s + 0.0271\, s^2$
VOC	$0{,}4494 - 0{,}00888\, s + 5{,}21*10^{-5} s^2$	$0.1978 - 0.003925\, s + 2.24*10^{-5} s^2$

Figure 5: CO emissions for gasoline cars

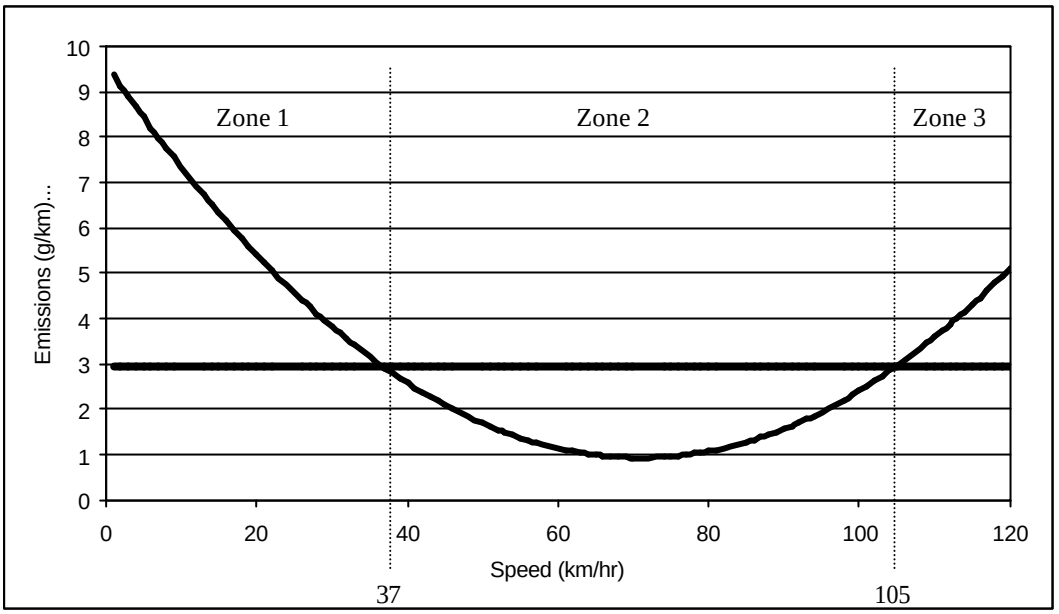


Figure 5 compares the speed dependent emission function for *CO* emissions (U-shape curve) versus the emissions at a constant speed of *105* km/h (bold horizontal line at *3* g/h). Based on the above graph, we can construct three zones requiring different actions:

1) Zone 1: where emissions are underestimated using constant speeds
2) Zone 2: where emissions are overestimated using constant speeds
3) Zone 3: where emissions are underestimated using constant speeds

The emissions observed in zone *1*, are emissions typically occurring in congested situations (when speed is low or going to zero). Using a constant speed to calculate emissions, neglects this basic observation. For the *CO* case, the first breakpoint between the first and the second zone, lies around *37* km/h. Under *37* km/h emissions are underestimated using the constant speed. The second breakpoint (between zone *2* and *3*) lies at *105* km/h. Between *37* km/h and *105* km/h *CO* emissions are overestimated using the constant speed. Above *105* km/h, they are again underestimated. The minimum of the *CO* emissions function lies around *71* km/h. Table 3 gives all relevant speeds of the breakpoints for the CO_2, *CO*, NO_x and *VOC* emission functions for both gasoline and diesel cars.

Table 3: Breakpoints and minimum of the emission functions for gasoline and diesel cars

Gasoline	Breakpoint 1-2 (km/h)	Minimum	Breakpoint 2-3 (km/h)
CO_2	51	77	105
CO	37	71	105
NOx	*na*	50	105
VOC	68	85	105
Diesel	Breakpoint 1-2 (km/h)	Minimum	Breakpoint 2-3 (km/h)
CO_2	45	75	105
CO	56	80	105
NOx	42	74	105
VOC	68	88	105

4. Results for the Revised Emissions model

We are interested in the difference between the emissions caused by a passenger car driving at a constant average speed and a passenger car driving at a flow-dependent speed. For a highway the predetermined speed used in MEET is 105 kilometers per hour. We adjust the emissions functions of MEET by using the flow-dependent speeds calculated with the queueing model *TRAQ* and thus explicitly taking into account the speed effects of congestion.

