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**TAMT**

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***Transport  
Activity  
Measurement  
Toolkit***  
*for on-road vehicles*

*Practitioners' Guide*

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## **Disclaimer**

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## **Version**

The version of the TAMT appliance described in this Practitioners Guide is Beta-1.0 available at <http://code.google.com/p/tamt/>. This open source software can be expected to undergo continual improvements and changes which may not be reflected in the text of this Guide. The issues list available on <http://code.google.com/p/tamt/issues/list> should indicate those changes that have been incorporated.

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## Acronyms and Abbreviations

ANPR	Automatic number-plate reader
ASCII	American Standard Code for Information Interchange
ASIF	Emissions decomposition based on travel activity, modal shares, energy intensity and the emissions factors for each fuel
BRT	Bus Rapid Transit
CDM	Clean development mechanism
CER	Certified emission reduction
CH <sub>4</sub>	Methane
CO	Carbon monoxide
CO <sub>2</sub>	Carbon dioxide
COPERT	European Computer program to Calculate Emissions from Road Transport
EEA	European Economic Area
EFFECT	Energy forecasting Framework and Emissions Consensus Tool
EU	European Union
EU-15	EU-15 area countries are: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden and United Kingdom
EU-27	EU-15 area countries plus: Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia
EURO	Refers to the European emission standards
FAA	US Federal Aviation Administration
FKT	Freight-tonne kilometers traveled
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GPS	Global Positioning System
HC	Hydrocarbons
HD	Heavy Duty vehicles
HDB	Heavy-duty buses
HDC	Heavy-duty commercial vehicles
I&M	Vehicle Inspection and Maintenance
IDE	Integrated development environment
IPCC	Intergovernmental Panel on Climate Change
IVEM	International Vehicle Emissions model
LDV	Light-duty passenger Vehicles (Pickups, vans, SUVs)
LDC	Light-duty commercial Vehicles
M&E	Monitoring and Evaluation
MDB	Medium-duty minibuses
MOBILE	US-EPA Vehicle Emission Modeling Software
MOVES	US-EPA next-generation Motor Vehicle Emission Simulator
MRV	monitoring, recording and verifying
MVO	Moving vehicle observer
NAMA	Nationally Appropriate Mitigation Action
NMEA	National Marine Electronics Association
NMT	Non-motorized transport
NO <sub>x</sub>	Nitrous Oxides
O-D	Origen-Destination
PC	Passenger Car

PKT	Passenger kilometers traveled
PM	Particulate Matter
QA/QC	quality assurance/quality control
SOx	Oxides of Sulphur
SQL	Structured Query Language for accessing databases
SUV	Sports Utility Vehicle
TAMT	Transport activity measurement toolkit
TX	Taxi
UNFCCC	United Nations Framework Convention on Climate Change
US-AEP	US-Asia Environmental Partnership
US-EPA	US Environmental Protection Agency
UTC	Coordinated Universal Time
VER	verifiable emission reduction
VKT	Vehicle kilometers travelled
VOC	Volatile Organic Carbon compounds
W2 (or 2W)	Two-wheeler motorized vehicles
W3 (or 3W)	Three-wheeler motorized vehicles

### *Why is vehicle activity so important to climate change and to local air quality?*

In 2008, for the first time in history, more than half the world's population -- 3.3 billion people -- lived in urban areas. Over the next 20 years, this number is expected to jump to an unprecedented 5 billion urban inhabitants, mostly in the developing world. This increasing urbanization will be most notable in Africa and Asia where the urban population is expected to double by 2030.

Although urbanization is frequently cited as a major cause of greenhouse gas and local air pollution emissions growth, it could be better understood as one of the crucial links between climate and development. Urbanization is a major driver of development and once in cities, people tend to increase their mobility dramatically, driving an increase in greenhouse gas and other emissions from transport.

The demand for transport is not limited only to urban environments<sup>1</sup>. As each economy becomes richer its demand for passenger and freight mobility increases. Even in Europe<sup>2</sup> where people are seen to be enjoying a generally stable and elevated standard of living, passenger transport (expressed in passenger-kilometers per annum) continues to grow particularly in aviation and cars. This increase in car usage coupled with a tendency to have a lower number of passengers per car, has been sufficient to offset the improvements gained in vehicle fuel efficiency over recent years.

As we shall see in this section, passenger and freight transport demand in Europe continues to grow at an accelerated pace. For developing countries, which currently have an unsatisfied demand for both passenger and freight transport, even greater growth rates in passenger and freight transport demand can be expected over the coming decades.

This accelerated growth is particularly problematic for on-road transport. The increasing transport demand—often evidenced in private motorization—if not accompanied by adequate growth in infrastructure and facilities, leads to rising congestion, time loss, and air quality deterioration that can stifle economic growth and quality of life. However, developing more road space and infrastructure can in fact worsen the problem allowing private vehicle usage to expand to fill the available space. Additionally, private-vehicle-centric development can easily lock-in the economy to a high carbon pathway that can be difficult to change in future years.

Finding the delicate balance of policy options to achieve long-term improvements in on-road transport and reduce the impact of its externalities is critical and needs to be tailored to

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<sup>1</sup> See Box 1 for a description of how passenger and freight movement is often analyzed by location and by mode

<sup>2</sup> The data and graphs on the EU in this section are taken from EU Report 1 / 2008, Climate for a transport change, TERM 2007: indicators tracking transport and environment in the European Union

each locale. This requires measurements both to design the interventions and evaluate their impacts. This transport activity measurement toolkit (TAMT) has been developed specifically to simplify this measurement process by providing a standardized software<sup>3</sup>, data collection forms, and a consistent standardized methodology, as explained in this guide.

## Passenger mobility

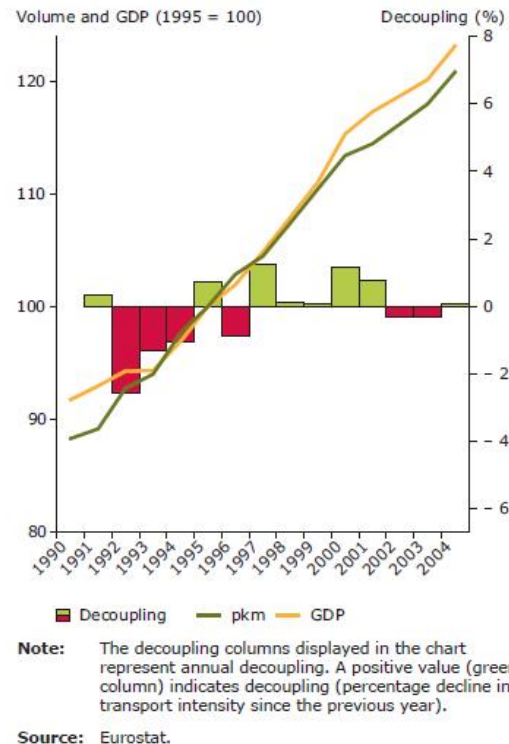


Figure 1 - EU Passenger transport continues to increase

Figure 1 shows how, over the 14 years, from 1990 to 2004, the increase in passenger-kilometers in Europe has been slightly less than GDP. Partly this is because car ownership levels are stabilizing. In 2005, the average car ownership level in the 32 European Economic Area (EEA) member countries reached 460 cars per 1,000 inhabitants, compared with 335 in Japan and 777 in the USA. However in most developing countries, current car ownership levels are considerably lower as can be seen in Figure 2 and are growing much faster as these economies aspire to a "Western" standard of living and thus very substantial increases in passenger car (and motorcycle) ownership and passenger-kilometers travelled can be expected in these countries.

