Flow improvements and vehicle emissions: effects of trip generation and emission control technology

FLOW IMPROVEMENTS AND VEHICLE EMISSIONS: EFFECTS OF TRIP GENERATION AND EMISSION CONTROL TECHNOLOGY

Robert B. Noland
Mohammed A. Quddus

Centre for Transport Studies
Dept. of Civil and Environmental Engineering
Imperial College London
London SW7 2AZ
United Kingdom

Ph: 44-(0)207-594-6036
Email: r.noland@imperial.ac.uk

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Abstract

This research examines whether road schemes that increase the availability of road space or which smooth the flow of traffic result in increased vehicle pollution. Economic theory has found that increases in road space and the consequent decreases in travel time will tend to increase total vehicular travel, an effect known as induced travel. The net impacts of induced travel on vehicle pollution have largely been a matter of conjecture with some arguing that policies to reduce congestion (by adding more road space) will reduce pollution by smoothing the flow of traffic and reducing stop and go traffic. This paper uses a micro-simulation model (VISSIM), integrated with a modal emissions model (CMEM), to evaluate the overall strategic policy question of how changes in available road capacity affects vehicle emissions. The analysis examines alternative vehicle fleets, ranging from a fleet with no emission control technology to relatively clean Tier 1 vehicles. Results are presented showing emission break-even points for CO, HC, NO_X, fuel and CO_2. Increased traffic is found to quickly diminish any initial emission reduction benefits.

Keywords: vehicle emissions, induced travel, trip generation, flow improvements, micro-simulation

Introduction

Changes in road network configurations and increases in road capacity are often aimed at improving the overall flow of vehicles within the network. A further justification for capacity increases has often been the reductions in vehicle emissions that can be achieved by smoothing traffic flows. This is achieved by reducing the number of acceleration events within the traffic stream as well as reducing idling. As a policy for reducing environmental impacts, traffic flow improvements have been repeatedly criticized by the environmental community as being potentially counter-productive. This is due to the potential for increases in vehicle travel that could be induced by any changes in total trip times. This paper seeks to examine this issue using micro-simulation methods and a modal emissions model, overcoming some of the limitations of current forecasting procedures.

Standard approaches for modelling vehicle emissions cannot adequately account for changes in accelerations. The US EPA Mobile model, California's EMFAC model, and the UK method specified in the *Design Manual for Roads and Bridges* are all based on a fixed driving cycle and only average speeds can be varied (Highways Agency, 1999). Recent research projects have developed modal emissions models capable of evaluating variations in emissions. The European MODEM model and the CMEM model developed at the University of California, Riverside, are the only two that are readily available. MODEM is based on 1993 vehicle data and CMEM is based on 1997 vehicle data (An et al., 1997; .Jost et al., 1992)

Demand modelling approaches are typically used to estimate changes in vehicle flows from various network changes. The assignment stage of a four-step travel demand model will specify the flow and average speeds on given links within a network. The demand modelling element is subject to errors in the individual data used to estimate various elements of the model as well as the vagaries involved with actual model estimation. These modelling approaches also infrequently account for the changes in travel times associated with traffic flow improvements, and thus do not adequately account for associated behavioural effects, in particular any new trips that may be generated by the change in travel times.

These uncertainties in modelling techniques have led to disagreements over the impact on vehicle emissions of improving traffic flows. Many planners and traffic engineers have long argued that these sort of improvements are critical for both reducing congestion and reducing emissions. In the US, this has led to air quality funds actually being used to expand road capacity (via the Congestion Mitigation and Air Quality program). Environmental activists have often argued that these types of projects are not beneficial for improving air quality and may actually make things worse.

Recent empirical studies of induced travel effects have established that behavioural reactions to capacity enhancements will lead to an increase in total travel (Hansen & Huang, 1997; Noland, 2001; Noland & Cowart, 2000). Noland and Lem (2002) provide a good overview of many of the recent studies. Both Fulton et al. (2000) and Cervero & Hansen (2002) estimated models that firmly establish a causal relationship between added road capacity and increases in total vehicle kilometres of travel. Induced travel effects will occur from any network change that reduces travel times, including those aimed at traffic flow improvements.

The research presented here is an attempt to resolve whether induced travel, in particular the generation of new trips, diminishes or off-sets the reduction in emissions from flow improvements. This builds on previous work in this area by Stathopoulos & Noland (2003) that used the VISSIM micro-simulation model and the CMEM database to evaluate these issues. Stathopoulos & Noland (2003) analyzed an arterial merge and a coordinated traffic signal and found that emissions of CO, NO_X and HC were initially reduced. Exogenous increases in the number of vehicles within the simulation found that this initial benefit quickly disappeared. The implicit travel time elasticities associated with the exogenous increase in demand were well within those estimated in the literature, implying that in the long-run induced increases in travel lead to overall increases in total emissions.

Dowling (2005) examined these issues by building a very detailed travel demand and land use model that attempted to account for most induced travel effects. Specific projects were evaluated by Dowling using the CMEM model based on the outputs from the travel demand model (and compared to a base case scenario). Dowling was unable to find significant increases in emissions associated with induced travel. The inherent uncertainties in the travel demand modelling process and the relatively small scale of the project analyzed made it difficult to clearly isolate an increase in traffic from the flow improvements that were modelled. If anything, this highlights the uncertainties associated with more traditional approaches.

