A Critical Look at the Relationships between the Urban Transport System and Vehicle Emissions

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1 Introduction

Emissions of Transport and passenger vehicles are major contributors to air-pollution. Transport air-pollution worsens the urban air-quality. It is anticipated, over the next decade that the levels of nitrogen oxides (NO_X) and particulate matter (PM) in the air will be critical determinants for urban air-quality (Joumard *et al.*, 1996; ECMT, 2001). Whereas, in the Sydney Region over the past decade the concentrations of ozone (O_3) and nitrogen dioxide (NO_2) have exceeded several times both the National Health standards and the Medical Research Council standards (NSW, 1994). The effects of transport air-pollution on health are cumulative, and affect a large population for long terms. More than 133 million people lived in counties in the US where monitoring revealed that air-quality standards were violated at least for one air-pollutant in 2001 (EPA/QAQPS, cited in USEPA, 2005). Transport air-pollution affects the environment at all levels and impacts the public health. The increases in levels of PM_{10} and ambient ozone, the latter of which is formed by NO_X and HC, caused between 21 percent and 38 percent of total deaths in England and Wales during the heat wave in August 2003 (Stedman, 2004).

Air-pollution, in general, creates a large economic cost to societies. Air-pollution is estimated to cost the European Union approximately €37 billion per annum, equivalent to 0.6 percent of gross domestic product (GDP), of which 90 percent is attributed to road transport (DG VII, cited in Marsden *et al.*, 2001). The local pollution in a number of European countries is estimated between 0.03 and 1.05 percent of gross national product (GNP), in terms of costs of human health, material damage, and vegetation decline (Kageson, cited in Quinet, 1997).

The health effects of transport air-pollution are major concerns for the public. Transport air-pollution affects the public health, particularly the aged population. Air pollution in the US increased significantly the use of medical care by the elderly (Fuchs and Frank, cited in VTPI, 2002). Transport air-pollution induces large costs of medical treatments. The costs of medical treatments in Australia are estimated AU$34 million for CO, AU$4.5 million for NO_2, and between AU$95 and AU$285 million for O_3 (McGregor *et al.*, 2001). While, in the US the costs of the medical treatments are estimated between US$656 and US$5,696 million for CO, between US$640 and US$3,308 million for NO_2, and between US$129 and US$1,094 million for O_3 (Table 1).

Table 1 Costs of Air Pollution of Vehicles

Emissions	Ambient pollutant	Health effects	Lower bound*	Upper bound*
CO	CO	mortality	302	3,743
		hospitalisation	48	148
		headaches	306	1,805
NO_X	NO_2	sore throat	341	1,749
		excess phlegm	157	817
		eye irritation	142	742
NO_X, HC	O_3	asthma attacks	13	231
		lower resp. illness	52	446
		upper resp. illness	16	136
		eye irritation	48	281

Source: McCubbin and Delucchi (1996)
* in the U.S.A., expressed in millions 1990 US$

2 Emissions of Gasoline-Fuelled Vehicles

Although technological advances have reduced more than 90 percent of emissions from passenger vehicles, passenger vehicles are still major environmental and public health concerns (MacLean *et al.,* 2003). Passenger vehicles are large percentage of transport modes in many countries. They are the main mode in all cities in Australia, and account for two-thirds of the energy consumed by road transport. Road transport between 1998 and 1999, consumed 78 percent of the total energy of the transport sector (ABS, 2002). Emissions of new models measured on test drive-cycles have declined 96 percent for hydrocarbons (HC), 97 percent for carbon monoxide (CO), and 87 percent for nitrogen oxides (NO_X) (Pickrell, 1999). The improvements were less in the case of on-road vehicles. In the US for example, the average emissions per mile of the on-road fleet have declined 79 percent for HC, 73 percent for CO, and 58 percent for NO_X (Pickrell, 1999). Several factors contribute to the variances between emissions of new models on test drive-cycles and emissions of on-road vehicles, such as (BTS, 1997): (i) emissions testing procedures, (ii) exhaust after-treatment systems, (iii) tampering with engines, and (iv) on-road driving conditions.

Vehicle emissions are primarily produced by the engine and simultaneously emitted by the exhaust. Gasoline-fuelled vehicles common to passenger vehicles emit significantly three key emissions, namely carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_X) mainly as nitric oxide (NO). Both HC and CO are products of incomplete oxidation of the fuel in the engine. Figure 1 illustrates the formation of vehicle emissions in conventional internal combustion engines.