<sup>3</sup> This is referred to as the TAMT Appliance or TAMT.

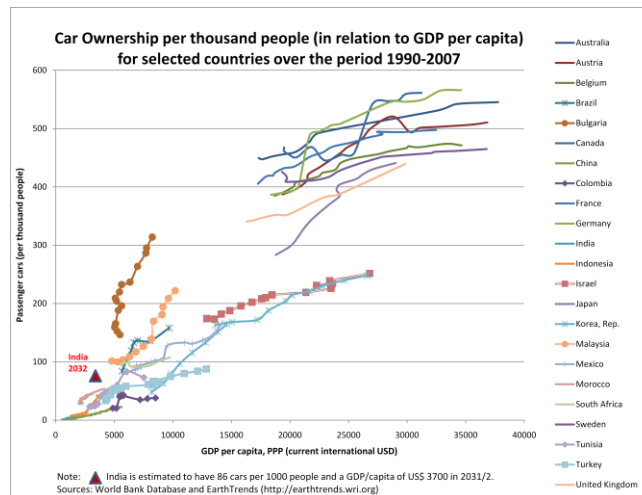


Figure 2 - Car Ownership in relation to GDP per capita in selected countries

### Freight mobility

For freight, a similar situation exists. Even in Europe, freight transport is growing faster than the economy as can be seen in figure 3. Freight transport is measured in freight tonne-kms per annum and as can be seen in Figure 4, even in Europe where rail transport is well established, the modal share of on-road freight transport continues to grow.

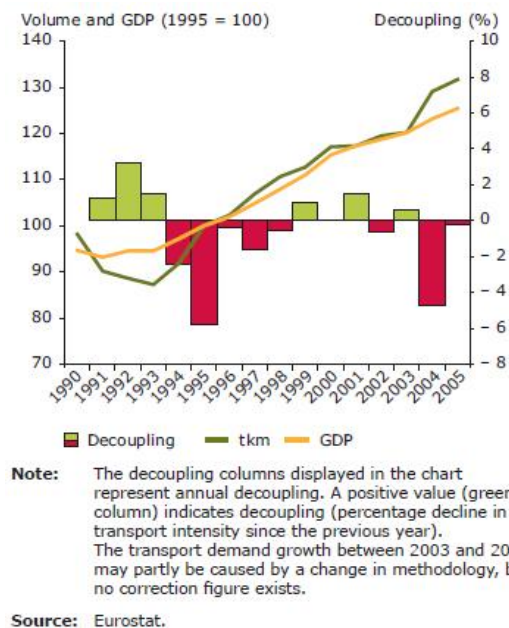


Figure 3 - EU Freight transport growth outpaces economic growth

Again, in many developing countries where the rail and other freight transport infrastructure is insufficient, slow and/or already operating near capacity, higher relative growth rates for on-road freight transport may be expected.

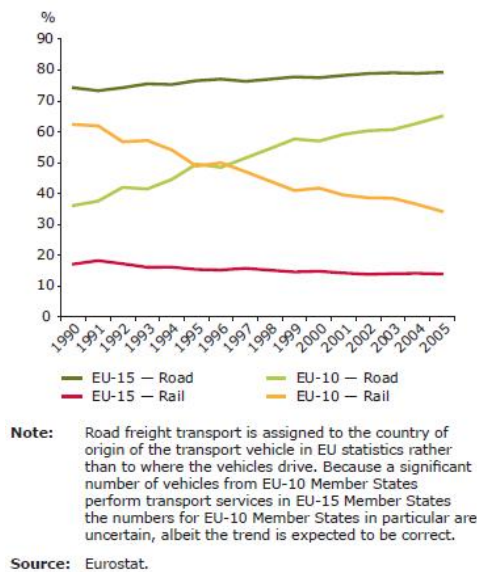


Figure 4 - The EU modal share road in freight transport continues to grow.

This high growth in on road passenger and freight transport, can lead to congestion, increased travel time, and increased emissions of both greenhouse gases and local air pollutants.

### *GHG emissions from the Transport Sector*

On the global level, the transport sector currently generates nearly one quarter of worldwide energy-related CO<sub>2</sub> emissions, accounts for about 19% of energy use, and is the sector most closely linked to fossil fuel consumption. Over the period from 1992 to 2004, global emissions of CO<sub>2</sub> increased by 27% but energy demand from the transport sector which is an indicator of global transport emissions, increased by 37% of over the same period. Whilst the rate of growth of transport demand, energy consumption, and greenhouse gas emissions is highest in developing countries, even in developed economies - such as the European Union -- transport energy use is growing faster than the overall economy. Figure 5 shows how greenhouse gas emissions from transport increased by more than 27 % between 1990 and 2005 in EEA member countries. EU-15 Member States are responsible for 83 % of the total (not including international aviation and maritime transport). This increase in emissions has occurred even though vehicle fleets are becoming more efficient. Thus the increased volume of transport has caused the increase in emissions. Over the same period, total greenhouse gas emissions in the EU-27 fell by 7.9 percent. China, on the other hand, is the country that saw the fastest increase in transport demand, energy consumption, and greenhouse gas emissions with CO<sub>2</sub> emissions and energy demand growing 108% and 168% respectively over the same period.

Of this global energy use, approximately three quarters were consumed by on-road motorized transport [50% by passenger and 24% by freight].

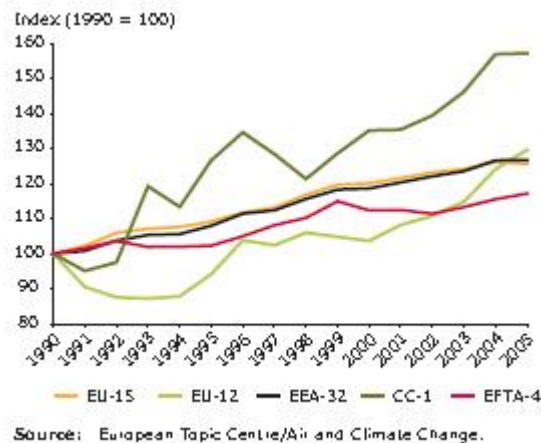


Figure 5 - Trend in GHG emissions from transport in the EU (1990-2005)

Whilst Figure 5 shows an increase in greenhouse gas emissions from transport in some EU countries of up to 50% between 1990 and 2005, in many developing countries the increase is, and will be, far greater. In a study conducted by the World Bank for nine East Asian cities<sup>4</sup> a projected increase in greenhouse gas emissions from on road transport of 142% was forecast between 2007 and 2020 under a business as usual development scenario as shown in Figure 6. Opportunities were identified that if implemented would reduce this increase to only 50% through investing in various abatement measures such as improving the supply of public transport, applying traffic demand management techniques, promoting the uptake of higher technology vehicles, and making changes in land use and land use planning amongst other measures.