The linking of micro-simulation models with modal emissions models has been done by others. Rakha & Ahn (2004) and Rakha et al. (2004) linked

INTEGRATION with various modal databases, including data collected via on-board systems. Park et al. (2001) linked the VISSIM model with the European MODEM model and compared results with both measured data and estimates from standard procedures. Hallmark et al. (2000) used the MEASURE modal emissions model to evaluate the impact of changes in signal timing. One difficulty identified by all this work is the difficulty of comparing results from different models. However, this does not preclude the examination of relative effects using the same modeling structure. As yet, detailed studies of alternative policies and how these models can be used are limited.

The work presented here expands upon previous work in several ways. First, it more precisely accounts for cold start effects from newly generated trips, including additional travel associated with those trips. Second, a high speed merge, typical of a motorway merge is simulated (as opposed to the slower speed arterial merge in Stathopolous and Noland, 2003). Finally, different vehicle fleet profiles are examined. These include a fleet representative of average emissions in 1997, a fleet with no catalytic converters, and a fleet of US EPA Tier 1 vehicles which were the cleanest vehicles within the CMEM database. This allows us to evaluate how on-going technical improvements in emission control technologies have affected the ability to obtain emissions reductions from traffic flow improvement projects.

Analysis Methods

The basic method of analysis is to combine the capabilities of a micro-simulation model with a modal emissions database. In this research the VISSIM micro-simulation model was used in combination with the CMEM modal emissions database. Functionally this involved taking the micro-simulation output and feeding this into the software provided with the CMEM database. The network analyzed was designed to be simple. In this case a simple motorway merge was coded into VISSIM. Both VISSIM and CMEM are described followed by a description of the simulations analyzed for this work.

Microscopic Traffic Simulation Model – VISSIM

A microscopic traffic simulation model describes the behaviour of individual drivers as they react to their perceived surroundings. VISSIM is a microscopic stochastic, discrete, time step and behaviour-based traffic simulation model developed by PTV AG Karlsruhe, Germany (PTV, 2003). It simulates traffic flow on the road network by moving driver-vehicle-units as single entities. The traffic flow algorithms are based on a psycho-physical car following model for longitudinal vehicle movement and a rule-based algorithm for lateral movement as originally developed by Wiedemann (1974, 1991).

Four driving modes are defined in VISSIM. These are free driving, approaching, following and braking. The speed of the vehicle, the distance and speed differences between vehicles, and the individual characteristics of the driver and the vehicle are used to establish accelerations in each driving mode. The driver can also make the decision to change lanes according to routing requirements and the observed environment, such as approaching a junction or merging into a fast-moving lane. There is no restriction on specifying a range for the desired speed and traffic flow on a link.

Gomes et al. (2004) carried out a calibration study of the VISSIM model for a unidirectional motorway with on-ramp control. This study concluded that the simulation environment of VISSIM is well-suited for motorway studies involving complex interactions. Testing and validation of the VISSIM model has been done by Fellendorf and Vortisch (2001). Version 3.7 of VISSIM was used for the simulations presented here.

Comprehensive Modal Emission Model (CMEM)

Typical emissions models currently in use are the EMFAC series of models in California developed by the California Air Resources Board (CARB), the EPA Mobile model used in the rest of the U.S., and the UK DMRB method as described in the *Design Manual for Roads and Bridges* (Highways Agency, 1999). These are all based upon standardized driving cycles and can only account for changes in average speeds. More recently, a microscopic modal emissions model, the Comprehensive Modal Emissions Model (CMEM), has been developed (Barth et al. 1999, 2001; An et al. 1997). This model allows second-by-second emissions estimation based on network changes that affect the dynamic behavior of vehicles in traffic (such as acceleration and deceleration behavior).

The CMEM model is based upon second-by-second tailpipe emissions data collected from 343 light-duty vehicles (LDVs) tested under a variety of laboratory driving cycles with a new dynamometer emissions testing protocol. The driving cycle used to develop CMEM was the Modal Emissions Cycle (MEC) developed as part of the CMEM project. CMEM was validated using the Federal Test Procedure (FTP) and the US06 schedule. The majority of the vehicles tested were based on California emissions control standards, while a small sampling (10.8%) were based on standards applicable in the rest of the US.

All 343 LDVs were divided into 26 categories based on vehicle type (car/truck), emissions status (normal/high emitter), fuel control technology, emission control technology, power to weight ratio, and accumulated mileage (Barth et al., 2000). The three basic groups of vehicle technology category were normal emitting cars (39.5% of the tested fleet), normal emitting light-duty trucks (27.3% of the tested fleet) and high emitting vehicles (33.1% of the tested fleet). The high emitting vehicles were defined as those having CO, HC or NO_X emissions at least 1.5 times higher than the certification standard for the vehicle. Vehicles with no catalytic converter were also included and represented 2.3% of the tested fleet. These were the highest emitting category of all the vehicles tested. On the other hand, Tier 1 certified vehicles (27.6% of the tested fleet) were from the Model Year (MY) 94 or later and were the cleanest vehicles in the fleet at that time. While this emissions data is dated, it represents the most recent modal emissions data that is readily available for analysis.