4.1 Approach

We use data from a counting station of a regularly congested highway as input. Every hour, the number of cars passing a certain point is aggregated and sent to the governmental agency collecting the data. This hourly number of vehicles corresponds to the flow (q) in our queueing model. For this application, we selected a counting station on highway E40 (headed towards Liege from Brussels). The representative zone (d) for this counting station is *3.5* kilometers.

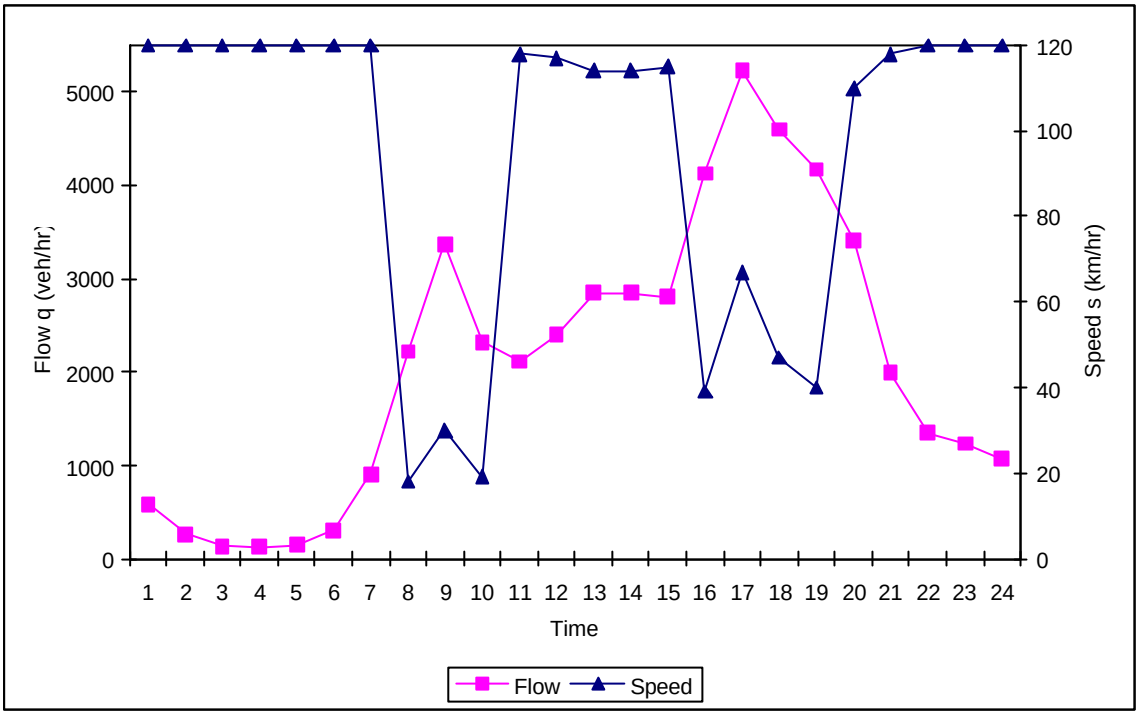
To calibrate our model, we first calculate the maximum possible traffic density at this counting station. Based on historical data (from the last *3* years), the maximum observed flow at the selected counting station on this road is *5490* vehicles per hour ($q_{max}{}^{h}$). Note that this maximum is a real-life demonstrated maximum (and not the engineering capacity of the road, which is *6000* vehicles per hour). Assuming that this flow of *5490* vehicles per hour occurred during a day with the best possible conditions, e.g. very good weather (c_a and c_s set to the lowest possible values), *TRAQ* calculates that this flow corresponds to a maximum traffic density C of *142* vehicles per kilometer.

After calibrating the model for this road, the analysis is started for a randomly chosen day (weekday, no holiday period and no accidents). For this day, we set the coefficient of variation of inter-arrival times (c_a) equal to *0.5*, the coefficient of variation of service time (c_s) equal to *0.7*. These values are chosen such that the maximum flow that occurred on this specific day (which is smaller or equal to the historical maximum capacity) is within the possible speed-flow-density diagram. Using these coefficients of variation makes it possible to observe the maximum flow of *5490* vehicles on this random day. Nominal speed (*SN*) is set equal to the maximum highway speed allowed in Belgium: *120* km/h. From the calibration, we know that the maximum traffic density observed on this road is *142* vehicles per kilometer.