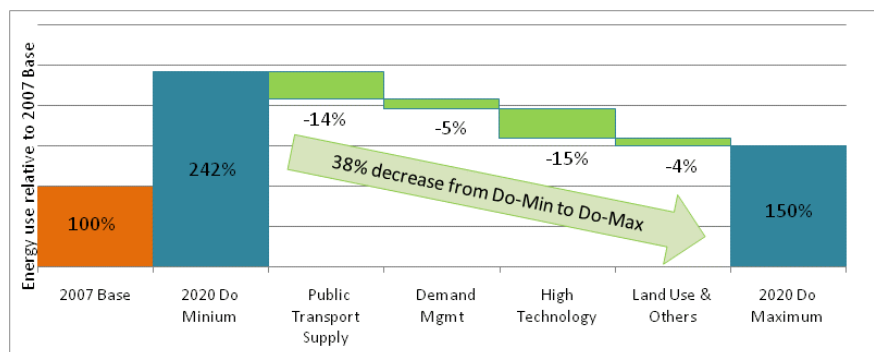


Figure 6 - Projected increase in GHG missions in 9 East Asian cities

## Local pollutant emissions from the Transport Sector

Whilst the problem of increasing greenhouse gas emissions from vehicles has only recently been recognized, the problem of local pollutant emissions from vehicles has long been considered a problem. Since 1992, increasingly strict legislation has applied to the emissions from new vehicles in the EU covering carbon monoxide [CO] Nitrous oxides [NOx] hydrocarbons [HC] and particulate matter [PM]. In the US, Federal "Tier 1" regulations went

<sup>4</sup> The cities included in this study were Bangkok, Beijing, Chengdu, Guangzhou Hanoi, Ho Chi Minh City, Jakarta, Manila and Ulaanbaatar.

into effect starting in 1994, and tighter "Tier 2" standards have been phased in from 2004 to 2009. Under these standards cars and light trucks [SUVs, pickups, and minivans] are treated differently under certain standards.

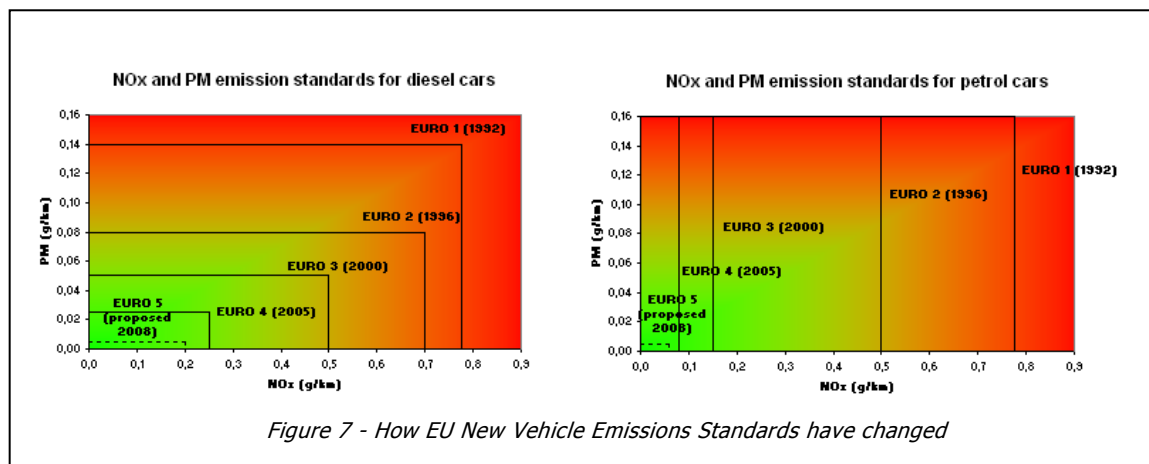


Figure 7 gives an indication of how far new vehicle emissions standards have advanced in the EU. Similar advances have been made in the US standards. In both, the reduction in tailpipe emission of local pollutants has been sufficient to "solve" the problem of local air quality by more than off-setting the increase in vehicle usage. Figure 8 shows the resultant trends in local pollutant emissions from transport which takes into account the time required for new-vehicle technology to be adopted by the in-use vehicle fleet through vehicle renewal and fleet growth.

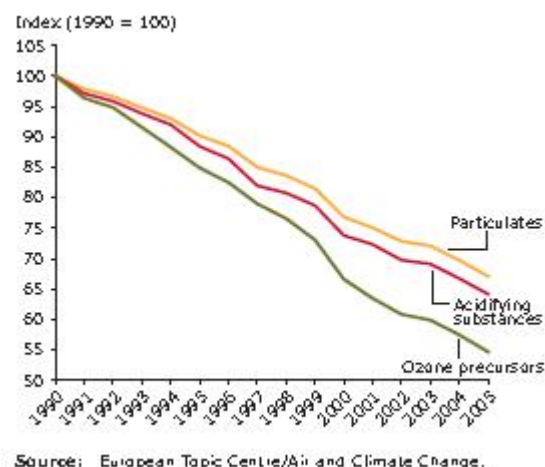


Figure 8 - Trend in Local Pollutant emissions from transport in the EU (1990-2005)

As can be seen in Figure 8, the net result of applying strict tailpipe emission legislation has been that despite the increased vehicle fleet and increased mileage per vehicle per year, the emissions from the total active in-use fleet have dropped by more than half over the 15 years from 1990 to 2005.

Over the same period the CO<sub>2</sub> emissions from these vehicles has increased driven by the consumer desire for larger, heavier, and more powerful vehicles and coupled to the increase vehicle ownership and use.



## *The need for measurement of vehicle activity*

There is an old engineering adage that you cannot improve something that you are not measuring. This is particularly true for on-road transport emissions, and our desire to reduce both global and local emissions highlights the need to be able to accurately measure them, and detect and monitor changes over time. Whilst for other sources of emissions like power plant smokestacks it is possible to go and measure the output of each, the vast number of vehicles, operated under different driving styles and conditions, makes such measurement techniques impossible and requires statistics and sampling techniques to be used. The process is further complicated by the fact that the "do nothing" or "business as usual" scenario involves vehicle emissions constantly changing over time due to changes in the size and characteristics of the vehicle fleet, in vehicle owners' driving habits, and in the driving conditions that these vehicles find on the routes that they commonly use.

Vehicle activity measurements have many practical applications towards analyzing development pathways and options, defining policy packages, designing interventions, and determining the outcome of each. Whilst the measurement techniques can be the same, different levels of precision may be required for different projects. In some, such as the UNFCCC CDM, low levels of uncertainty are essential whilst for others, directional guidance (that indicates if a situation is improving or deteriorating) may be all that is required.