Additional limitations of CMEM include: (1) it does not represent real-world driving conditions as data was collected using a dynamometer; (2) it is unable to estimate emissions from heavy goods vehicle (HGV) such as trucks and buses; and, (3) it is incapable of estimating particulate emissions such as PM10, PM2.5. Despite these limitations, it is still the best available modal emissions model available for the analysis presented here.

Details of Simulated Scenario

A hypothetical road network of a motorway merge was coded in VISSIM as shown in Figure 1. As can be seen, a 2-lane motorway of length 3 km (link-1) merges with a 3-lane motorway of length 3 km (link-2). The merged route is a 3-lane motorway of length 3 km (link-3). All links are assumed to be one-way. Each of the lanes has a width of 3.5m which is typical for UK motorways.

The merge section is designed according to the method suggested in PTV (2003) in order to best represent a real-world motorway merging situation. The vehicles entering from link-1 join the mainline traffic stream (link-2) by changing lanes within the merge section. In order to avoid an unexpected queue on link-1, in case of heavy traffic flow, vehicles can also merge from the left lane of link-1 onto the main road section further downstream from the first merge point. A proper design of the merge section is important as the amount of traffic on the resulting stream (link-3) depends to some extent on the design.

Link-1 and link-2 are then populated with vehicles. These are cars and heavy goods vehicles (HGVs). The number of HGVs is kept low (at 5% of total traffic) compared with the number of cars so the simulation has traffic more typical of a morning peak period.[1] The base case traffic flow on links 1 and 2 is set such that there is initially a considerable level of traffic congestion.

The level of congestion and total emissions within the simulation largely depend on the desired speed distribution of vehicles. Therefore, two different desired speed distributions were used as shown in Figure 2. The first distribution assumes a relatively low speed where the mean speed is 75 km/h and the maximum is 120 km/h. The second distribution assumes a relatively high speed in which the mean speed is 121 km/h and the maximum is 160 km/h. In order to have a sizeable level of congestion in the network, the traffic flow on links 1 and 2 were set at 1,850 veh/h and 3,650 veh/h respectively for the first desired speed distribution and 1,900 veh/h and 3,700 veh/h respectively for the second desired speed distribution.

[1] Emissions from the HGV's are not estimated, these are only included to more realistically simulate the traffic flows.

After assigning links with the appropriate traffic flow, the simulation was then run for a specified time period (3 hours) with the initial congested network. VISSIM records simulation time (sec), vehicle ID, vehicle type (car or HGV), speed and acceleration on a second-by-second basis for all vehicles within the network. Once second-by-second speed and acceleration data are available, CMEM is used to estimate the Total Vehicular Emissions (TVE) for the whole simulation period for each pollutant from this initial congested road network. This is denoted as TVEinitial.

Each vehicle is assigned a particular category (out of 26 vehicle categories, as discussed previously) and a soak time. In the analysis conducted here, three different selections of vehicle categories were included. One represented a typical fleet mix (based on the Riverside County sampling of vehicles in the study). Another represented high-emitting vehicles (i.e., those with no catalytic converter). The final category included only Tier 1 vehicles, which were the cleanest vehicles sampled in the development of the CMEM database.

After estimating total emissions for each pollutant from the initial congested road network (TVEinitial), the next step is to expand the network such that the traffic flow is smoothed. This can be done by introducing an additional lane on link-3 creating a 4-lane motorway. As capacity in link-3 increases, the average speed of the vehicles on that link also increases and there are fewer acceleration or deceleration events. The total emissions would then decrease from reducing the stop and go traffic.

Induced travel effects are then exogenously simulated by increasing the traffic in the simulated network. The emissions are estimated based upon incremental 1% increases in the number of vehicles fed into both link-1 and link-2. This is done until a “break-even point”, where emissions are equivalent to those in the initially congested base case, are reached. The break-even point will naturally vary for each pollutant. The total vehicular emissions are estimated from the expanded network and denoted as TVEinduced. Figure 3 outlines the procedure used. TVEinitial is calculated from the initial congested network for one occasion only, whereas the TVEinduced is calculated from the extended network each and every time the traffic flow is increased by 1% on both link-1 and link-2.

Specification of the soak time allows different assumptions about cold start effects to be analyzed. This is important as cold start emissions from motor vehicles are generally high compared with hot stabilized emissions. If it is assumed that each and every new vehicle entering the motorway due to induced travel includes a cold start, then it is essential to include this in the calculation of total induced emissions. Cold start emissions of HC, CO, NO_X, Fuel use and CO_2 for a vehicle can be estimated using the CMEM ‘CoreMode’ model. For example, the total exhaust emissions of a normal emitting car (CMEM category 5) based on a six hour soak time and running for six minutes between 0 and 40 mph) is found to be 17.1 gm (HC), 848.7 gm (CO), 14.7 gm (NO_X), 1259 gm (Fuel) and 2603.5 gm (CO_2) Estimates (based on the corresponding vehicle categories) are added to the total simulated emissions to account for cold starts from new induced trips.