Combining the speed-flow-density diagrams (from *TRAQ*) and the observed hourly flow, the effective speeds s_1 and s_2 are calculated for each hour of the day. Analysis of historical data for this part of the highway, gives us an indication about the characteristic moments of congestion during the day on that highway (peak hours) and enables us to distinguish between the lower speed (s_1) and higher speed (s_2). From 8 A.M. until 10 A.M. and from 4 P.M. until 7 P.M. during weekdays the highway has a high probability of being congested. Empirical data confirms the validity of this observation (Daganzo, 1997 and Hall, 1996). At the above time intervals, we assume that vehicles drive at the lower speed, s_1 of the speed-flow-density diagram. For the rest of the day vehicles are assumed to drive at the higher speed, s_2. From this point forward we refer to this assumption as the *Speed-Change Assumption*. Figure 6 shows the results of the speed and flow profile for the considered weekday on that segment of the highway.

We see that in hours 8, 9, 10 and 16, 17, 18 and 19 the speed drops drastically. The reason for this is the speed-change assumption (the road gets very congested and vehicles then drive at the lower speed s_1 of the speed-flow-density diagram). Combining these speed and flow results of *TRAQ* and the emission functions of MEET, we calculate the pollutants produced during this day on the specified section of the highway. As a basis for comparison, the same MEET emission functions are recalculated with the same flow data, but with the flow-independent speed of *105* km/h for this highway.

Figure 6: Speed and flow profile for a specific weekday on highway E19

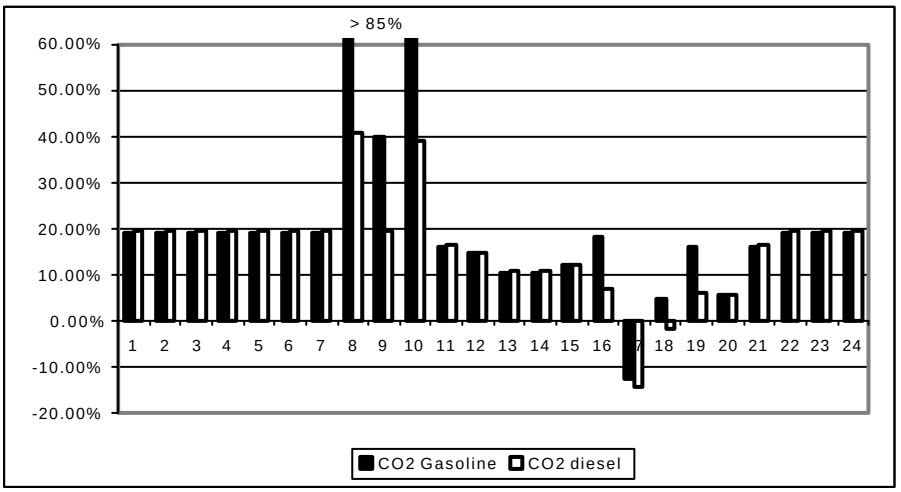


4.2 Results

CO_2 Emissions

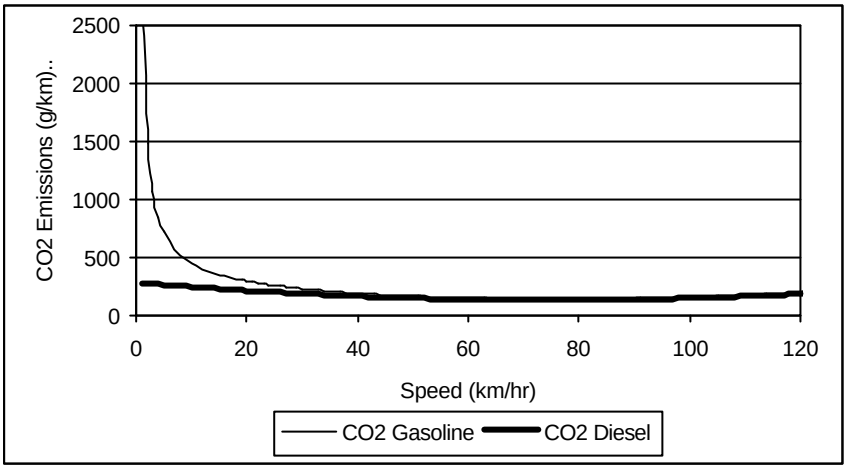
Figure 7 shows the results of this analysis for the CO_2 emissions. For each hour of the considered day, the percent difference between the emissions with a constant speed and those with the flow-dependent speed is plotted. A positive (negative) number means that, when using the using the constant speed to calculate emissions, real emissions are under (over)estimated.