Examples of the use of vehicle activity measurements include:

- **Traffic and transport modeling** require vehicle activity measurements to calibrate the models to local conditions. This can cover the complete spectrum from national-level proposals, through city-level master plans, to local area, traffic light synchronization projects.
- **Air Quality Management.** The determination of emissions inventories is an essential first step in developing improvements in local air quality. Here, all critical sources must be adequately included for a cost effective selection of control measures to be designed. In many regions, on-road transport can be the largest source of emissions and often it is the fastest growing
- **Low carbon development planning** studies need vehicle activity measurement to define their baseline reference scenario and evaluate low carbon options. Effective low carbon development involves prioritizing actions and investments across all sectors of the economy and often on-road transport is a critical part of the problem that additionally offers many low marginal abatement cost options to reduce greenhouse gas emissions.
- **Nationally Appropriate Mitigation Actions (NAMAs)** in on-road transport and Kyoto accord **clean development mechanism** (CDM) projects require monitoring, recording and verification (MRV) of emissions derived from vehicle activity both to define the baseline reference case, measure the impact of the different intervention levers that are activated, and determine the resultant certified, of verifiable, emission reductions (CERs and VERs) for credit.
- **Investment project appraisal** can also require evaluation—to varying levels of uncertainty—of the project outcomes where changes in vehicle activity directly impact congestion, travel time, and local and global emissions.

## *What is in this Guide?*

The purpose of this practitioners guide is to give practical advice on how such measurements can be made, the techniques that can be used, and the frequency and location of such measurements.

This guide is intended to provide useful advice for anyone who is looking to perform vehicle activity measurements with or without using the TAMT Appliance. It does however, also provide a users-manual for the TAMT Appliance.

The guide starts off in **Chapter 1** by discussing factors that influence motor vehicle emissions and how they can be determined. **Chapter 2** introduces the concept of link-based emissions measurements and the transport activity measurement toolkit (TAMT). **Chapter 3** goes into detail on the TAMT Appliance; how it is designed, how to install and run. **Chapter 4** discusses the definition of the project boundary and zones. This theme continues in **Chapter 5** that looks at road hierarchy and commercial, industrial, and residential sub-zones. **Chapter 6** discusses different methods used in traffic counts and how the TAMT Appliance uses this data. **Chapter 7** offers different ways to measure vehicle driving speed and drive cycle whilst **Chapter 8** specifically looks at how GPS loggers can be used in conjunction with the TAMT Appliance to accomplish this task. **Chapter 9** leads us through the output reports available from the TAMT Appliance. This is followed by **Chapter 10** that introduces the need for determining the in-use vehicle fleet characteristics and how this can be achieved. **Chapter 11** looks at the practicalities of how to calibrate emissions and fuel consumption factors to local conditions whilst **Chapter 12** introduces cold start emissions and how to derive cold start information. **Chapter 13** evaluates the linkages between vehicle activity and passenger and freight movements. **Chapter 14** looks at fieldwork; quality control, quality assurance, and best practices on how to conduct surveys and data processing. Finally **Chapter 15** gives a set of sample forms that can be used in sampling which link to an attached multi-lingual spreadsheet.

This document also has five appendices:

Appendix A reviews commonly used fuel-use and local emissions models;

Appendix B gives the level of disaggregation needed for emissions factor determination;

Appendix C gives a description of the EFFECT model; and

Appendix D gives an all-important summary of the method of evaluating and expressing the uncertainty of measurement results that should be used in all survey work.

### ***Box 1:- Location and Mode***

The movement of passengers and freight is often analyzed by location and by mode. Location refers to urban, rural, and Inter-city and Long-distance transport, whilst mode refers to the type of transport used. Whilst this Practitioners' guide focuses on on-road transport, it is useful to put this in the context of other transport modes to assure a common nomenclature:

#### ***Location***

**Urban** covers passenger and freight transport internal to built-up areas, including trips having at least one end in the built-up area. Typically it consists of short trips (up to around 15 km).

**Rural** transport is passenger and freight transport in low-density areas (i.e. as opposed to urban transport). It is mainly concerned with the local road network used for any purpose (including passenger trips, and by freight pick-up and delivery). This distinguishes it from inter-city and long distance which use the primary multimodal network. It often addresses issues relevant to the equity and accessibility.

**Inter-city and Long-distance** covers passenger and freight transport over longer distances by rail, road, air, and waterborne transport. It requires large-scale, long-distance transport infrastructure such as expressways and highways, high-speed rail links, airports, shipping terminals, and pipelines. It includes the movement of passengers and freight between urban agglomerations and with their surrounding economic watershed areas.

#### ***Mode***

**On-road** covers all transport which runs exclusively or principally on roads. 'Roads' include all forms of thoroughfare ranging from a track to a highway, as well as associated infrastructure (bridges, cuttings, tunnels, parking areas, etc). On-road includes systems such as Bus Rapid Transit (BRT) that uses segregated roadways, as well as vehicles that share common road space.

**Non-motorized transport (NMT)** modes include walking and cycling and often share the same infrastructure as on-road transport, however good design and implementation caters to their specific needs with unobstructed pavements, road crossings, defined pedestrian zones, dedicated bike paths, and last but not least, separated bike lanes and secure parking facilities.

*Other transport modes include:*

**Rail** transport which can be further subdivided into heavy rail, light rail, tram, metro. Whilst heavy rail is principally used for inter-city and long distance transport including commuter services to the large urban areas, light rail, tram and metro are typically used within such urban areas.

**Air** includes all airborne passenger and freight movements. The focus is on commercial aviation relying on dedicated airport infrastructure and air traffic management systems.

**Waterborne** consists of maritime transport, short-sea shipping, inland navigation, estuarial shipping, and support facilities.

## *Introduction*

### *Looking at the factors that influence motor vehicle emissions*

Motor vehicle emissions consist of a large number of pollutants resulting from different processes. The most commonly considered are exhaust emissions, which result from fuel combustion and are emitted from the vehicle exhaust tailpipe.

Key pollutants of concern from exhaust emissions include Carbon Monoxide (CO), Carbon Dioxide (CO<sub>2</sub>), Hydrocarbons (HC), Oxides of Nitrogen (NO<sub>x</sub>), Oxides of Sulphur (SO<sub>x</sub>), Particulate Matter (PM), air toxics (for example: 1,3-butadiene, benzene, formaldehyde, etc.) and visibility reducing species (e.g., ammonia, sulfates, PM<sub>2.5</sub>, etc). CO<sub>2</sub> is the principal greenhouse gas that causes global warming.

Carbon Monoxide and Carbon Dioxide result from the oxidation of the carbon in the vehicle fuel, and once in the atmosphere the CO oxidizes into CO<sub>2</sub>, thus the ultimate amount of CO<sub>2</sub> that will be emitted can be determined from the amount of fuel consumed and the carbon content of that fuel via carbon mass balance. Similarly the Oxides of Sulphur emitted from the vehicle's exhaust pipe are determined exclusively by the amount of Sulphur in the fuel consumed.

However for the other pollutants, it is not so easy since the amount emitted varies considerably according to the engine's technology, the instantaneous operating conditions of the engine and the vehicles exhaust after-treatment devices installed. For example, NO<sub>x</sub> is principally generated when the engine is operating with a lean fuel/air mix at high temperatures and pressures whilst PM is mainly generated whilst the engine's rotational speed is increasing and/or when it is operating with an instantaneously rich fuel/air mix. The emission of all these other pollutants cannot be directly related to fuel consumed since they depend on the operating conditions (or drive cycle) of the vehicle.