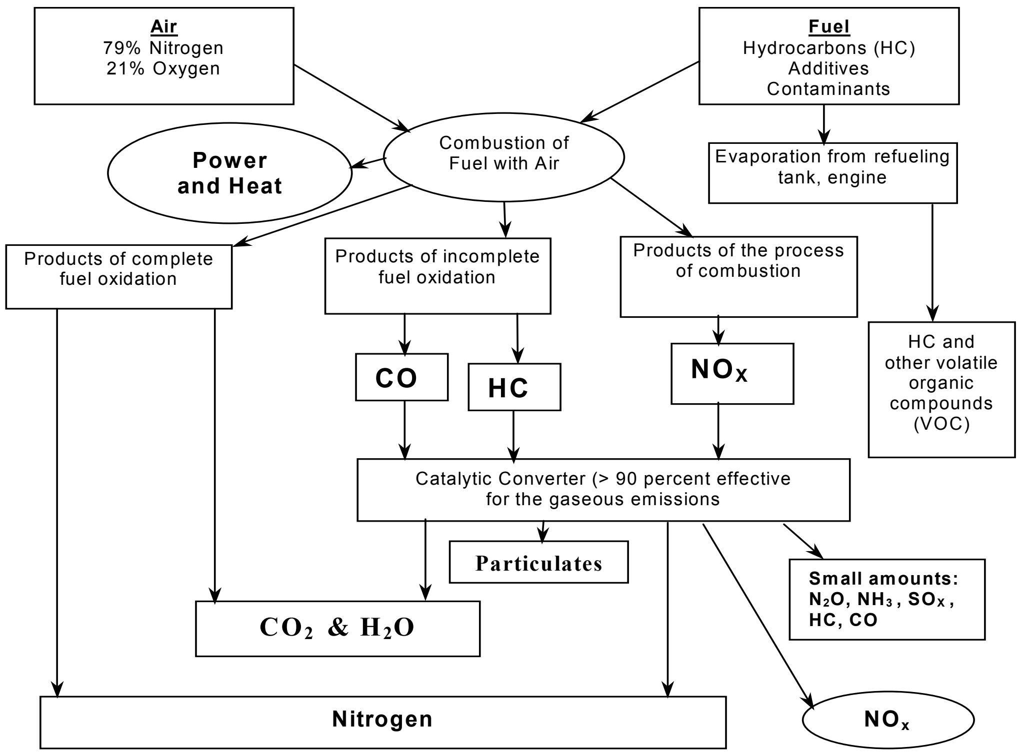

Figure 1 Vehicle Emissions in Gasoline-Fuelled Vehicles

Source: Houghton (1995)

The combustion process in the engine occurs almost instantaneously in the short time of the engine cycle. An air-fuel mixture flows in the cylinder in the first stroke – induction – of the engine cycle. Then, during the second stroke – compression – the mixture is compressed, and the pressure and temperature are raised. The presence of O_2, N_2, and HC molecules in the air-fuel mixture under high levels of pressure and temperature in the cylinder, initiates several simultaneous interdependent combustion reactions within a finite but very short time.

The oxidation of fuel and the formation of NO_X are intimately linked (Heywood, 1988). The reactions that produce HC, CO, and NO_X are interdependent, and there are cause-effect relationships between these emissions. There is heat and mass transfer both at the molecular level of the combustion reactions and the macro level of the combustion system. At the molecular level, for example, the thermal energy released by other combustion reactions, and also oxygen atoms (O) made available by other combustion reactions initiate Zeldovich's chain that produces NO_X. The combustion reactions are complex. The combustion reactions that produce CO and NO_X are not completely identified, and they do not attain equilibrium. Research is still underway to predict NO_X accurately (Mattavi and Amann, cited by Stone, 1992).

Various fuel equivalence ratios, i.e., strengths of the air-fuel mixtures, produce various concentrations of HC, CO, and NO_X. The process of combustion creates constantly variable environment, in the combustion chamber, of temperature, pressure, and substance concentrations. The variations determine the reactions and products of combustion. For example, as the concentrations of O_2 increases, CO tends to decrease (Figure 2).