Figure 7: CO_2 emissions difference for gasoline and diesel vehicles



For most hours of the day, for both gasoline and diesel vehicles, the flow-dependent emissions are higher than the constant speed. Only in hour 17, we see an over-estimation using the constant speed emissions model. If we look at the specific emission functions for CO_2 for both diesel and gasoline cars, we see that the speed at hour 17 (*68* km/h) lies in zone 2 (Figure 8).

Figure 8: CO2 emission functions for gasoline and diesel cars

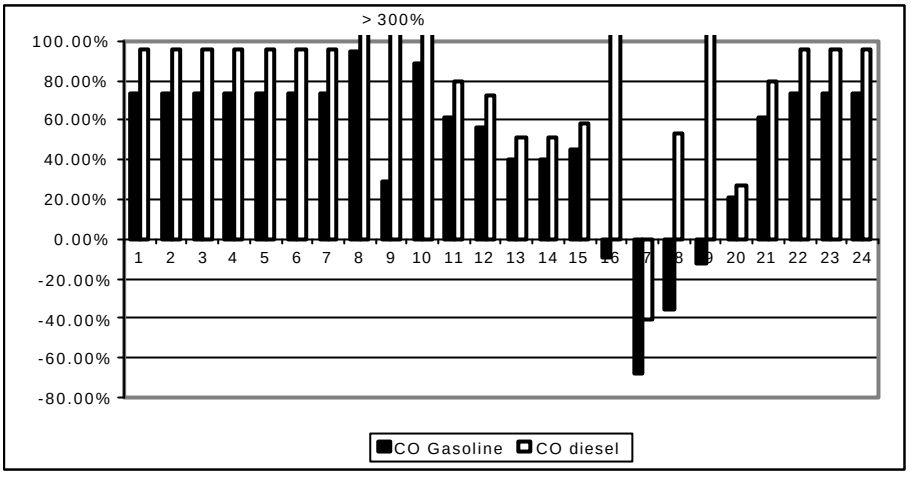


For this day, total CO_2 emissions are under-estimated by *20%* for gasoline cars and by *11%* for diesel cars. Total emissions for the diesel cars are less, because the CO_2 emission function for diesel cars does not differ much from the emission function with a constant speed of 105 km/h (see Figure 8).

CO emissions

Figure 9 with the results for the *CO* emissions, shows that the differences between the constant speed emissions and flow-dependent emissions, are very high in the hours of congestion for vehicles using diesel. During these hours all speeds are within zone 1 where constant speed emissions lead to an underestimation.

Figure 9: CO emissions difference for gasoline and diesel vehicles

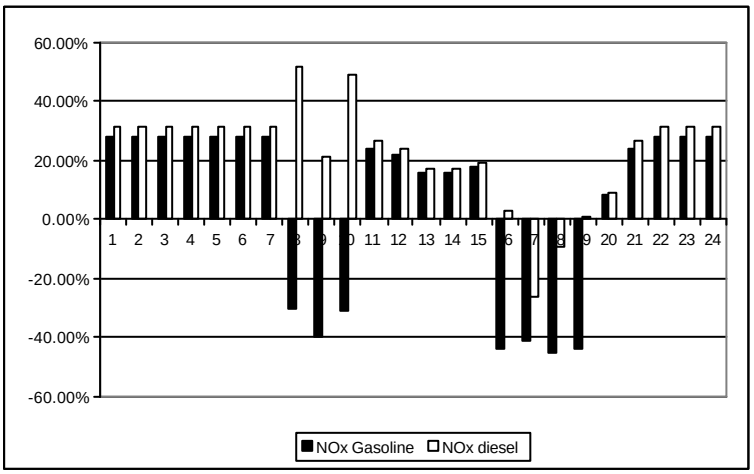


Aggregating, the total *CO* emissions are under-estimated by *23%* for gasoline cars and by *93%* for diesel cars.