In addition to exhaust emissions, there are a variety of evaporative emission processes from motor vehicles. Evaporative emission processes are solely limited to Hydrocarbons. These evaporative processes include:

- **Running evaporative emissions** - Evaporative emissions from liquid or vapor fuel leaks occurring while the engine is operating.
- **Hot soak emissions** - Emissions occurring due to volatilization of fuel in the fuel delivery system following engine shut-off. Residual engine heat volatilizes the fuel.
- **Diurnal emissions** - Emissions from the vehicle fuel tank due to higher bulk liquid temperatures and fuel vapor pressure. These result from rising ambient temperatures heat input from the vehicle's exhaust system, or heat reflected from the road surface.
- **Resting evaporative emissions** - Evaporative emissions other than hot soak, diurnal, and refueling emissions that occur while the engine is not operating. Resting losses occur primarily from fuel leaks and permeation of vapor through fuel lines.

Cold starts are engine starts that occur when the engine temperature is below that at which the catalyst starts to operate (light-off threshold, roughly 300°C) or before the engine reaches its normal operation temperature for non-catalyst equipped vehicles. These have higher CH<sub>4</sub> (and CO and HC) emissions.

Over-emission occurs not only because of the low catalyst conversion efficiency but also because most gasoline engines are designed for fuel enrichment to improve drivability during cold start conditions. Depending on the vehicle technology and temperature, conventional gasoline engines can emit more than 3 times the CO under cold-start conditions than normal hot running. VOC levels can be almost 3 times hot-running levels and the fuel consumption can be fifty percent higher, all albeit for a relatively short period of 180-240 seconds.

The cold start emission factors should therefore be applied only for this initial fraction of a vehicle's journey (up to around 3 km) and then the running emission factors should be applied. Cold start additional emissions may be important to consider if the vehicle has been stationary (with the engine turned off) for more than 30-60 minutes. Total emissions are calculated by summing emissions from the different phases, namely the thermally stabilized engine operation (hot) and the warming-up phase (cold start).

Evaporative emissions are also caused during refueling by the displacement of air from the vehicle's fuel tank. While the vehicle is the source of the emissions, they occur while the vehicle is stationary and at known locations, such as gasoline stations and are typically classified as an area source emission rather than a vehicle emission.

There are also additional sources of PM emissions from motor vehicles. The largest of these is entrained road dust, which is dust picked up by the vehicle tires and suspended in the air by the wake turbulence from the vehicle. Entrained road dust emissions are treated as an area source. Other non-exhaust PM sources include tire wear and brake wear. These sources are typically insignificant compared to exhaust PM and entrained road dust and, therefore, are sometimes omitted from emission inventories.

The generic equation to calculate vehicle emissions is the following:

$$Emission = \sum_{a,b,c,d} (Distance_{a,b,c,d} \times Emissions\ Factor_{a,b,c,d}) + \sum_{a,b,c,d} C_{a,b,c,d} \quad (1)$$

Where:

Emission = emission (g)

Emissions Factor<sub>a,b,c,d</sub> = emission factor (g/km)

Distance<sub>a,b,c,d</sub> = vehicle distance travelled (VKT in km) during thermally stabilized engine operation phase for a given mobile source activity (km)

C<sub>a,b,c,d</sub> = additional emissions during warm-up phase (cold start) (g)

a = fuel type (e.g., diesel, gasoline, natural gas, LPG)

b = vehicle type

c = emission control technology (such as uncontrolled, catalytic converter, etc.)

d = operating conditions (e.g., urban or rural road type, climate, or other environmental factors)

Both the Emissions Factors and the Additional Emissions from cold start can be directly measured under the specific operating conditions for the vehicles in-use in a study area, but

this is not generally recommended due to high cost per test involved and the large sample size needed to obtain statistically significant results over many vehicle types. However, for projects that focus on one type of vehicle (such as, for example in Bus Rapid Transit (BRT) involving a high capacity bus operating on a segregated corridor), local measurements may be obtained for that predominant vehicle type.

Usually Emissions Factors and the Additional Emissions from cold start are obtained from emission models such as the US-EPA MOVES or MOBILE models, or the EEA's COPERT model. These emission factor calculations contained in these models are derived from empirical testing of many thousands of vehicles over different drive cycles and include detailed fleet models that enable a range of vehicle types and control technologies to be considered. The use of emission models can help to ensure consistency and transparency because the calculation procedures are well defined.

The cold start emissions can be quantified in different ways. MOBILE gives additional emissions per start. This is added to the running emission and so requires knowledge of the number of starts per vehicle per year. This can be derived from knowledge of the average trip length. The European model COPERT has more complex temperature dependant corrections for the cold start emissions. A description and comparison of these most commonly used emissions factor models is given in Appendix A.

Due to the complexity and steep learning curve of the US-EPA models, The University of California at Riverside along with Global Sustainable Systems Research was commissioned to develop a simpler "light" version called the "International Vehicle Emissions model" (IVEM). The IVEM model was designed to estimate emissions inventories from motor vehicles in developing countries. It was originally developed to assist these countries in:

- Policy scenario analysis
- Focus control strategies and transportation planning;
- Predict how different strategies affect local emissions.

IVEM is an easy way to go if the vehicle fleet is predominantly of US technology whilst COPERT has the advantage of producing emissions factors for European emission-standard vehicles, which are the technological point of reference for most developing countries. Accordingly, the World Bank incorporated COPERT speed-sensitive emissions factor formulae into its Energy forecasting Framework and Emissions Consensus Tool (the EFFECT model) which has been used, so far, in the India and Brazil low carbon growth studies to look at future emissions from on-road transport and in China, Indonesia, Mongolia, Philippines, Thailand, Vietnam.

The EFFECT model's on-road transport module goes beyond emissions inventory estimation and evaluates how emissions could be expected to change over a typically 20-30 year period based on different scenarios of policy actions.

The application of COPERT within the EFFECT model calculates and uses emissions factors for over 250 types of vehicles under different running conditions, binned into 5kph or 10kph speed bins. For each vehicle type, the resultant emissions factors (for CO, CO<sub>2</sub>, HC, NO<sub>x</sub> and PM) take into account the following variables:

- Ambient monthly temperature
- VKT fraction by speed group
- Average trip length
- Grade and load (Heavy Duty (HD) vehicles only)



- Accumulated mileage degradation
- Number of trips per day
- Biofuel mix

A full description of this emissions factor model is given in Appendix A - Fuel-use and Local Emissions Models.

### Methodological Approach - The ASIF Decomposition

The relationship that is the basis of many methods to determine global and local emissions from passenger travel and freight can be formalized, mathematically, as follows:

$$G = A * S_i * I_i * F_{i,j}$$

where:

**G** is the emissions from the particular transport sector,

**A** is total travel or freight activity (in passenger- or ton-kilometers),

**S** is a vector of the modal shares,

**I** is the modal energy intensity of each mode *i*.

**F<sub>i,j</sub>** represents the emissions factors for each of the fuels *j* in mode *i*,

As can be seen, this differs from Equation 1 in that it calculates global and local emissions from passenger and freight travel activity (in passenger-kilometers and ton-kilometers) instead of vehicle activity (in vehicle-kilometers).

