AIR POLLUTANT AND GREENHOUSE GAS ROAD TRANSPORT INVENTORY USING COPERT AUSTRALIA

Leonidas Ntziachristos[1], Christos Samaras[1], Robin Smit[2], Rhiannon Tooker[2] and Giorgos Mellios[3]

[1] Lab of Applied Thermodynamics, Aristotle University, GR 54124, Thessaloniki, Greece

[2] Department of Science, Information Technology, Innovation and the Arts, Air Quality Sciences, Inventory and Air Assessment, Brisbane, Australia

[3] EMISIA SA, Antoni Tritsi 21, GR 57001, Thessaloniki, Greece

Abstract

This paper presents a new software tool which can be used to predict air pollutant and greenhouse gas emissions from a complete fleet of road vehicles operating in a given region. The tool, named 'COPERT Australia' is based on the harmonised European approach to estimate road vehicle emissions. However, the model has been substantially revised and calibrated to reflect Australian fleet characteristics and operational conditions. The capabilities of the software tool are demonstrated by applying it to the calculation of road transport emissions in the State of Queensland.

Keywords: air pollution, emission inventories, emission modelling, greenhouse gases

1. Introduction

Road transport is a significant source of air pollutants, both in the United States of America (USA) and in the European Union (EU). According to the 2008 US Emissions Inventory, road vehicles alone are responsible for 58% and 40% of total CO, and NO_x emissions, respectively (Rao *et al.*, 2013). The corresponding numbers in Europe are 33%, and 42%, respectively (EEA, 2012). Due to the vicinity of roads to residential areas, population exposure to road transport pollution is more important compared with other sources (Zhu *et al.*, 2005).

In Australia and New Zealand, interest in road transport related air pollution is growing. Traffic related pollution is a health risk factor in major cities (e.g. Pereira *et al.*, 2010). For example, in Sydney, road vehicles are responsible for 51% and 62% of total CO and NO_x emissions, respectively (NSW EPA, 2012); which is not much different to cities around the world. This is why the Australian Government has introduced new vehicle emission control standards that, in the case of light duty vehicles, already specify requirements that go beyond the 2016 model years. These new emission standards align automotive emission control with the most recent Euro standards.

Assessing and monitoring the impacts of new emission standards and other measures on air quality is challenging. Road transport reflects a range of vehicle fuels and technologies and a variety of operational conditions. Accurate estimation of emissions requires a sound knowledge of the on-road vehicle fleet characteristics (categorisation and emission control technology), travel patterns (e.g. speed distribution) as well as climatic conditions. Then the fleet activity needs to be combined with appropriate emission factors to calculate total emissions. This process is technically demanding and prone to uncertainties.

In addition to air quality, climate change and greenhouse gases (GHGs) emissions produced by road vehicles have also been at the forefront of environmental policy and science. Developing and modelling scenarios on how different technological solutions may reduce the emission of GHGs is therefore necessary to support relevant policies.

2. Method Outline

2.1. General Approach

COPERT Australia estimates emissions of exhaust and non exhaust pollutants. Exhaust pollutants are produced during engine operation and include CO, VOC, NO_x, PM and NH_3. Several of these pollutants are split into subgroups. For example, NO_x are split into NO and NO_2, PM is split into different size fractions and carbonaceous species, and VOCs are split into several individual groups and species, including saturated, aromatic and polyaromatic hydrocarbons. GHGs are also calculated, including CO_2, CH_4 and N_2O. The model can also estimate sulphur dioxide and several heavy metal emissions, provided that fuel properties are known,

Exhaust pollutants are classified according to their production mechanism into hot and cold-start ones. Hot emissions (E_{HOT}) are the ones produced after the engine and the emission control system have been thermally stabilized – hence the term 'hot'. The cold-start part refers to the few minutes until the engine has been warmed up. Due to the inefficient combustion and emission control system activity during warm-up, cold-starts result to an extra emission over the hot emission level.

For a given activity level, expressed as total vehicle kilometers travelled (VKT) for the period concerned, hot emissions are calculated by means of equation (1).

$$E_{HOT} = VKT \times e_{HOT} \quad (1)$$

The emission factor (e_{HOT}) in eq. (1) represents the mean emission level of the on-road fleet, and it is expressed in g km^{-1}.