NO_x Emissions

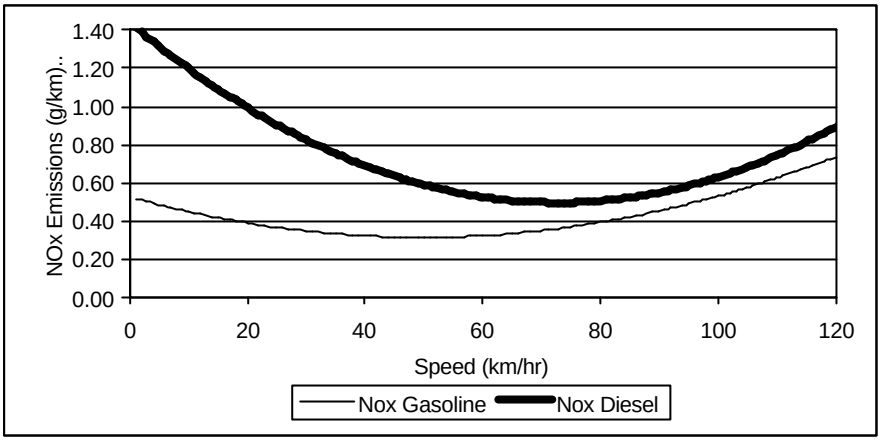
The total NO_x emissions (Figure 10) are under-estimated for this day, by *13%* for diesel cars but are over-estimated by *11%* for gasoline cars compared to the constant speed emissions. This over-estimation is due to the specific shape of the NO_x emission function (Figure 11).

Figure 10: NO_x emissions difference for gasoline and diesel vehicles



For all speeds lower than *105* km/h, the emissions for gasoline cars are systematically overestimated when using the constant speed emissions: the emissions function for gasoline cars lies always under the constant speed emissions. Only for speeds higher than *105* km/h, the constant speed emissions are an underestimation of the real emissions (figure 11).

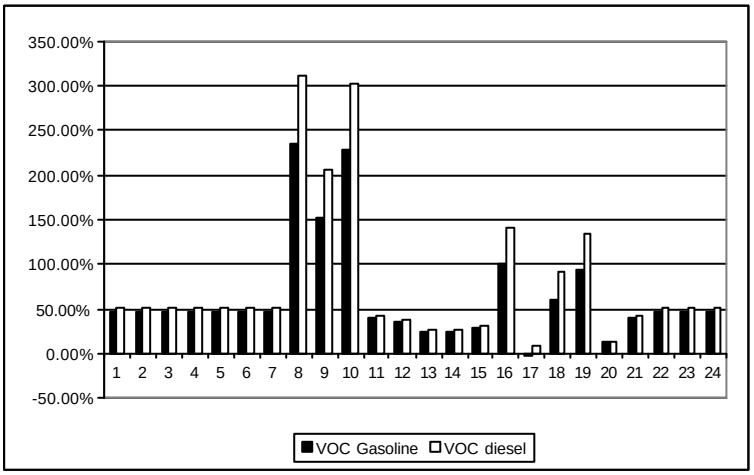
Figure 11: NO_x emission functions for gasoline and diesel cars



VOC Emissions

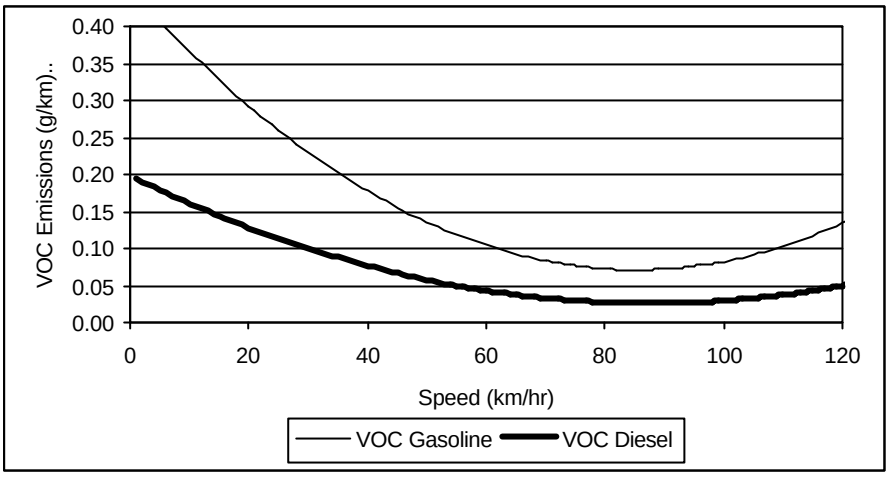
Finally, Figure 12 for the *VOC* emissions shows that for all hours, the flow-dependent speed emissions are higher than the constant speed emissions. Again the same observation as before: in hours where heavy congestion is assumed, we see that emissions with the flow-dependent speed are more than *300%* higher than constant speed emissions.

Figure 12: VOC emissions difference for gasoline and diesel vehicles



The total *VOC* emissions are under-estimated for this day, by *91%* for diesel cars and by *68%* for gasoline cars using the constant speed. To be complete we show the used *VOC* emission functions in Figure 13. This figure shows that for the constant speed of *105* km/h the emissions are almost at the minimum of the emission function for gasoline and diesel cars. Any deviation from this constant speed, will then almost always lead to higher emissions.