Each of these terms responds—at different rates—to different underlying forces (incomes, prices, policies, new technologies, and so forth). The modal energy intensity term itself is composed of several components:

$$I_i = E_i * \frac{1}{U_i} * \frac{1}{O}$$

where:

**E<sub>i</sub>** is the technical efficiency of mode *i* (the energy consumed per capacity ton- kilometer),

**U<sub>i</sub>** is the capacity utilization coefficient, and

**O** is the operational optimum coefficient.

**E** itself can be split into an **eN**gine and a **M**otive intensity component. The former, **N**, describes the amount of energy input to produce a given amount of power at the engine flywheel. The latter, **M**, refers to the amount of engine flywheel power needed to produce a capacity ton- or person-kilometer.

Clearly, this latter component is related to various characteristics of the vehicle. Note that **M/U<sub>i</sub>** provides an indicator of how *capacity* intensive a given vehicle fleet is, that is, how appropriate the sizes of the vehicles are to the tasks to which they are put. Determining the loading of the vehicle (in passengers or freight-tonnes) and the vehicles' load capacity is important to be able to relate freight ton- and person-kilometers to vehicle-kilometers and forecast the future vehicle usage that would be required to mobilize future transport needs.

The Box "Methodological Approach - The ASIF Decomposition" gives a more specific decomposition that is the basis of many methods to determine global and local emissions from passenger travel and freight. When a transport model is used--and has been calibrated by an extensive origin-destination (O-D) survey-- the basis of the travel estimation and thus the basis of the emissions estimation is the number of passenger- and freight-tonne-

kilometers transported--the "A" in "ASIF". However, when the emissions inventory is survey-based, it is often easier to survey vehicle movement than passengers and freight movement by mode and link and the formula is re-expressed in terms of vehicle activity. The relationship between vehicle movement and passenger and freight movement still has to be established though. This is done by surveying occupancy (passengers and tonnes of freight transported per vehicle) and compared against the capacity of each vehicle to determine the load factor of each. This calculation should include "dead-heading" when the vehicle runs empty, and both peak and off-peak operation.

$$PKT = \sum_i VKT_{p,i} \times PPV_i \quad (2)$$

$$FKT = \sum_i VKT_{f,i} \times TPV_i \quad (3)$$

where:

PKT = Passenger kilometers traveled  
 FKT = Freight-tonne kilometers traveled  
 VKT = Vehicle kilometers traveled  
 PPV = Passengers per vehicle  
 TPV = Freight tonnes per vehicle  
 i = vehicle type

Thus when forecasting emissions the following sequence is often used;

1. Survey vehicle activity in the base year. Survey vehicle occupancy.
2. Calculate passenger- and freight-tonne-kilometers transported in the base year
3. Forecast changes in passenger- and freight-tonne-kilometers transported by mode over the forecast period
4. Convert to vehicle activity in each forecast year, based on projected vehicle occupancy ratios and changes in vehicle capacity.

### *How can you determine GHG and local emissions from on-road transport?*

There are two basic overall approaches that can be used (see Table 1), often in conjunction.

The **top-down approach** calculates greenhouse gas and local emissions from the amount of fuel consumed. This approach gives an accurate estimation of CO<sub>2</sub> and SO<sub>x</sub> emissions because both are directly related to the amount of carbon and/or sulfur in the fuel. It does not do a good job for the other local pollutant emissions, which depend far more on the vehicle technology and specific drive cycle under which they are used. This top-down approach is particularly useful for large study areas where the border effects are small or negligible. For example, in a country where cross-border traffic is negligible as compared to the traffic within the country, determining the transport-related CO<sub>2</sub> emissions from fuel sales is a valid approach and recommended by the UNFCCC. However, as study areas become smaller this approach becomes less valid. For a metropolitan area, it is hard to ignore: (i) the effect of fuel that is purchased within the area being used by vehicles outside of that area; and (ii) the amount of fuel that will be purchased outside of the area and consumed by vehicles operating within the metropolitan area. Often these two conditions do not balance. In the US, the use of a top-down approach based on fuel sales is not recognized as being a valid source of emissions data at the State level, and errors are compounded for smaller municipal or city level study regions.



For such smaller areas a **bottom-up approach** must be used where emissions are calculated on a per-distance basis. This is also the most valid approach, particularly when calculating local pollutants, for country level mobile source emissions inventories.

*Table 1 - Characteristics of top-down and bottom-up approaches*

Top-down approach	Bottom-up approach
<p>Fuel based:</p> <p>CO<sub>2</sub>, SOx emissions calculated based on burned fuel</p> <p>Emissions = Fuel used x Heating value x Emission factor</p> <p>Simple and accurate for CO<sub>2</sub> since emissions are primarily dependent on the carbon content of the fuel consumed provided that it is possible to determine how much fuel was burnt in the study region even though it was bought outside. Not accurate for CO, HC, NOx, and PM emissions which depend on specific vehicle technology and driving cycle</p> <p>Challenge: Gathering reliable data on fuel use and fuel characteristics (heating value , emission factor)</p> <p>Used for:</p> <ul style="list-style-type: none"> <li>• Calculating CO<sub>2</sub> and SOx emissions in large, country-level study areas</li> <li>• Reality-check calculations</li> </ul>	<p>Distance based:</p> <p>CO<sub>2</sub>, CO, HC, NOx, PM emissions calculated for each vehicle type based on distance travelled</p> <p>Emissions = Distance travelled x Emission factor</p> <p>CO<sub>2</sub>, CO, HC, NOx, PM emission factors differ with vehicle type and vehicle activity</p> <p>Challenge: Gathering data about vehicle activity (distance travelled) and vehicle characteristics</p> <p>Used for:</p> <ul style="list-style-type: none"> <li>• Calculating local pollutant emissions in large study areas</li> <li>• Calculating local and global pollutant emissions in smaller study areas</li> </ul>

As can be seen in table 1, the bottom-up approach has far greater data requirements than a top-down estimation based on fuel sales. When working in large areas where most vehicles used in the area are registered in the area, the emissions are often calculated from the active population of vehicles registered in the area x annual kms per vehicle. However, when working in smaller study regions there can be little correlation between the vehicles that are used in the region and those resident there and the calculation has to be based on the kms of roadway and measured vehicle flows.

An example of a small study region could be a Bus Rapid Transit (BRT) corridor, where the number of vehicles that use this road space bears no relationship to the number of vehicles that are registered as being resident on that street. Here, the emissions along the corridor have to be calculated based on traffic flow counts over the 24-hour period for this roadway. The TAMT model/Appliance is designed specifically to help the project developer in this latter case.