Cold-start emissions are calculated by the expression shown in equation (2). In this, β is the fraction of the total activity before the engine has reached its normal operation temperature, and it is a function of the vehicle technology, the ambient temperature and the mean length of the trip performed by a particular vehicle type. The term in parentheses corresponds to the over emission level compared to the hot emissions.

$$E_{COLD} = \beta \times VKT \times e_{HOT} \times (e_{COLD} / e_{HOT} - 1) \quad (2)$$

Non-exhaust emissions calculated by the software include hydrocarbon emissions resulting from fuel evaporation of spark-ignition vehicles. Evaporation losses can occur through the fuel canister, which is used to vent the fuel reservoir, through the non-metallic fuel lines or plastic fuel reservoir walls, or through losses in fuel line connectors and fittings. In COPERT Australia, evaporation losses are considered to occur from the daily variation in temperature (diurnal), in stationary condition after hot operation (soak) and during vehicle operation on the road (running losses). A specific method is used to estimate the contribution of each part and then total evaporation emissions are calculated following equation (3). Evaporation increases for highly volatile fuels, such as low ethanol blends. Hence they are important in Australia where E10 biofuel blends are used in a number of States.

$$E_{EVAP} = E_{DIURNAL} + E_{SOAK} + E_{RUNNING} \quad (3)$$

A final source of emissions is wear of vehicle components, primarily brakes and tyres. The wear contributes to the total PM generation by the vehicle. Studies have shown that for a typical petrol passenger car, the amount of wear contributing to airborne PM is larger than the contribution of exhaust sources (van der Gon *et al.*, 2013). Hence this should not be ignored in air emission inventories. COPERT Australia does not include emission factors for road surface wear and resuspended road dust, which both depend on the condition of the road rather than the technology of the vehicle. However, these sources need to be taken into account when air quality model results are compared with measurements.

The method also provides functions to calculate the fuel consumption of the individual vehicle types. The total fuel consumption calculated per fuel can then be compared to the official figures of fuel sold in the region as a validation step.

2.2. Emission Factors

In COPERT Australia emission factors are expressed as a function of the mean (travelling) speed. This is defined as the ratio of the distance covered over a certain period of time and is not the spot speed of the vehicle.

Definition of the exact period of time or distance boundaries for which the emission factors are valid is not straightforward. The European version of COPERT has been satisfactorily used and/or validated at a street level (e.g. Gualtieri, 2010), a city level (e.g. Borge *et al.*, 2012), and a country level (e.g. Cai and Xie, 2007).

The hot running and cold start emission factors in COPERT Australia have been developed on the basis of 100 m driving segments (Smit and Ntziachristos, 2012; 2013), using driving profiles representing real-world vehicle operation in Australia. The test data have been made available from various Australian test programmes that were conducted over time. These emissions data have been collated in a verified emissions database with about 2,500 modal emission tests and about 12,500 individual bag measurements, which have been analysed to derive the emission factors used in COPERT Australia.

The range of driving conditions that can result in the same average speed increases as the average speed drops. Hence, the representativeness of emission factors that only take into account average speed and not speed dynamics is compromised at lower speeds. Including driving dynamics (e.g. mean positive acceleration) in addition to average speed in the description of the emission factor may lead to a more precise emission factor value. However, average speed is a straightforward parameter to obtain either from traffic models or from monitoring of street activity, while a universal approach to describe driving dynamics does not exist. Also, monitoring and classifying driving dynamics of a complete fleet across a city road network for a long period of time is cumbersome and costly. Therefore, it seems that average speed is a good compromise between accuracy of emission factor and accuracy of the input data (Smit *et al.* 2010). Research indicates that it can safely been used down to a city level and city segments (Borge et al., 2012).

Application of the average speed emission factors to even higher resolution could be acceptable, but this definitely requires experience and careful consideration by the user to ensure that the modelled driving situations are not too different from the range of situations used to derive the emission factors.

2.3. Vehicle type coverage

The method of COPERT Australia contains emission factors for 223 individual vehicle types. A general catgorization of the individual vehicles is shown in Table 1. Australian data have been used for the large majority of emission factors available. Any gaps have been filled with emission information from the European version of COPERT, considering the equivalencies between the Euro and ADR standards.