Figure 13: VOC emission functions for gasoline and diesel cars



4.3 Relaxing the Speed-Change assumption

Because we suspected that the emission peaks during the time intervals 8 A.M. until 10 A.M. and 4P.M. until 7 P.M, were partly the consequence of the assumption of lower speed on the speed-flow diagram, we recalculated the emissions for the time-dependent flow without this assumption (thus always taking the upper speed s_2). Table 4 shows that even without the Speed-Change Assumption, the total emissions calculated with a flow-dependent speed are significantly higher than the constant speed emissions.

Table 4: Overview of the results

	Gasoline	Diesel	Gasoline	Diesel
Emissions	**With assumption**		**Without assumption**	
NO_x	*- 11%*	*+ 13%*	*+ 8%*	*+ 10%*
CO_2	*+ 20%*	*+ 11%*	*+ 6%*	*+ 6%*
CO	*+ 23%*	*+ 93%*	*+ 22%*	*+ 31%*
VOC	*+ 68%*	*+ 91%*	*+ 18%*	*+ 18%*

For diesel cars, dropping the congestion assumption lowers the difference of constant speed versus dynamic speed in emissions. For gasoline cars, the *VOC* emissions decrease substantially when relaxing the speed-change assumption, but the NO_x emissions increase substantially (from *–11%* to *+8%* difference).

4.4 Sensitivity of the Results

As emissions are mainly dependent on speed, which in our queueing model depends upon the choice of the coefficients of variation of inter-arrival times and of service time, we performed a

sensitivity analysis to determine the impact of a change in these parameters on total emissions. For each possible combination of c_a and c_s (going up to 1 and down to 0.5 from the base case $c_a = 0.5$ and $c_s = 0.7$ with step 0.05), *TRAQ* calculated the total emissions for CO_2, CO, NO_x and VOC. This sensitivity analysis results in a lower and upper bound to the under-estimation of dynamic speed emissions versus constant speed emissions (Table 5).

Table 5: Lower and upper bound for the under-estimation of emissions with Speed Change assumption

	Gasoline cars				Diesel cars			
	NO_x	CO_2	CO	VOC	NO_x	CO_2	CO	VOC
Lower	-15%	+19%	+23%	+67%	+13%	+11%	+92%	+90%
Analysis	-11%	+20%	+23%	+68%	+13%	+11%	+93%	+91%
Upper	-8%	+320%	+59%	+124%	+31%	+23%	+179%	+163%

From Table 5, it is clear that our above described results are very close to the lower bound of total emissions, which is due to our values of the parameters: starting from c_a equal to 0.5 and c_s equal to 0.7, decreasing the coefficient of variation of service times (c_s), increases speed only with 1.30%. This potential increase in speed is too small to have a substantial decreasing effect on total emissions. We observe the same result if we recalculate total emissions but without the *Speed Change Assumption* (Table 6).

Table 6: Lower and upper bound for the under-estimation of emissions without Speed Change assumption

	Gasoline cars				Diesel cars			
	NO_x	CO_2	CO	VOC	NO_x	CO_2	CO	VOC
Lower	-6%	+5%	+14%	+14%	+8%	+5%	+28%	+16%
Analysis	+8%	+6%	+22%	+18%	+10%	+6%	+31%	+18%
Upper	+10%	+306%	+50%	+80%	+23%	+17%	+120%	+103%

From Tables 5 and 6, it is clear that the maximum under-estimations of emissions can be very substantial (e.g. CO_2 and VOC for gasoline cars and CO and VOC for diesel cars). The upper bound corresponds with very congested roads, again confirming the substantial effect of congestion on emissions.