And even when working in large, country-level areas the bottom-up approach is needed to be able to evaluate the impact of policies to reduce fuel use. The top-down approach could give an accurate representation of the CO<sub>2</sub> emissions from the overall vehicle fleet but unless this fleet can be disaggregated into specific vehicle types and the CO<sub>2</sub> emissions

calculated for each type, it will not be possible to determine the impact of different policy measures like, for example fuel efficiency standards for passenger cars. Thus the bottom-up approach requires disaggregating the in-use vehicle fleet into groups of vehicle with similar emissions. An accurate representation needs a fine level of disaggregation. The factors that should be taken into account are:

Vehicle Fleet Activity

- VKT Mix by type of vehicle
- VKT Mix by type of fuel
- VKT Mix by type of road

Vehicle Speed and Operating Mode (drive cycle)

- Speed Mix by type of vehicle
- Speed Mix by type of road

Cold starts and trip length

Annual Mileage Accumulation Rates and impact of good maintenance (I&M)

Other Influencing Factors

- Temperature
- Fuel Characteristics (Reed Vapor Pressure)
- Other correction factors

## *Measuring changes in vehicle emissions*

The reasons for measuring vehicle emissions is usually to detect changes in emissions, and to be able to evaluate the success of the infrastructure investments or policy interventions that brought about these changes. Most of these interventions can be characterized within the Avoid, Shift, Improve framework as shown in Figure 9. They may have been brought about by strictly local concerns--such as reducing congestion or combating the health impacts of air pollution--or through other mechanisms such as the National Appropriate Mitigation Actions (NAMAs) that developing countries will implement to achieve their development trajectory goals with lower GHG emissions.

In all cases, a monitoring, recording and verifying (MRV) framework needs to be established to evaluate the change in emissions over a period of time and this needs to be carefully thought out so that emissions change may in fact be reliably measured. This means that the measurement and modeling uncertainties should be ideally at least an order of magnitude less than the emissions variation that is to be detected. This can require careful design of the measurement boundaries and how the dynamic baseline will be established.

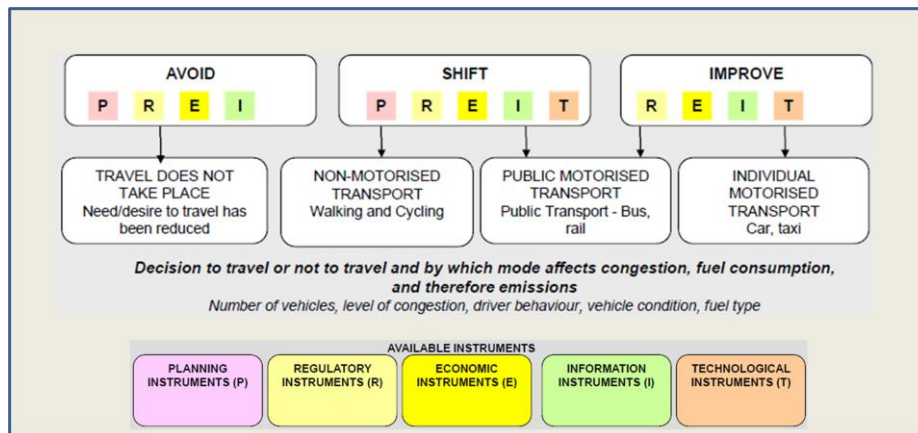


Figure 9 - Avoid, Shift, Improve framework

## Boundaries

All assessments of emission impacts require a careful definition of the study area boundaries and an evaluation of the leakage effects that may be involved. Boundary leakage effects can reduce or increase the emissions within the study area due to cross-boundary traffic and/or fuel sales. Also, the way the boundary is defined can have a major impact on the report results. Consider, for example these following three definitions of the study boundary:

1. Vehicular emissions within a specified geographical area  
*Includes the emissions of all vehicles within the area, independently of where there are registered and from where they bought fuel*
2. Emissions from vehicles registered within a specified geographical area  
*Includes emissions from registered vehicles wherever they operate, and excludes the emissions within the area of vehicles registered elsewhere*
3. Vehicular emissions from fuel purchased within a specified geographical area  
*Independent of vehicles and where they are operated.*

Evidently the results generated under each of the three definitions will be totally different.

Usually emissions measurements are made with the intention of measuring and verifying changes brought about by policy or other interventions. Whilst care must be taken while defining the project boundary to minimize leakages, it is important that the boundary is not made too large as that may render emissions changes impossible to measure. Take the following case:

A BRT project in Mexico City involved a 19.3 km corridor that crossed the whole city. The project involved reducing emissions from the BRT buses (which could be directly measured) plus an impact on the CO<sub>2</sub> emissions from other vehicles operating in the city.

Initially it was thought that the project boundary should encompass the whole of Mexico City's Metropolitan area particularly since this would be large enough to enable the top-down method for evaluating CO<sub>2</sub>e emissions to be considered. However, when looking at the numbers it was seen that the total fuel consumption from vehicles in Mexico City's Metropolitan area generated (in 2005) approximately 24,000,000 tons of CO<sub>2</sub>e per annum whilst the project emissions reduction from the BRT was expected to be of the order of 46,000 tons.



Figure 10 - Mexico City's Metropolitan Area

Having such a large boundary would have meant that the emissions reduction would be of the order of 0.2% of the total emissions and it is evident that the uncertainties involved in the measurement and modeling process would have been larger, making this emissions reduction immeasurable against such a large baseline. Finally, the decision was taken to model the emissions on the route itself and it was only in this way, by having a tight boundary around a restricted geographical area, that it was possible to ensure that the measurement uncertainties could be held at a level that enabled the emissions change to be measured.

## Baselines

Within the complex, highly-evolving transport structure of any modern economy or metropolis, any transportation project or policy intervention will be but one of many (current and future) projects that affect transport patterns and intensities and GHG emissions. Many individual projects will have interactions and dependencies; and all of them will be affected by the multiple other dynamic changes that constantly occur. Thus the impact of a project cannot be evaluated against an as-is base-case “the **now** moment-in-time” since this also will change over time.

For the impact of a project to be evaluated, a dynamic base-line needs to be constructed showing what can be expected to have happened if the project had not taken place (the contra-factual without-project case in Figure 11). This requires evaluating many factors that would have caused changes even without the project. The project’s measured results can then be compared at a future point in time against this counter-factual baseline case.

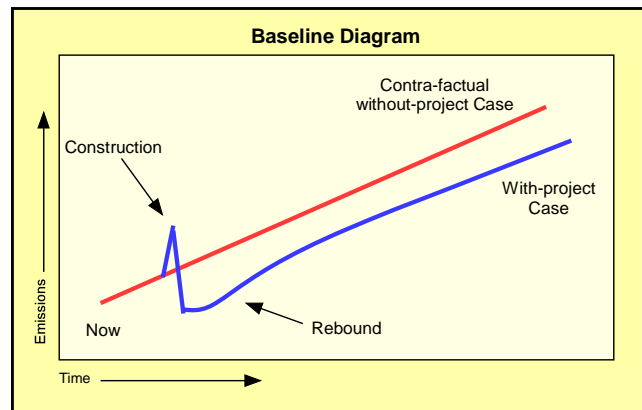


Figure 11 - Dynamic Baseline

If for example, growing motorization is causing increasing congestion, a project designed to alleviate traffic could be judged a success if it reduces congestion compared to what would have occurred without the project, even though the average travel time in ten years time is greater than at present.

At any moment in time, the dynamic baseline must adjust the numbers in accordance with the changes that really occurred in population, vehicle-technology mix and vehicle-kilometers-traveled (VKT) etc so that emissions factors and fuel economy numbers are automatically updated. This counter-factual baseline case should not be a mere projection of historic trends; it needs to take into account all the changes that would have had a high probability of occurring in the absence of the project.