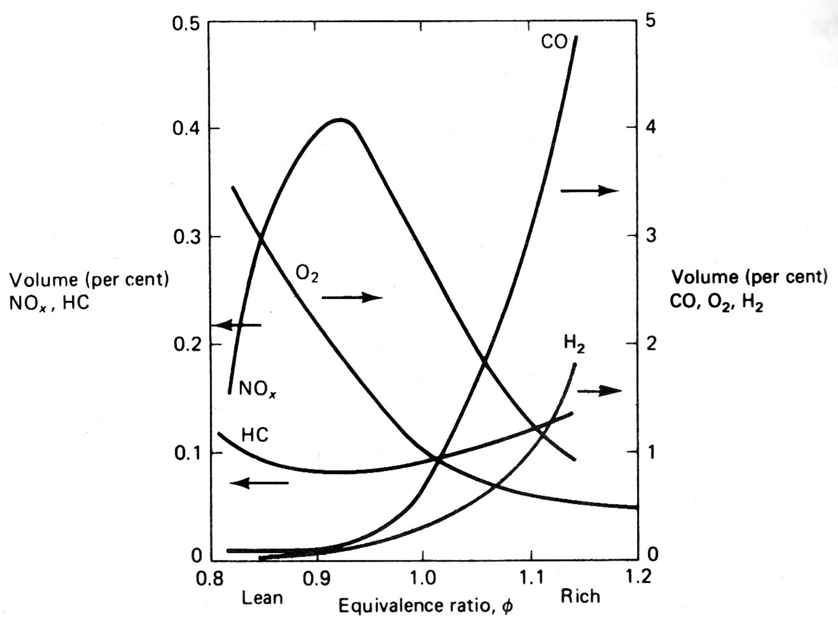

Figure 2 HC, CO, and NO_X in Mixtures of Various Equivalence Ratios

Source: (Matthey, cited in Stone, 1992)

3 Vehicle Design Variables

Vehicle design variables are interrelated, and affect collectively vehicle emissions. It is difficult to isolate the effects of a single variable on emissions (Schäfer and Basshuysen, 1995; Heywood, 1982). Engine-operating conditions also influence vehicle emissions. For example, both rich and lean conditions emit higher HC and lower NO_X (NSW Parliament, 1994). Variables, such as engine speed, engine load, thermal conditions of both the engine and catalyst, and driving behaviour, determine the vehicle operating conditions, and thereby affect emissions. Vehicle design variables and operational factors act together to determine the levels of emissions. Moreover, the maintenance status of vehicles plays an important role in the determination of emissions. The maintenance of vehicles particularly when altered from manufacturers' procedures and specifications increase some emissions. For example, NO_X is increased when vehicles are tuned more finely (NSW Parliament, 1994).

Additionally, various engine processes produce various vehicle emissions. CO and NO_X are principally produced by chemical and kinetic mechanisms of the engine, and HC by the physical processes of the engine and the physics of combustion in the chamber (Fomunung *et al.*, 1999; Patterson and Henein, 1972). CO is almost unaffected by driving modes except under hard accelerations, while HC and NO are greatly affected by engine loads and driving behaviour (LeBlanc *et al.*, 1993). It is not possible to eliminate all emissions. General Motors showed that the concentrations of CO and NO are negatively related for various fuel equivalence ratios (Figure 3); they use a simulation program to model the combustion process during an engine-cycle.

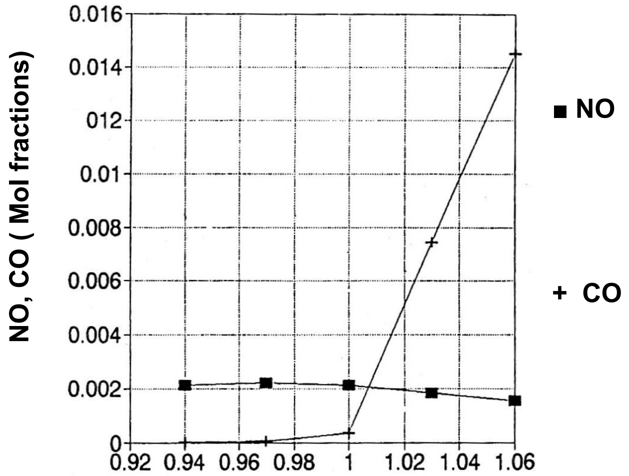

Figure 3 **CO and NO emissions**

Source: (Pulkrabek, 1997)

A change in one variable that reduces normally one emission may increase one or more other emissions (Schäfer and Basshuysen, 1995). CO depends almost exclusively on the air/fuel ratio, whereas NO_X and HC depend on several other influences, such as the chamber area, cylinder displacement, and ignition timing.

CO emissions are reduced under fuel-lean operations, but lean operations have negative effects on the power of the engine. Similar to CO, HC is reduced under fuel-lean operations until the flammability of the mixture is reduced. Thereafter, HC is increased by lean operations. Also, HC is reduced if a second spark plug is added to the chamber; starting the flame at two points will reduce both the path of the flame to proceed and the time of the reactions to occur, and thereby will reduce quenching of the flame (Pulkrabek, 1997).