2.4. Application to Queensland

The first step in applying COPERT Australia to Queensland was to create the vehicle population input table that reflects the level of detail required for COPERT Australia. Queensland vehicle registration data (TMR, 2013) were used, which provide information on the number of registered vehicles in Queensland by post code and other variables. All registered vehicles that are typically non-road vehicles were removed from the dataset (e.g. mobile machinery), as were all registered vehicles that are not motorised (e.g. boat trailers, horse float trailers). Each vehicle was then attributed to the appropriate COPERT Australia vehicle type using information on vehicle make and model, year of manufacture, registration category, fuel type, number of cylinders, body shape and gross vehicle mass (GVM).

Table 1. Coverage of vehicle types in COPERT Australia

<table>
<tr><th>Category</th><th>Types</th><th>Fuels</th><th>Emission Control Standards</th></tr>
<tr><td>Passenger Car</td><td>Small (<2.0 l)
Medium (2.0-3.0 l)
Large (≥3.0 l)</td><td>Petrol
Diesel
LPG
E10</td><td>Uncontrolled
ADR27
ADR37/00-01
ADR79/00-05</td></tr>
<tr><td>SUV</td><td>Compact (≤4.0 l)
Large (>4.0 l)</td><td>Petrol
Diesel
E10</td><td>Similar to PC
+ADR36
(SUV-L)
+ADR30
(SUV-Diesel)</td></tr>
<tr><td>Light Commercial Vehicle</td><td>GVM ≤ 3.5 t</td><td>Petrol
Diesel</td><td>Uncontrolled
ADR36 (P)
ADR30 (D)
ADR37/00-01
ADR79/00-05</td></tr>
<tr><td>Heavy Duty Truck</td><td>Medium
Heavy
Articulated</td><td>Petrol
Diesel
LPG</td><td rowspan="2">Uncontrolled
ADR30
ADR70
ADR80/00-05</td></tr>
<tr><td>Bus</td><td>Light Bus (≤8.5 t)
Heavy Bus(>8.5 t)</td><td>Diesel</td></tr>
<tr><td>Moped</td><td>2-S
4-S</td><td rowspan="2">Petrol</td><td rowspan="2">Uncontrolled
Euro 1-3</td></tr>
<tr><td>Motorcycle</td><td>2-S
4-S <250 cm^3
4-S 250-750 cm^3
4-S ≥750 cm^3</td></tr>
</table>

The second step was to estimate total VKT activity. VKT cannot be measured directly but can be estimated using different methods including analysis of odometer reading databases, combination of traffic volume and road length data (either from road-based traffic counts or transport models) and household travel surveys. A number of data sources (ABS, 2011; BITRE, 2011) were examined, compared and used to create an estimate of total annual VKT for 2010 for Queensland by main vehicle type. Total VKT estimates were created the main categories in Table 1 (excluding mopeds), split by diesel, petrol and LPG.

Annual mileage is a function of vehicle type and vehicle age. Vehicle utilization curves were sourced from BTCE (1996) and combined with the Queensland vehicle stock table that was created in the first step. The utilization curves were then calibrated to reproduce the total VKT estimates for each vehicle type that were computed in the second step. This ensures that total VKT for the Queensland fleet is equivalent to reported values, and at the same time achieves the required breakdown of annual mileage by main vehicle type, fuel type and ADR category. The calibrated age-mileage relationships are also used to compute accumulated mileage for each COPERT Australia vehicle class.

As a last step the use of ethanol blends (E10) in the petrol light duty fleet was estimated. This was done by considering the total use of E10 in Queensland (DRET, 2010), which is about 22% (mass) of total petrol/E10 use in 2010, as well as consideration of E10 suitability for LDVs by model year. With respect to the last point, Pre-1986 vehicles are not ethanol compatible and practically all post-2003 vehicles are ethanol compatible, with a rising portion of 1986-1998 MY vehicles being ethanol compatible as a function of model year (DEWHA, 2008). A summary of the results of this method is shown in Table 2.

Table 2. Split of total activity by vehicle category and fuel type in the Queensland region.