Total simulation time was set at 3 hours. This would be similar to a typical morning peak. The random seed in VISSIM was kept constant for each simulation. The stochasticity within VISSIM would naturally lead to some variation if alternative random seeds are used. While this could affect the absolute values of estimated emissions, the overall trends would be similar. The humidity level is set in CMEM to 80 grains H_2O/lb of dry air and kept constant throughout the simulation.

Results

Overall twelve sets of simulations were conducted to determine the break-even points for emissions of HC, NO_X, CO, CO_2 and fuel consumption. Three fleet definitions were used. These were 1) the full fleet mix within the CMEM database, 2) no catalytic converters, and, 3) Tier 1 vehicles that represent the cleanest vehicles in the sample. This provides us with some indication of how improvement in vehicle emission technologies over time affects the break-even points for each pollutant. The expectation is that as vehicles become cleaner, there will be a smaller reduction in emissions from initial effects associated with smoothing traffic flows. This would lead to break-even points for cleaner fleets that occur more rapidly with increased vehicle trips.

Cold starts are accounted for in two ways within the simulations. First, it is assumed that the generated trips exogenously fed into the simulation have randomly assigned soak times. This would imply that these trips are not necessarily new trips as many would not contain a cold start. To explicitly include cold starts, all the new trips are modelled based upon a 6-hour soak time and a period of 6 minutes travelling at a speed of 0 to 40 mph before entering the simulated network.

Finally, as described above, two sets of desired speeds were used in the simulations. In the actual simulations, the desired speeds translate into a distribution of actual speeds. Figure 4 shows the actual distribution of speeds under the base case simulation. This distribution varies for each simulation as demand is increased.

Figure 4 shows that, on average, when the desired speed is higher, the actual speeds will tend to be higher.

Figure 5 displays an example of the incremental results for CO emissions with the higher desired speed distribution for the no-catalyst case. The horizontal line shows the initial level of emissions under the congested base case simulation (13,935 kg). The initial level of emissions after the capacity expansion is 7,811 kg. The two cases shown include the random hot soak times (lower line) and all cold starts (upper line). The break-even points occur when emissions return to the former level of 13,395 kg. This is at a flow of 6,495 vehicles for the all cold start scenario and 6,947 vehicles for the random hot soak scenario.

Tables 1-3 display the results for the simulations with no catalyst, clean vehicles (Tier 1), and all vehicles, respectively. Several general trends are immediately apparent. When all new trips include a cold start, the break-even points occur sooner than when hot soak times are randomly assigned. This is unsurprising as cold starts would account for proportionately greater emissions.

When the desired speed distribution is higher, break-even points generally occur with relatively more vehicles. This affect appears largest for CO and NO_X in the no-catalyst scenario (Table 1), but is also large in the mixed fleet scenario (Table 3). Initial congestion levels are about the same in both speed distribution scenarios, but this was achieved by setting the initial flow at 5600 veh/h in the higher speed case. The higher desired speed may allow the induced trips to not generate congestion levels as quickly thus giving larger break-even points.

In comparing the results between different vehicle categories, there is relatively little difference between the no-catalyst and mixed fleet simulations.

However, results are quite different for the Tier 1 clean vehicle scenario. In the latter, break-even points are substantially lower for CO and HC (3.2% and 2.4% in the cold start scenarios). The break-even point for NO_X is actually a bit higher than in the mixed vehicle scenario (11.6% versus 6.8% for all cold starts). Fuel consumption and CO_2 break-even points are similar.

The absolute magnitude of emissions is considerably less for the clean vehicle simulations. This is shown in Table 4 which shows results without cold starts for the induced trips. For example, HC emissions are only about 10% of those in the no-catalyst scenario. CO_2 emissions, however, are larger in the clean vehicle category, but this is likely due to the selection of vehicles in this category which are generally larger vehicles than those in the no-catalyst (or mixed fleet) category. For example, the Tier 1 light-duty trucks included a category with gross vehicle weight greater than 8500 lbs. While there is a small CO_2 penalty for those vehicles with catalytic converters, this is unlikely to result in such a large difference.

Table 4 also shows the short-term emissions reduction benefit from the improved traffic flow. Clearly this beneficial effect is substantially diminished as vehicles become cleaner. Therefore, while our general result suggests that the strategy of improving flows to improve total emissions is likely very short-lived with older vehicle fleets, the benefit of short-term reductions in absolute emission reductions is much smaller with newer cleaner vehicle fleets.

Analysis of Break-even Elasticities

In order to assess the realism of our exogenous demand estimates, we can calculate the travel demand elasticities associated with the respective break-even points of each pollutant for the various simulations. Typical travel demand elasticities are expressed in terms of the change in vehicle miles of travel with respect to a given change in travel time. Since the miles traveled in our simulations are fixed, we can estimate break-even elasticities using just the vehicle volumes (Stathopoulos and Noland, 2003). Therefore, elasticities can be calculated from:

$$\varepsilon = \frac{T}{v}\left(\frac{\partial v}{\partial T}\right)$$

Where *T* is travel time and *v* is the volume of traffic.