Unlike HC and CO, NO_X is reduced by different ways. Reducing either the duration or the temperature of combustion reduces NO_X. Also, retarding the ignition reduces NO_X, because it reduces the peak temperature and pressure of combustion. However, retarding ignition has negative effects on both the power and the fuel economy. Additionally, re-circulating a fraction of the exhaust gas reduces NO_X. Exhaust gas re-circulations (EGR) increase residuals in the cylinder by reducing both the temperature of combustion and the flame speed, and thereby reduce NO_X. An EGR between 5 percent and 10 percent is likely to halve NO_X (Stone, 1992), but also is likely to lower the overall efficiency of the engine by reducing its limits to lean operations.

4 Transport Factors that Contribute to Emissions

The relationships between the urban transport system and vehicle emissions are approached from different perspectives, by different expertise, and using various details. Moreover, various combinations of vehicle emissions are investigated. The results of various studies are not comparable, especially because testing conditions vary in different regions, and also due to lack of a common vocabulary used by specialists in various disciplines to describe various influences. Also, according to Beydoun and Guldmann (2006) measurement units create further uncertainty. Some studies express emissions in g/mile or g and others in concentrations, such as percentage and ppm.

4.1 Types of Vehicle Emissions

Vehicle emissions vary with engine operating conditions, of which stabilised and transient are two main conditions (Patterson and Henein, 1972). Vehicle emissions are classified into cold start, warming-up, hot stabilised, and high power, as follows:

1. Cold start emissions: Cold start emissions are most likely to arise under urban driving conditions, such as starting and frequent stop-start conditions (Venigalla *et al.*, 1995b). Approximately twenty-five percent of all journeys in Great Britain are cold starts of less than 3 km (Stead, 1999). Emissions of cold engines are double those of hot engines (Stead, 1999). The USEPA has defined cold starts, for non catalyst-equipped vehicles, as any start that occurs 4 hours or later following the end of the preceding trip, and for catalyst-equipped vehicles, 1 hour or later following the end of the preceding trip (Venigalla *et al.*, 1995a; 1995b). Cold starts are responsible for large percentages of total vehicle emissions. Catalyst-equipped vehicles that travel less than 6 km produce 34 percent of the total vehicle emissions, of which 27 percent are of cold engines and 7 percent are of hot engines (Bendtsen and Thorsen, 1995).

2. Warming-up emissions: the time needed by the engine and the catalytic converter to reach stabilised thermal conditions influences strongly vehicle emissions. HC and CO are sharply elevated during warming-up conditions.

3. Hot stabilised emissions: occur under normal engine temperatures between 80 ºC and 90 ºC (Boulter *et al.*, 1997). During which, ambient temperatures do not have a significant effects on both the engine and the catalytic converter (Laurikko, 1997). Hot start, for non catalyst-equipped vehicles, is any start occurs within less than 4 hours after the end of the preceding trip, and for catalyst-equipped vehicles within less than 1 hour after the end of the preceding trip (Venigalla *et al.*, 1995a; 1995b).

4. High power – enrichments – emissions: events of accelerations and travelling upgrades affect strongly vehicle emissions. When vehicles accelerate onto a freeway or go uphills they are under wide-open throttle (WOT) conditions, and therefore under enrichment conditions. Kelly and Groblicki (1993) studied the effects of enrichment conditions on vehicle emissions, and showed that commanded enrichments for 451 seconds, equivalent to 1.2 percent of the study time, contribute to 88 percent of the CO emitted over 352 miles in 10.6 hours. Also, they found that commanded enrichments affect both HC and CO with CO 60 times more, and did not affect NO.

4.2 Urban Transport System and Vehicle Emissions

Three combined factors contribute to road traffic pollution, namely traffic mix, traffic volume, and traffic flow conditions (Nicolas, 2000). In the urban transport system, we identify four categories that contribute to emissions of gasoline-fuelled vehicles, and hence affect the urban air-quality, as follows: (i) traffic flow conditions, (ii) vehicle operational variables, (iii) driving behaviour, and (iv) vehicle technology (Figure 4).