Type	Petrol	Diesel	LPG	E10
PC-S	16.38%	0.64%	0.27%	4.71%
PC-M	7.38%	0.84%	0.15%	2.15%
PC-L	12.13%	0.13%	1.29%	3.25%
SUV-C	5.29%	0.45%	0.00%	1.56%
SUV-L	4.83%	4.87%	0.00%	1.35%
LCV	8.96%	10.35%	0.84%	2.49%
RT	0.06%	4.17%	0.00%	-
AT	0.00%	3.02%	0.00%	-
BUS-L	0.10%	0.55%	0.10%	-
BUS-H	0.00%	0.24%	0.04%	-
MCY	1.42%	-	-	-

For validation of the overall calculation, fuel consumption data had also to be made available. Fuel consumption or energy data are available from a number of sources (ABS, 2011; BITRE; 2011; DRET, 2010; BREE, 2012). The data have different levels of detail. For instance, the 'Survey of Motor vehicle Use' or SMVU (ABS, 2011) combines petrol and E10 together in a category called "petrol" and does not distinguish between ULP and PULP, whereas DRET (2010) does distinguish between ULP, PULP and E10. The fuel data were first converted to mass units (tonne) using fuel density and lower heating values for each type of fuel. Then financial year data were converted to calendar year data by taking the average of the overlapping financial years (e.g. 2010 is the average of 2009-2010 and 2010-2011 financial years).

The petrol sales and consumption data from DRET and BREE will contain a small fraction that is not used by road transport. BITRE (2011) estimates that this fraction has been relatively constant over time (about 5%). It appears that the SMVU data provides the most accurate total petrol use data for road transport, but APS data have been used to split the SMVU data into ULP, PULP and E10 use for Queensland. Differences in estimated diesel use by road transport from the data sources vary substantially (up to 75%), where SMVU reports the lowest consumption of 9.2 million tonnes of diesel, and BREE and DRET both report 16.2 and 15.5 million tonnes, respectively. The diesel sales and consumption data from DRET and BREE contain a substantial fraction that is not used by road transport. BITRE (2011) estimates that this fraction has increased in time (about 45% in 2007). It appears that the SMVU data provides the most accurate total diesel use data for road transport. Since DRET (2010) provides LPG data specifically for automotive use, and given the small sample size of the SMVU, it appears that DRET provides the most accurate estimate of LPG use for road transport. No data could be found for automotive CNG use in Queensland. BREE (2012) reports CNG and LPG use for road transport in Australia in PJ, which after conversion to tonnes, shows that CNG makes up about 4% of the combined LPG and CNG consumption.

3. Results

COPERT Australia can calculate various results. These include total emissions of different pollutants by vehicle category and vehicle technology, split between different modes of operation (urban, rural, highway), cold-start vs. hot start emissions, etc. In this study, we provide some indicative results that correspond to the area of Queensland for the year 2010. Each annual run with COPERT Australia takes approximately 2 to 3 minutes on a normal PC.

The first point to check when performing a calculation is how much the calculated total fuel consumption by fuel type matches the statistical value provided by the authorities in the area concerned. In our case, the statistical and calculated fuel consumptions did not differ by more than ±5% for gasoline and diesel. Although further refinements would be possible to bring this difference to zero percent (e.g. tuning of the mileage per vehicle category or adjustment of the split between urban driving and other modes), this was not attempted in this paper. However, this is a useful exercise to understand the sensitivity of the model and, presumably, to also improve the input data.

Table 3 shows the percentage contribution of different vehicle categories to key pollutants and total fuel consumption. Most of the activity is conducted by PCs that correspond to more than 1/3 of total fuel consumed in the area. However, vehicle categories contribute differently to the different pollutants. Passenger cars remain the highest contributor to CO and VOC. In particular for VOC, fuel evaporation is a significant source, corresponding to 16% of total VOC emissions from PCs. On the other hand, the diesel dominated heavy-duty truck (HDT) category is the prime contributor to NO_x and PM_{10} emissions. While

HDTs correspond to only ~7% of total activity in the region (Table 2), they produce 45% and 36% of total NO_x and PM_{10}, respectively. It is clear that policies that have to address emissions of these two pollutants should primarily focus on HDTs.

Table 3. Percentage contribution of different vehicle categories to total key pollutant emissions and fuel consumption.