5. Implications for the public and private sector

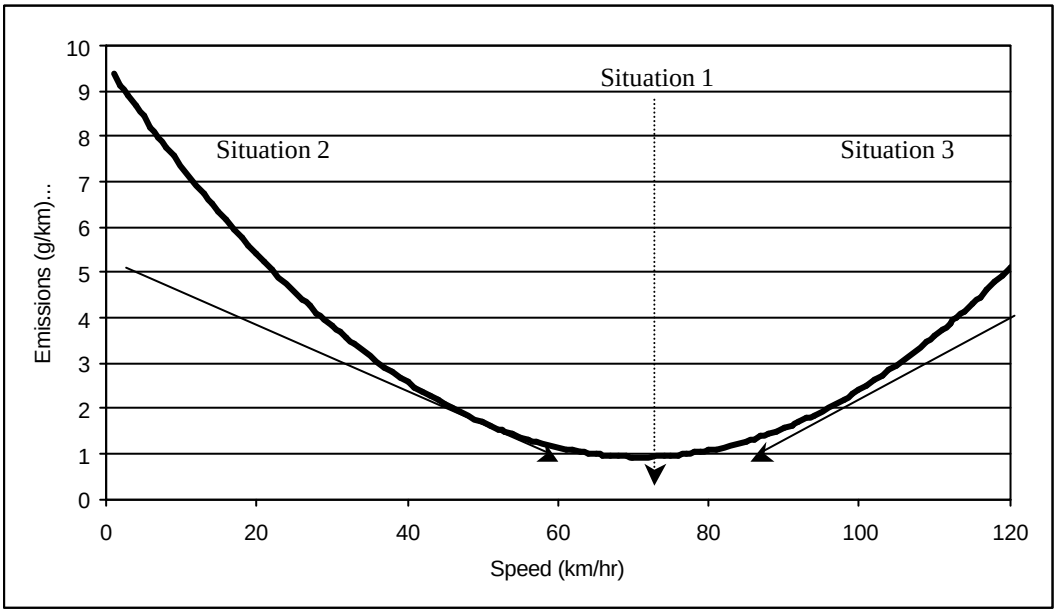
In the previous section, we showed that using constant speed emission models like MEET, leads to a substantial underestimation of real emissions. The reason for this is that an average speed does not account for the speed decrease that may occur during congested periods or for higher speeds during uncongested periods. As stated in section 1, this could have a significant impact

on on strategy evaluation, both on the side of the private companies involved in road traffic as well as on the side of the public sector managers responsible for the general well being.

5.1 Public sector

Decisions made by the Strategic Regulator based on the constant speed emissions model will always be suboptimal. Lower emissions, produced by the existing car fleet, can be accomplished by controlling the nominal speed limits. Each emission function has a certain speed where emissions are minimal. This means that without structural changes (new technologies, like more efficient engines,….), emissions can not be lower than this minimum. The actions a Strategic Regulator takes to get to this minimum vary depending on the initial situation (Figure 14).

Figure 14: CO emissions for gasoline cars



Three different starting situations can occur: Situation 1 is ideal since the effective speed is exactly the speed that minimizes emissions (optimal speed). No actions from the Strategic Regulator are required as emissions are already at a minimum. Situation 2, where the effective speed is lower than the optimal speed, corresponds to congested roads. In this situation, actions should be focused on limiting the number of vehicles entering the highway to increase speed. Situation 3, where speed is greater than the optimal speed, corresponds to uncongested highways (free flow). The maximum speed allowed on the highway should be decreased such that the

effective speed approaches the optimal speed. These evaluations concern only the environmental impact of emissions, and these conclusions would have to be tempered and balanced against the direct economic consequences of speed regulations, but the direction of the altered optimal balance will be as noted.

Since actions depend on the initial situation (optimal speed, lower speed or higher speed), the use of models that do not take these speed differences into account, will lead to inefficient decisions. Governments trying to balance the damage from emissions against the economic consequences of traffic regulation should naturally use models that provide at least approximately correct answers. The problem for a Strategic Regulator is the choice of the optimal regulated speed. As each emission function has a different optimal speed where emissions are minimized, the choice for the optimal speed is dependent upon the public sector manager's chosen strategy. If priority is to reduce greenhouse gasses, minimizing the CO_2 emissions is predominant. The optimal speed is then the speed where CO_2 emissions are given priority. However priorities can change: in the summer months when decreasing ozone can become more important. At this point the Traffic Manager faces a very operational decision problem. The optimal speed is then dependent upon the NO_x and VOC emission functions. The consequence of changing priorities is that the action for decreasing NO_x and VOC emissions will be optimal for these pollutants, but will be sub-optimal for CO_2 emissions. A possible approach to this problem would be adding weights to each priority as a function of status conditions (weather, time of the year,…) and then determining the optimal speed.

In Belgium, one measure being considered to decrease the ozone level is setting the maximum speed to *100* km/h instead of the present *120* km/h. The consequence will be that the effective speeds will be lower and closer to the optimal speeds for the NO_x and VOC emission functions. Limiting the maximum speed, however, is only useful in situations with no congestion. In congested situations, limiting the maximum speed, may (in the extreme case) lead to higher emissions and will certainly have direct economic losses in increased travel times as well. Again,

the presence of operational models, incorporating the relationships between various scenarios, model parameters and emissions is extremely important and useful.