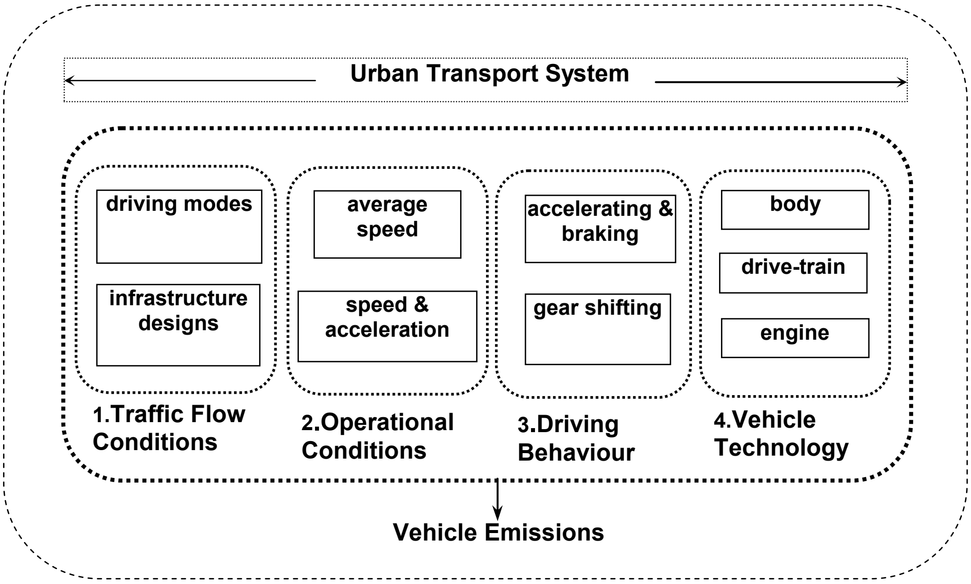

Figure 4 Transport and Vehicle Emissions: the Interfaces

4.2.1 Traffic flow conditions

Vehicle emissions depend on traffic flow conditions of a traffic stream. Traditionally, vehicle emissions are described by modal approach, such as idle emissions, cruising emissions, acceleration emissions, and deceleration emissions. While recently instead of using driving modes to describe vehicle emissions, four engine states are used in a new approach to describe vehicle emissions, such as stoichiometric emissions, cold / warm start emissions, enrichment emissions, and lean-burn emissions (An *et al.,* cited in Marsden *et al.*, 2001).

Vehicle emissions are affected by the infrastructure class that influence significantly traffic flow conditions, such as free and congested flows, and stop-start conditions. Emissions of congested flows are generally five times free flows emissions (Nicolas, 2000). The impacts of road infrastructure on emissions have been investigated by several studies, e.g., (Várhelyi, 2002; El-Fadel *et al.*, 2000; Al-Suleiman and Al-Khateeb, 1996; Robertson *et al.,* 1996). On one hand, HC and CO tend to decrease with the increases in average speeds of traffic and with reductions in frequencies of idling and accelerating, while on the other hand NO_X tends to increase. In contrast, Watson and Lu (1993) claimed that stop-start conditions produce five times more NO_X, three times more CO and HC, and require100 percent more fuel.

Additionally, vehicle emissions are affected by the road gradients. The gradients of roads affect the quantity of air that flows into the combustion chamber, and also affect the aerodynamic forces on the vehicle (Sturm *et al.*, 1996). A few models consider road gradients when predicting vehicle emissions (Latham *et al.*, 2000). Nevertheless, when models take into consideration altitudes and gradients, HC differ by 21 percent, CO by 40 percent, and NO_X by 15 percent (Sturm *et al.*, 1996). Vehicle emissions are double when travelling uphills (Cicero-Fernández *et al.*, cited in Fomunung *et al.*, 2000). Travelling uphills produce consistently more NO_X, whilst travelling downhills produce less NO_X (Potter and Savage, cited in Cloke *et al.*, 1998). Pierson *et al.* (1996) summarised automotive emissions from mountain tunnels in the US and found that, in most cases, NO_X increased from zero at slopes of –3.76 percent to five times the level-road NO_X at +3.76 percent. They also showed that CO and HC were maximum uphill in some cases, and in other cases were maximum downhill. The highest observed HC was downhills, and the lowest observed HC was on a level road.

4.2.2 Operational conditions

The mainstream literature uses average speeds for investigating the effects of operational variables on vehicle emissions. Despite the fact that, several studies suggest using vehicle kinetics or products of instantaneous speeds and accelerations to obtain more realistic values (Guensler, cited in Ericsson, 2001; Le Blanc *et al.*, 1995; André and Hammarström, 2000; Negrenti *et al.*, 2001).

In general, vehicle emissions are minimal for average speeds between 40 km/h and 60 km/h, and are triple for speeds between 10 km/h and 15 km/h (OECD, 2004; The Royal Commission on Environmental Pollution, 1995). On one hand, NO_X tends to increase with high speeds, on the other hand both HC and CO tend to increase with lower speeds that are typical of congested flow conditions. Ward *et al.* (cited in OECD, 2004) found that NO_X is low between 35 km/h and 40 km/h, while HC is low between 55 km/h and 65 km/h (Figure 5).