Sector	CO	NO_x	VOC	PM_{10}	FC
PC	49.4	22.4	51.1	25.9	34.8
SUV	14.7	9.20	13.5	6.81	16.2
LCV	27.6	20.1	24.1	28.1	20.0
HDT	2.32	45.3	5.13	35.9	26.3
Bus	0.13	2.66	0.53	2.25	2.06
MCY	5.82	0.42	5.71	0.95	0.61

Figure 1 shows how different emission control categories contribute to total emissions of NO_x for selected vehicle categories. Passenger cars falling into the ADR 37/00 and SUV and LCV falling into the ADR 36 emission control technologies are the single most important contributors of NOx for light duty vehicles. The picture is more or less the same for the other key pollutants. ADR 37/00 represents ~23% of the PC vehicle fleet in Queensland but 47% of total NO_x emissions. This is the result of the reduction in emissions as technology progressively improves. This also shows that efficient policies to limit exhaust emissions should not only focus on introducing stringent new emission control technologies but to also address emissions of the older vehicle stock. Successful examples in this direction include implementation of regular inspection and maintenance schemes, accelerated replacement campaigns by means of financial or taxation incentives and/or retrofitting possibilities, in particular for diesel vehicles.

Nowadays, much attention is given to PM emissions due to their health effect and environmental impacts. Figure 2 shows the relative contribution of exhaust and non-exhaust (tyre and brake wear) sources to total $PM_{2.5}$ and PM_{10} emissions. Non-exhaust sources are important contributors, in particular for PM_{10} where they correspond to almost one third of total emissions.

The higher contribution to PM_{10} than $PM_{2.5}$ is due to the size distribution of non-exhaust particles, which is shifted to larger sizes compared with exhaust PM.

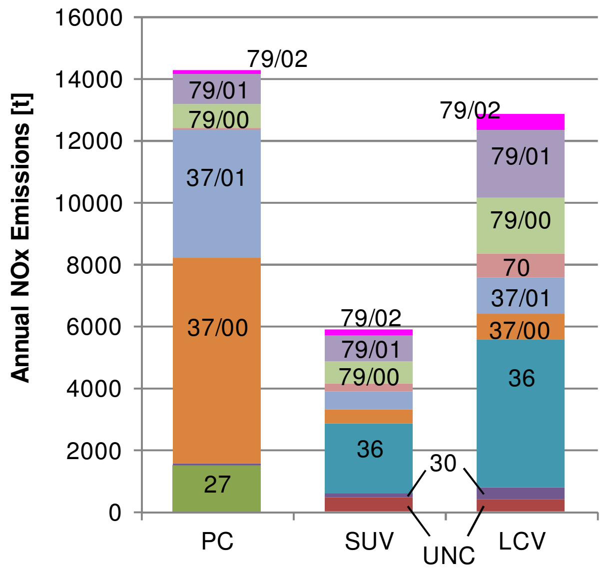

Figure 1. Contribution of different emission control technologies to total NOx emissions for selected vehicle categories.

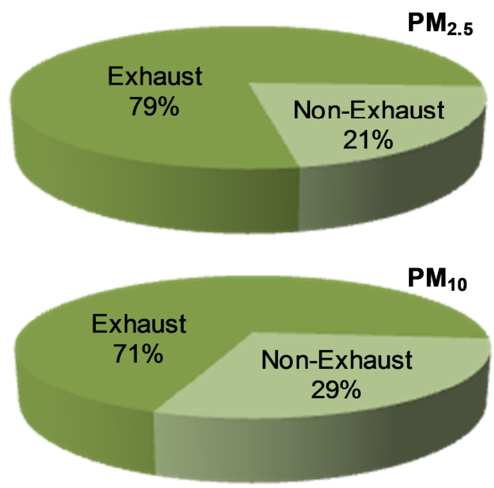

Figure 2. Exhaust and non-exhaust source contribution to $PM_{2.5}$ (top) and PM_{10} (bottom),

4. Conclusions

- A dedicated emission method and software tool for the Australian road vehicle fleet has been prepared and applied to Queensland.
- The tool is able to calculate exhaust and non-exhaust emission sources of practically all relevant pollutants from road transport, including GHGs.
- The contribution of different vehicle categories to emissions depends on the pollutant considered. Diesel vehicles are prime contributors to NO_x and PM, while spark ignition ones mostly contribute to CO and VOC.

- Older vehicle technologies contribute disproportionally to total emissions, because of their relatively high emission levels. Policies that address these emissions may result in a rapid clean-up of the Australian vehicle fleet.

Acknowledgments

The Australian Government is acknowledged for commissioning vehicle emission test programs that have collectively provided the (unverified) empirical emissions data used in this research.