Goodwin (1996) cites travel time elasticities in the range of -0.5 to -1.0. Graham and Glaister (2004) in a review of travel demand elasticities cite ranges between -0.20 (short-run) to -0.74 (long-run) for travel time elasticities. These provide a base-line for what type of break-even elasticities are likely to be realistic. Any values below the long-run estimates would suggest that overall emissions would increase. Or put another way, the break-even estimate would be a low estimate of how much traffic would be generated from the flow improvement.

The percent reductions in travel times at the emissions break-even points are shown in Table 5. Table 6 contains break-even elasticity estimates. As the latter table indicates, there is a large range of elasticities represented by our exogenous estimate of travel demand. These range from some values that exceed 1.0, which are probably not realistic estimates of potential demand responses, to one as low as 0.07 which is well below the range of statistical estimates of expected demand elasticities. Thus, those values below the expected range would suggest that the break-even point has occurred before all the potential newly induced demand has been accounted for.

Several general conclusions can be gained by examining the break-even elasticities. First, when it is assumed that all the new generated trips are cold starts, the elasticity values generally fall within the expected range. This occurs regardless of the emission control technology of the vehicles simulated. Second, the clean vehicle simulations tend to give smaller elasticity values, suggesting that these effects are even stronger as the fleet becomes cleaner. Even when it is assumed that not all new trips include a cold start, the elasticities are smaller for the clean vehicle category. The key conclusion here is that the break-even elasticities for the clean vehicle and mixed vehicle categories, especially under the assumption of new trips containing a cold start, are realistic and within the bounds of estimated travel time elasticities in the transport literature. Thus, we would not expect a long-term reduction in emissions from this type of traffic-flow improvement.

Despite the fact that this result suggests these sort of policies will not reduce aggregate emissions, Table 5 suggests there may still be some travel time benefits. These are larger for the clean vehicle and mixed vehicle fleets. However, this may also suggest that the exogenous demand estimates are too low and that additional trips would be generated, adding to total emissions that further off-set any travel time savings. The benefit of allowing additional trips is clearly apparent and thus one would still likely have a reduction in emissions per vehicle on the network. However, this type of benefit needs to be traded off against any aggregate increase in emissions.

A final point that should be considered, is that while those areas with relatively clean fleets will not obtain emission reduction benefits from traffic-flow improvement policies, those areas with large numbers of high polluting vehicles, may still find some beneficial effects.

Conclusions

This work has used micro-simulation techniques and a modal emissions model to develop a simple scenario that examines the effect of improving traffic flows on vehicle emissions. The findings here confirm the results shown in Stathopoulos & Noland (2003) that any initial emissions reductions are quickly overtaken by increased trips. Extending this previous work, the effect of different vehicle vintages based on alternative vehicle emission technologies was examined. Of particular interest, this showed that the short-term emissions benefits of flow improvements are negligible for modern clean vehicles.

This issue has long been controversial. This work suggests that those who have argued that benefits are short-lived and rapidly diminished by induced trips, were likely correct. But it also suggests that these arguments are likely dated. Newer technologies that reduce vehicle emissions suggest that short-term benefits are virtually non existent in absolute grams of pollutants reduced (at least for HC and CO) and thus that future emissions growth is more closely correlated with overall growth in total trips and vehicle-kilometres of travel, rather than being affected by congested traffic conditions. However, if substantial numbers of vehicles with malfunctioning emissions control systems are on the road, there might still be emissions reduction benefits.

One caveat associated with this work is that the modal effects associated with particulates, from heavy-goods vehicles as well as from cars, are yet to be fully understood. Further research is clearly needed in this area to fully model the modal effects of particulate emissions as well as the exposure that may occur under congested conditions.

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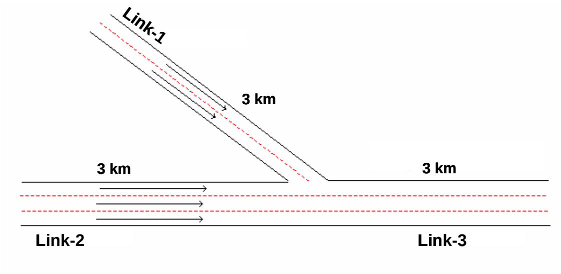