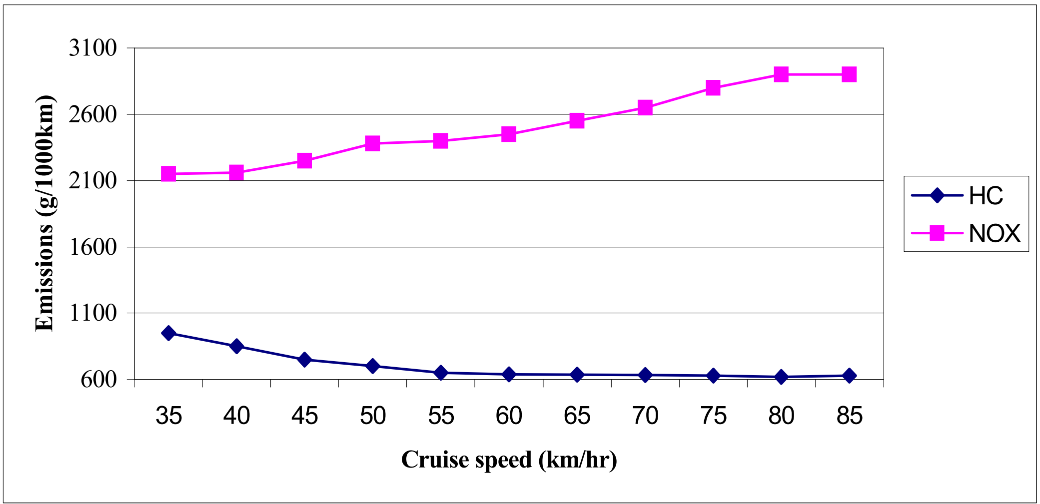

Figure 5 The effects of travel speed on HC and NO_X emissions

source: Ward *et al.* (cited in OECD, 2004); approximate plot

4.2.3 Driving Behaviour

Driving behaviour is defined by the way the driver handles the accelerator, the brake pedal, and the gear stick (Guensler, cited in Ericsson, 2001). A few studies measured the effects of driving behaviour on emissions. A study by Shih *et al.* (cited in Fomunung *et al.*, 2000) used the throttle openings to model driving behaviour. Another study by Gense (cited in OECD, 2004) investigated driving behaviour by observing the changes in emissions for various behaviours.

Aggressive driving, such as hard acceleration and deceleration, produce higher emissions and may alter the emitting status of vehicles from low emitters to high emitters (LeBlanc *et al.*, 1995). Gense (cited in OECD, 2004) found that aggressive driving increased CO by 750 percent, whereas very slow acceleration reduced NO_X by 18 percent (Table 2).

Table 2 The Effects of Driving Behaviour on HC, CO, and NO_X

Driving behaviour	% Aggressive*	%New**	% Egg ***
HC	+ 280	+31	+22
CO	+ 750	+78	+4
NO_X	+ 91	+7	-18

source: Gense (cited in OECD, 2004)
* aggressive : 80% more acceleration and 20% more average engine revolutions
** new : it combines defensive driving with special way of accelerating and shifting gears, it is the newest Dutch version of the Swiss “ECO_DRIVE”.
*** egg : very slow acceleration.

Calm driving significantly emits lower CO and HC than normal driving – moderate acceleration and braking –, and emits equal or even higher NO_X. De Vlieger (1997) found that calm driving –smooth driving using the highest gear—emits ten times lower emissions, in some cases than a sporty driving style. Sporty driving styles –sudden and high acceleration and heavy braking -- emit four times more HC and CO than moderate acceleration and braking for both urban and rural traffic conditions (De Vlieger, 1997).

The effects of gear shifting on vehicle emissions have been investigated by several studies. Ericsson (2001) adapted levels of the gear, among other variables, for studying emissions, and found that late shifting between the second and third gear increased both HC and NO_X. Cloke *et al.* (1998) noted that, under steady state conditions, emissions vary inconsistently with the gear selected, but do not differ greatly with the third or fifth gear for speeds between 50 km/h and 70 km/h.