Table 7 shows the effect of changing the speed limit on the total emissions for gasoline and diesel cars. In the hours without congestion (according to the speed-change assumption) emissions can be decreased substantially for all pollutants. More specifically, the *NOx* and *VOC* emissions decrease with *40%* and *64%* respectively for gasoline cars and with *43%* and *70%* respectively for diesel cars. Looking at the effect of decreasing the maximum speed for the congested hours, the effect on emissions is much smaller. Consequently, the day's total emissions reductions are smaller than the reductions occurring on the uncongested periods. Again, looking only at emissions without considering speed changes occurring during congested hours, leads to wrong conclusions and an overestimation of the real impact of this action.

Table 7: Effect of decreasing maximum speed from 120 km/h to 100 km/h

	NOx Gasoline	CO2 Gasoline	CO Gasoline	VOC Gasoline	NOx Diesel	CO2 Diesel	CO Diesel	VOC Diesel
no congestion	-40%	-25%	-117%	-64%	-43%	-26%	-156%	-70%
congestion	-1%	-2%	-4%	-3%	-2%	-2%	-4%	-3%
Total day	-25%	-12%	-48%	-20%	-20%	-12%	-36%	-19%

5.1 Private sector

As the public policy affects the whole economy, firms will have to consider the effects of the environmental actions made by the public sector managers. Logistic managers will have to take into account the emissions they produce on the road and not only the pollution made on their premises. This implies an integration of the environmental externalities in logistics' multi-criteria optimization, resulting in changed routing choices, including driving during other periods of the day,… The impact of the public sector managers' decisions concerning (the cost of) traffic flow emissions on the manufacturing and logistics functions of a company, constitutes a new research area with great relevance to logistics practice. Clearly, if public concern with greenhouse gases and atmospheric ozone pollution continues, governments will respond with regulations that will have significant impacts on private operators. Understanding these impacts and participating in the debate about the economic consequences of such regulations will certainly be a major

challenge for such private operators. The results of this paper indicate that such understanding will require more refined methods and models than have hitherto been used for the evaluation of traffic regulation. The payoff will be a better informed and more rational basis for public policy, including its impacts on the private economy.

6. Conclusions

Since the policy made by public sector managers, mainly depends on the models they use, accurate operational models are mandatory. Suboptimal decisions affect the entire economy and drive companies into decision making which can rather be worse than better for the society as a whole. Therefore government should use accurate and complete tools to support their operational policy conclusions, especially when it comes to regulating traffic, one of the very important characteristics of contemporary logistical activities. In addition, these regulations can significantly impact the way companies conduct their transportation planning, distribution organization, deliveries, shipments, etc… This paper has considered the effect of vehicle speed on air pollution and the potential public sector managers' actions for traffic flows.

Most traffic flow emissions models only consider the number of vehicles (flow) and neglect the speed of this flow. We showed that neglecting the congestion effect on emissions leads to an under-estimation of the real road traffic emissions. Traffic flow emissions depend mainly on the number of vehicles and the speed of these vehicles. Using counting data on the number of vehicles passing a particular point, we obtained the speed-flow-density diagrams with the queueing model *TRAQ*. This speed and flow data was then used as input for the MEET emission functions. Using this procedure, the emissions for each hour for a specific highway were calculated twice: first, with a constant speed used in the MEET emissions model and secondly, with a flow-dependent speed.

We concluded that the NO_x, CO_2, CO and VOC emissions are systematically under-estimated using a constant speed for gasoline vehicles and diesel cars respectively. Dropping the assumption of heavy congestion during peak hours of the day does not alter this conclusion. A

sensitivity analysis confirms this result for both cases (with and without the speed-change assumption).

These observations are crucial when it comes to the development of traffic measures to lower emissions. Using these more realistic results for emissions, the public sector manager can evaluate the effects of his chosen policy. Important here is that different priorities lead to different results and that priorities can change in time (e.g., heavier focus on ozone in the summer). These decisions, made by strategic and operational public sector managers clearly affect the private sector. And the differences can be quite significant. Thus, the dynamic queueing approach proposed has the potential for making important contributions to improving the decision making of both public sector managers and private companies related to logistics and traffic movements. In particular, this research suggests that private companies with logistics intensive operations should be active participants in insisting that public regulators use appropriate modeling approaches in assessing the overall impacts of their regulations.

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