Figure 1: Motorway merge road geometry

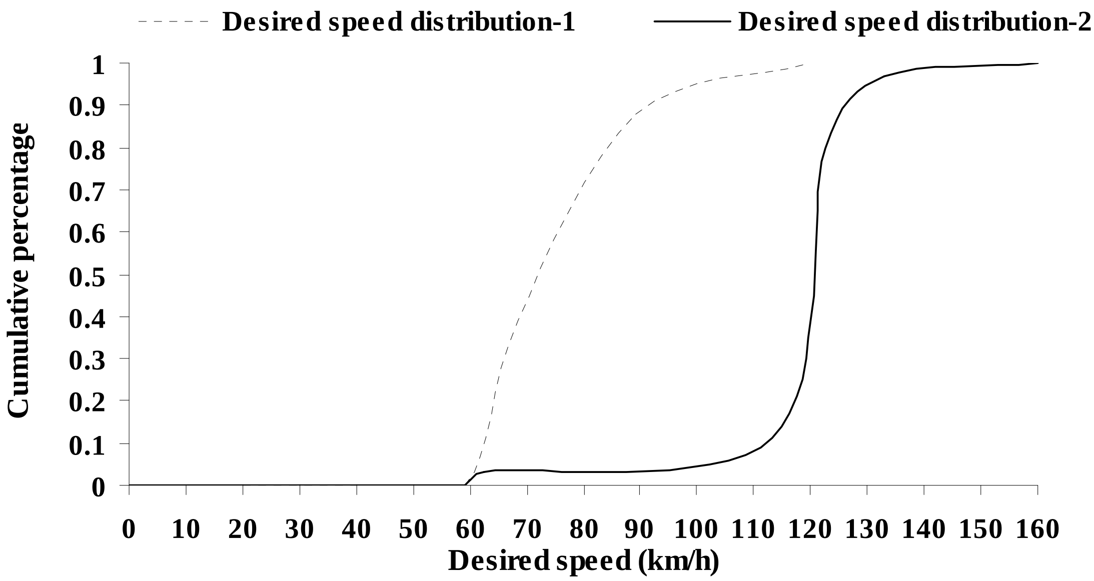

Figure 2: Desired speed distributions

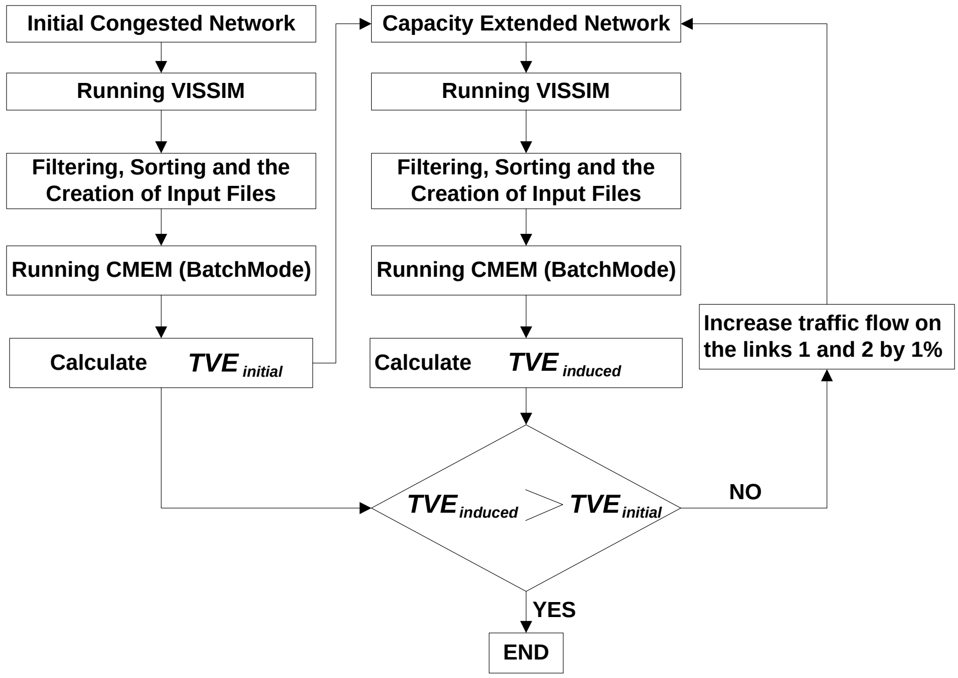

Figure 3: The Linkage of VISSIM and CMEM for Identification of "break-even point"