4.2.4 Vehicle technology

The impacts of vehicle technology on vehicle emissions have been investigated by many studies, such as (Burgess and Choi, 2003; OECD, 1996; Wong, 2001; Van den Brink and Van Wee, 2001; DeCicco and Ross, 1996; OECD 1991). Vehicle emissions are affected by several characteristics of the vehicle technology, such as engine technology, transmission system, and aerodynamic properties. In general, vehicle technology has been technically developed to achieve several targets, such as fuel-efficient, less polluting, lighter, safer and more comfort features. However, the process of developing new models is complex, and often compromise between conflicting targets. The main factors that influence the development of vehicle technology are combined in the following formula (Saarialho, 1993):

$$\mathbf{FDAT = f\ (\ 3C + 2L + E_{(3E+2E)} + 2P + 2M\ )}$$

where:

FDAT: Future development of automotive technology

3C **C**onsumer demands
Co-operation with the component industry
Competition

2L **L**egislation
Laws of the nature

3E **E**missions
Energy
Economy

2E **E**ngine technology
Electronics technology

2P **P**ower transmission technology
Packaging layout

2M **M**aterials technology
Manufacturing technology

5 Conclusions: Air-pollution resulting from vehicle emissions

It is a central interest of public to reduce air-pollution resulting from vehicle emissions. Transport pollution is not only a transport problem, but also is a public health problem. High concentrations of CO, HC, and NO_X cause many health problems when inhaled. They cause brain damage, several respiratory illness, respiratory infections, eye irritation, sore throat, and increase sensitivity to allergens, such as pollen.

Four groups of the urban transport system best describe the relations between the urban transport system and vehicle emissions, namely traffic flow conditions, vehicle operational variables, driving behaviour, and vehicle technology. The interfaces between the urban transport system and emissions are integral frame in a wider framework that includes a number of strategic tools (Appendix A). The framework assists planning transport to reduce the pollution resulting from vehicle emissions, and thus to reduce the adverse effects on public health Striking the right balance between transport goals and the protection of the urban air-quality is very important. When planning transport the best design options that serve transport objectives and contribute to less pollution must be selected. For example, various options with speed related effects offer appealing means for controlling vehicle emissions and guarding road safety (OECD, 1997).

Although transport is a major contributor to air-pollution, the pollution effects of several design options are not completely addressed. Particularly, the pollution effects are not addressed when deciding upon various design options, such as intersection configurations, speed limits, and traffic management schemes, e.g., traffic calming. Design options are compared generally in terms of less congestion and better safety, and also it is required to provide safety audit. Whereas, not always compared in terms of pollution and health effects. The pollution and health effects are only evaluated when preparing the environmental impact assessment, and in general terms for assessing the economic and social benefits of a project, and for designing mitigation measures.

The current traffic management schemes are not very effective to remedy the adverse pollution effects of vehicle emissions. They do not evaluate the impacts of changes in levels of a target emission on other non-target emissions (Dabbas, 2004). The interactive effects of vehicle emissions on air-quality must be addressed in order to use more effective strategies to reduce the severity of air-pollution and protect the urban air-quality. Traffic management schemes may reduce one or two emissions, but they may increase another emission. For example, the optimisation of traffic signals on one hand reduces CO and HC through minimising the overall traffic delay, and through allowing less numbers of stop-starts. On the other hand, it increases NO_X through improved average speeds (Marsden *et al.*, 2001). Also, traffic management schemes can be designed to restrict high polluting vehicles from travelling during certain hours of the day, or can prevent them from entering some urban areas, where the urban air quality is in a critical status.

6 Implications

To comprehend fully the effects of transport pollution on the urban air-quality, firstly it is important to acknowledge that vehicle emissions are interdependent. Accordingly, vehicle emissions should be modelled by using more appropriate and accurate tools, which acknowledge the interdependencies of vehicle emissions. Also, it is important to recognise that vehicle design variables are interrelated, and affect collectively vehicle emissions. Both operational and vehicle design variables act together to determine the levels of emissions. Additionally, it is important to investigate vehicle emissions in associations in order to understand more the possible links between vehicle emissions and enhanced greenhouse gases (Dabbas, 2004). A recent study by Yedla *et al.* (2005) found that urban transport strategies that target mitigating local pollution, such as total suspended particulate matter (TSP) and HC, also shows potential to reduce a non-target pollutant, such as CO_2 an enhanced greenhouse gas.

Stochastic modelling of vehicle emissions that investigates the effects of policy interventions, such as pollution control legislations, on air-quality are few although being valuable (Sharma and Khare, 2001). Stochastic modelling is valuable to evaluate various transport options, and to identify the associated impacts on public health. The Institute of Transport and Logistics Studies (ITLS) at the University of Sydney has been developing a strategic computerised tool TRESIS (Transportation and Environment Strategy Impact Simulator) as a policy advisory computerised tool to evaluate the impact of transport and non-transport policy instruments on urban travel behaviour and the environment with a wide range of performance indicators (Hensher, 2002). In the future, TRESIS will assess alternative transport polices and their impact on air quality. Research is on going in developing TRESIS, and to apply a more comprehensive and rigorous policy instrument for further assessing the urban air-quality. For example, TRESIS would incorporate the simultaneous effects of vehicle emissions in a number of ways, as follows:

- Predicting and modelling vehicle emissions simultaneously.
- Knowing the simultaneous effects of various traffic management schemes on CO, HC, and NO_X, For example, incident management may reduce some emissions and increase others.
- Identifying the health impacts that different transport strategies and changes to the road network will have on urban air-quality. Also, how various design options affect the urban air-quality, such as new speed limits on limited sections of a road.
- As a strategic prevention tool to study the effects of traffic control scenarios on the CO, HC, and NO_X emissions simultaneously, such as in response to incidents on highways.
- As a policy control interventions tool to justify that various traffic strategies will not further degrade the urban air-quality, such as the justification of traffic management schemes that reduce congestion on the road network.

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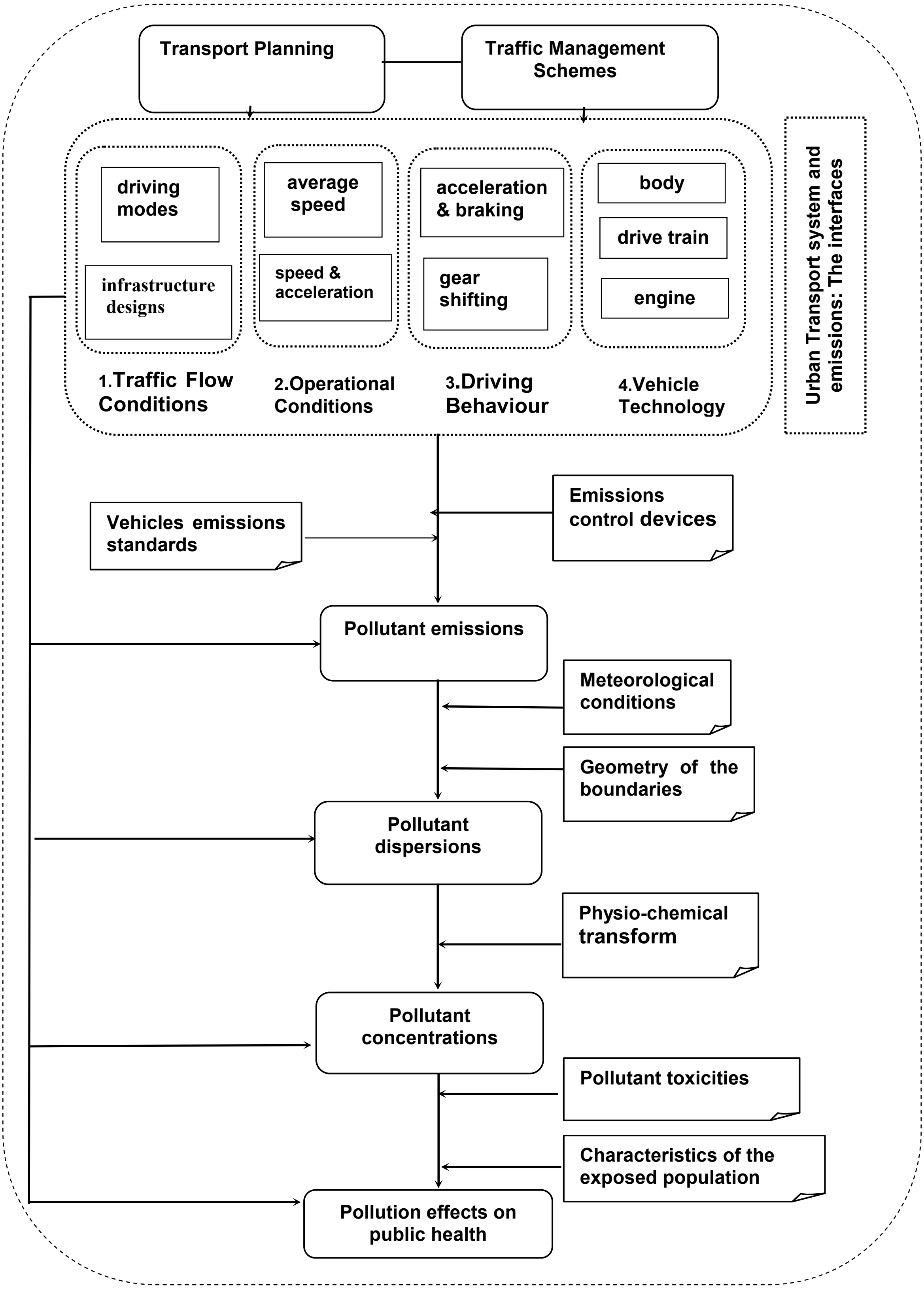
Appendix A



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