References

ABS, 2011, Survey of Motor Vehicle Use, Australia, 12 months ended 31 October 2010, www.abs.gov.au.

BITRE, 2011. Road Vehicle-Kilometres Travelled: Estimation from State and Territory Fuel Sales, Bureau of Infrastructure, Transport and Regional Economics, Report 124, ISBN 978 1 921769 29 0.

Borge R., de Miguel I., de la Paz D., Lumbreras J., Perez J., Rodriguez E. 2012, Comparison of road traffic emission models in Madrid (Spain), Atmospheric Environment 62: 461-71.

BREE, 2012, Australian Energy Statistics, BREE, Canberra, July 2012, ISSN 978 1 922106 34 6.

BTCE, 1996. Costs of Reducing Greenhouse Gas Emissions from Australian Cars: An Application of the BTCE CARMOD Model, Working Paper 24, Bureau of Transport and Communications Economics (BTCE). ISBN 0 642 24807 9.

Cai H., Xie SD. 2007, Estimation of vehicular emission inventories in China from 1980 to 2005, Atmospheric Environment 41:8963-79.

DEWHA 2008, Evaluating the Health Impacts of Ethanol Blend Petrol, Commonwealth of Australia, Department of Environment, Water, Heritage and the Arts (DEWHA), Final Report KW48/17/F3.3F, June 2008.

DRET, 2010. Australian Petroleum Statistics, Issue No. 173, December 2010, Department of Resources, Energy and Tourism (DRET), ISBN 978 0 9808716 4 7.

EEA (European Environment Agency) 2012, 'National emissions reported to the Convention on Long-range Transboundary Air Pollution (LRTAP Convention)', Results available online at www.eea.europa.eu.

Gualtieri G. 2010, A Street Canyon Model Intercomparison in Florence, Italy, Water Air and Soil Pollution 212:461-82.

Lonati G., Giugliano M., Cernuschi S. 2006, The role of traffic emissions from weekends' and weekdays' fine PM data in Milan, Atmospheric Environment 40:5998-6011.

NSW EPA (New South Wales Environmental Protection Agency) 2012, 'Air Emissions Inventory for the Greater Metropolitan Region in New South Wales'. Technical Report No. 1.

Ntziachristos L., Gkatzoflias D., Kouridis C., Samaras Z. 2009, 'COPERT: A European Road Transport Emission Inventory Model' In Athanasiadis et al. (eds.) 2009, Information Technologies in Environmental Engineering, p.491-504.

Pereira G., Cook A.; de Vos AJBM., Holman CDJ. 2010, 'A case-crossover analysis of traffic-related air pollution and emergency department presentations for asthma in Perth, Western Australia', Medical Journal of Australia 193:511-4.

Rao V., Tooly L., Drukenbrod J. 2013, '2008 National Emissions Inventory: Review, Analysis and Highlights', US Environmental Protection Agency report No. EPA-454/R-13-005.

Smit R., Ntziachristos L. 2012, COPERT Australia: Developing Improved Average Speed Vehicle Emission Algorithms for the Australian Fleet, Proceedings of the 19th International Transport and Air Pollution Conference, Thessaloniki, 2012.

Smit R., Ntziachristos L., Boulter P. 2010, Validation of road vehicle and traffic emission models - A review and meta-analysis, Atmospheric Environment 44:2943-53.

Smit, R., Ntziachristos, L. 2013, Cold Start Emission Modeling for the Australian Petrol Fleet, Air Quality and Climate Change, 47 (3), submitted for publication.

TMR, 2013. Vehicle registrations, Department of Transport and Main Roads, Queensland Government, available at https://data.qld.gov.au/dataset/vehicle-registrations/resource/adce3f5d-b6b8-4cce-880a-c3197a24d1ed, accessed 22 April 2013.

van der Gon HACD, Gerlofs-Nijland ME, Gehrig R, et al. 2013, 'The Policy Relevance of Wear Emissions from Road Transport, Now and in the FutureAn International Workshop Report and Consensus Statement', Journal of the Air and Waste Management Association 63:136-49.

Zhu Y.F., Hinds W.C., Kim S., Shen S., Sioutas C. 2005, 'Study of ultrafine particles near a major highway with heavy-duty diesel traffic',