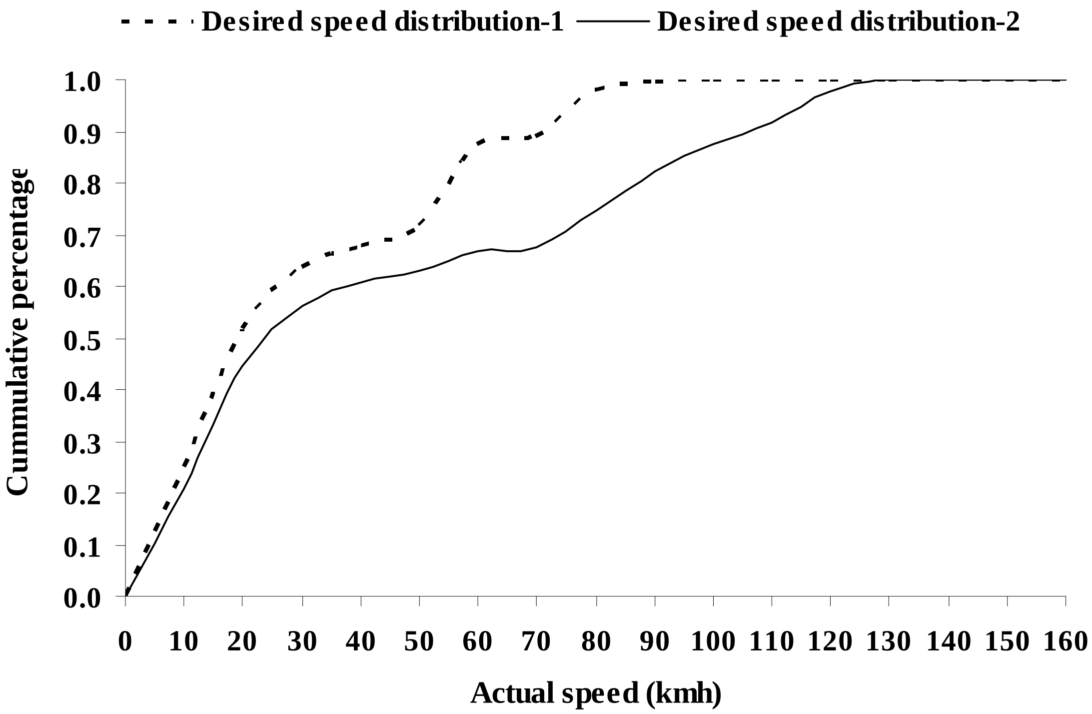

Figure 4: Actual speed distributions for the desired speed distributions 1 and 2 (VISSIM)

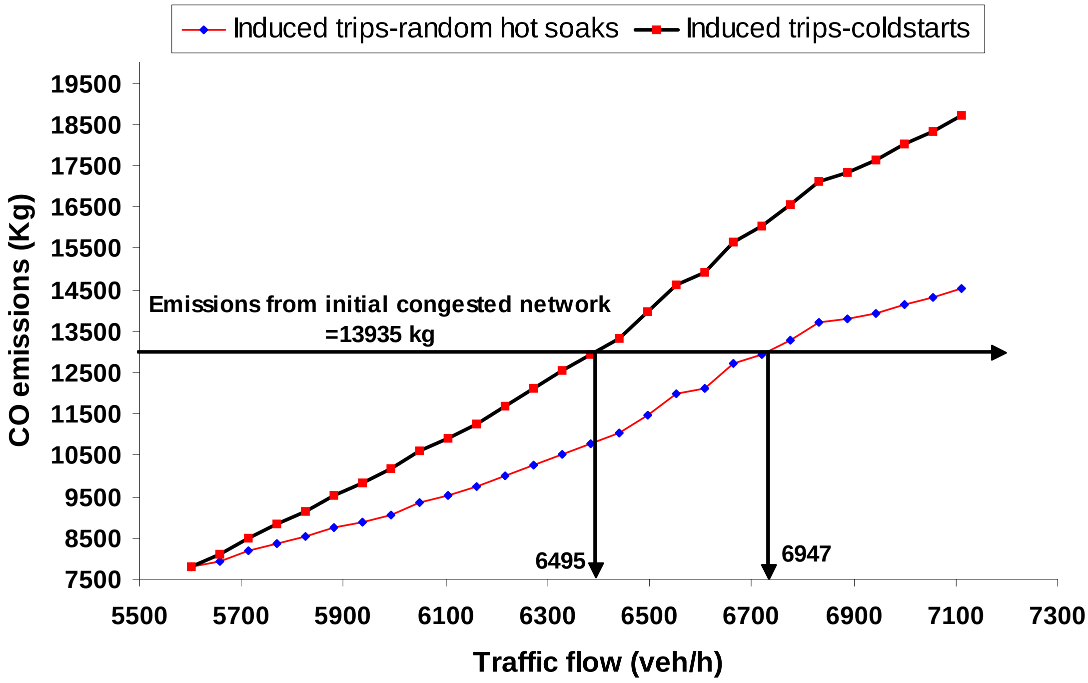

Figure 5: Identification of the break-even point for CO

Table 1
Identification of break-even point for 'NO CATALYST' vehicle category

NO CATALYST (Vehicle Category No. 1)					
		Random hot soaks		All cold starts	
Speed distribution-1 (Initial flow=5500 veh/h)	Pollutants	Break-even point (Traffic flow, veh/h)	% increased in traffic flow relative to the initial flow	Break-even point (Traffic flow, veh/h)	% increased in traffic flow relative to the initial flow
	HC	6642	20.8%	6283	14.2%
	CO	6456	17.4%	6014	9.3%
	NO_X	6439	17.1%	5984	8.8%
	Fuel	6613	20.2%	6180	12.4%
	CO_2	6591	19.8%	6344	15.3%
Speed distribution-2 (Initial flow=5600 veh/h)	HC	6762	20.7%	6547	16.9%
	CO	6947	24.1%	6495	16.0%
	NO_X	7054	26.0%	6487	15.8%
	Fuel	6805	21.5%	6547	16.9%
	CO_2	6762	20.7%	6600	17.9%

Table 2
Identification of break-even point for TIER1 vehicle category (Clean vehicles)

TIER 1: Clean vehicle category					
		Random hot soaks		All cold starts	
Speed distribution-1 (Initial flow=5500 veh/h)	Pollutants	Break-even point (Traffic flow, veh/h)	% increased in traffic flow relative to the initial flow	Break-even point (Traffic flow, veh/h)	% increased in traffic flow relative to the initial flow
	HC	5918	7.6%	5677	3.2%
	CO	5851	6.4%	5631	2.4%
	NO_X	6539	18.9%	6138	11.6%
	Fuel	6565	19.4%	6174	12.3%
	CO_2	6585	19.7%	6308	14.7%
Speed distribution-2 (Initial flow=5600 veh/h)	HC	6425	14.7%	6135	9.5%
	CO	6495	16.0%	6193	10.6%
	NO_X	6713	19.9%	6504	16.1%
	Fuel	6831	22.0%	6569	17.3%
	CO_2	6844	22.2%	6671	19.1%

Table 3
Identification of break-even point for mixed vehicle category

Mixed Vehicle Categories					
		Random hot soaks		All cold starts	
	Pollutants	Break-even point (Traffic flow, veh/h)	% increased in traffic flow relative to the initial flow	Break-even point (Traffic flow, veh/h)	% increased in traffic flow relative to the initial flow
Speed distribution-1 (Initila flow=5500 veh/h)	HC	6632	20.6%	6245	13.5%
	CO	6369	15.8%	5940	8.0%
	NO_X	6476	17.7%	5874	6.8%
	Fuel	6630	20.5%	6156	11.9%
	CO_2	6604	20.1%	6222	13.1%
Speed distribution-2 (Initial flow=5600 veh/h)	HC	6664	19.0%	6468	15.5%
	CO	6989	24.8%	6386	14.0%
	NO_X	6660	18.9%	6408	14.4%
	Fuel	6682	19.3%	6470	15.5%
	CO_2	6738	20.3%	6446	15.1%

Table 4
Comparison of emissions and fuel consumption before and after capacity expansion with the same traffic flow (initial congested) and two desired speed distributions, with random hot soaks (i.e., induced trips do not have cold starts).

		Mixed vehicle category		Clean vehicle category		No catalyst vehicle	
Emissions	**Network configuration**	**SD-1**	**SD-2**	**SD-1**	**SD-2**	**SD-1**	**SD-2**
HC (Kg)	Congested network	251	296	51	65	1056	1203
	Expanded network	**166**	**165**	**47**	**51**	**643**	**550**
CO (Kg)	Congested network	4154	7187	2301	4183	9062	13935
	Expanded network	**3179**	**4167**	**2090**	**2907**	**6589**	**7811**
NO_X (Kg)	Congested network	132	203	92	130	247	414
	Expanded network	**99**	**130**	**66**	**80**	**177**	**231**
Fuel (Kg)	Congested network	11827	15885	12696	17470	15408	20331
	Expanded network	**8505**	**9769**	**8861**	**10228**	**10626**	**11474**
CO_2 (Kg)	Congested network	30141	38095	36486	48629	31064	38527
	Expanded network	**21424**	**23882**	**24669**	**27707**	**21181**	**22261**

Table 5
Percent reduction in travel time achieved at emissions break-even point

Emission control technology		NO CATALYST Vehicle Category		Clean Vehicle Category		Mixed Vehicle Category	
Induced Trips		**Mix**	**All coldstarts**	**Mix**	**All coldstarts**	**Mix**	**All coldstarts**
	Pollutants	**Travel time (sec)**	**Travel time (sec)**	**Travel time (sec)**	**Travel time (sec)**	**Travel time (sec)**	**Travel time (sec)**
Speed distribution-1)	HC	14.95%	29.72%	32.52%	33.46%	15.14%	29.53%
	CO	24.49%	31.59%	32.71%	34.39%	28.22%	31.59%
	NO_X	24.67%	31.78%	20.56%	31.21%	24.30%	34.21%
	Fuel	15.89%	30.84%	17.94%	30.84%	15.70%	28.79%
	CO_2	17.20%	28.41%	17.38%	29.91%	15.89%	29.72%
Speed distribution-2	HC	14.87%	32.99%	39.10%	45.82%	17.52%	39.31%
	CO	4.68%	33.40%	33.40%	45.01%	3.87%	46.23%
	NO_X	2.85%	34.01%	16.09%	33.40%	17.52%	46.03%
	Fuel	11.41%	32.99%	10.79%	22.61%	17.31%	39.31%
	CO_2	14.87%	22.00%	10.79%	17.52%	16.50%	39.51%

Table 6
Break-even elasticity values

Emission control technology		NO CATALYST Vehicle Category		Clean Vehicle Category		Mixed Vehicle Category	
Induced Trips		Mix	All coldstarts	Mix	All coldstarts	Mix	All coldstarts
	Pollutants	Travel time (sec)	Travel time (sec)	Travel time (sec)	Travel time (sec)	Travel time (sec)	Travel time (sec)
Speed distribution-1	HC	1.39	0.48	0.23	0.10	1.36	0.46
	CO	0.71	0.29	0.20	0.07	0.56	0.25
	NO_X	0.69	0.28	0.92	0.37	0.73	0.20
	Fuel	1.27	0.40	1.08	0.40	1.31	0.41
	CO_2	1.15	0.54	1.13	0.49	1.27	0.44
Speed distribution-2	HC	1.39	0.51	0.38	0.21	1.08	0.39
	CO	5.14	0.48	0.48	0.24	6.41	0.30
	NO_X	9.12	0.46	1.24	0.48	1.08	0.31
	Fuel	1.89	0.51	2.04	0.77	1.11	0.39
	CO_2	1.39	0.81	2.06	1.09	1.23	0.38