The dynamic baseline thus should support changes in vehicle activity over the project period. This change in activity should account for the development/growth effect on output due to economic expansion together with any efficiency effect (as can be caused by sales of more fuel-efficient vehicles) which reduces the emissions per unit output over time (Figure 11).

When the project includes fleets of vehicles (such as public transport buses that belong to a company or pertain to an association) operating on a fixed route, their daily fuel consumption, cycle specific emissions, and kilometers traveled can be directly evaluated using data from the fleet or a representative sample of vehicles. For all other vehicles, the changes in travel time under the different traffic-loading conditions can be used with speed-sensitive fuel consumption and emissions factor curves to determine the differences between the project-activity and the baseline scenarios.

These speed-sensitive Emissions Correction Factors are developed by:

- Obtaining the best-available active-fleet fuel consumption or emissions data for the study area.
- Updating the vehicle fleet data to account for the technology level of the vehicles in operation in each year and for the annual VKT of each model and model-year of vehicle.
- Calibrating the fleet fuel consumption or emissions data against representative field samples on the route.
- Generating the Speed-sensitive Emissions Correction Factors at idle and differences between the distinct average speeds using normalized speed correction factors developed from one of the empirical-data-based emission factor programs (such as MOVES, COPERT).

### *Methods used to estimate vehicle activity*

There are three basic methods that are used to estimate vehicle activity:

- *Based on vehicle registration*  
In this method the number of vehicles registered in the study area is determined and their annual mileage is assumed to be driven only in the study area. If the study area is sufficiently large (country-level) these assumptions may be valid since they will only ignore cross-border traffic which in many countries is not significant. However for smaller areas this can introduce significant errors; (i) because vehicles other than those registered in the area, drive within the area; and (ii) because the vehicles that are resident in the area can drive a significant fraction of their annual mileage outside the area. Unfortunately the two errors often do not cancel each other. An example could be a city center that is principally offices/commercial areas. Most of the traffic will come from vehicles registered in residential districts outside of the city center.
- *Based on fuel sales*  
In this method the fuel sales within the study area are the key determinant. As above, if the study area is sufficiently large (country-level) these assumptions may be valid for gasoline since they will only ignore cross-border traffic that fueled elsewhere. However for diesel, large errors can be introduced by the consumption of diesel in generator sets, pumping sets and in industrial, construction, and agricultural off-road machines that buy fuel through the same retail distribution chain. Additionally long-haul trucks tend to buy fuel at the end of their trade routes, not in each city through which they pass. For smaller study areas this method can introduce significant errors. Additionally it does not allow the fuel consumed by different vehicle types to be evaluated, so a policy that targets passenger cars fuel economy cannot be evaluated on this basis.
- *Based on distance travelled*  
In this method the vehicle-kilometers travelled within the study area are the key determinant. This uses a concept of link-based emissions measurements that is valid for all sizes of study area. It does not have significant border-effect errors for any size of area and can be used in micro-areas such as a discrete intersection. Since it looks at the distance travelled by each vehicle type on each section of road it clearly differentiates emissions and fuel consumption by vehicle type. This method is described in detail below.

### *Link-based emissions measurements*

The transport activity measurement toolkit (TAMT) is designed around the concept of link-based emissions measurements.

Link-based emissions measurements, uses a logic of measuring vehicle flow on a road (vehicles per hour), and by knowing the length of that road to determine vehicle kilometers

traveled (VKT) in that hour. This VKT is then multiplied by an appropriate emissions factor to determine the emissions on that road during the hour.

If you could do this for every road in the study region, during every hour of the year and for each vehicle type, you would be able to aggregate the total emissions for the year by simply adding up the emissions from each type of vehicle.

This activity determination involves all vehicles that operate on the roads within the study region irrespective of where they are registered or domiciled, and irrespective of where they bought their fuel. Thus it is able to generate a true emissions "picture" from on-road transport, by eliminating most of the boundary effects that plague other methods, particularly in smaller study areas. It also allows emissions to be accurately assigned to specific vehicle types and specific routes and thus is useful in determining the emissions change that can be achieved through different policy interventions.

### *So, where is the complexity in link-based emissions measurements?*

To determine vehicle fuel consumption or emissions from vehicle activity, much data is required from different data gathering samples or field measurements:

1. **Vehicle counts** are needed to determine the flow of vehicles per hour along each street. Since it is impractical (or impossible) to measure the traffic on every street, the road system within the study region is subdivided (or Tagged) into sections of road with homogeneous or similar traffic flow and vehicle hourly flow counts are obtained on each Tag.

We know that the emissions from vehicles vary with vehicle speed and we know that the traffic on each section of the road varies by time of day, hence the need to measure the vehicle flow over the 24-hour period to take into account these changes in vehicle speed with changing congestion.

We also know that the emissions factors for different vehicle types will vary. Observers are able to count separately different classes of vehicles (2- and 3-wheelers, cars, taxi, light duty commercial, heavy duty commercial, small bus, large bus etc) but at normal traffic speeds have difficulty in distinguishing engine sizes, technology levels and fuels, etc. Because of this, the vehicle counts need to consider these different classes of vehicles, which in a later step will be disaggregated into sub-groups (by fuel use, engine displacement, and emissions technology) to which discrete emissions factors can be assigned.

Study areas may encompass any number of road tags. A simple study may consist of only one road tag on which traffic is sampled over one day. A default flow rate may be considered for those hours of the day with little traffic allowing measurements to be made over a limited period of, for example, 6 AM to 10 PM. A more complex study may involve several road tags and require several days of traffic flow measurement to reduce the uncertainty in the emissions estimation. This can generate a vast amount of data by class of vehicle, sampling point, day of week and hour of day.

2. **Vehicle speed and duty cycle.** Vehicle speed and drive cycle need to be known since emissions factors are speed sensitive for all types of vehicles. Usually the amount of



vehicle travel can be binned into different speed bins (of say 0-5 kph, 5.1-10 kph etc) so that specific emissions factors can be calculated for each bin and applied to the fraction of VKT corresponding to that bin.

In a simple study, three speed bins may be used corresponding to highway, principal or arterial, and local roads considering typical speeds during the year. If the study considers only one road type (such as in a highway construction project) only one speed bin may be needed. In the complex study, twenty 5-kph speed bins may be used with measurements taken during every hour of the day on each of multiple pre-defined road tags.

Vehicle speed can be measured by a moving observer technique (in which a seed-vehicle with or without GPS drives at the average traffic speed) on the affected streets. The TAMT suggested methodology takes this one step further by allowing low cost GPS loggers to be used to record actual trips made by local people during their normal daily duties and then assigning each segment of the trip to the corresponding Tags. This further extends the database contents which can include to several million second-by-second GPS speed registers.

By calculating the length of each road link, the TAMT Appliance processes the vehicle flow and speed data using SQL regressive weighted averaging to obtain simple output tables giving the VKT fraction for each vehicle type, technology, and fuel in 5 kph speed bins. It also generates other trip length and soak time information tables.

3. **Fleet Composition.** As we have seen above it is easy to visually separate the vehicles traveling down a road into nine different classifications, however a finer disaggregation than this is needed to be able to assign emissions factors. COPERT uses over 250 different combinations of vehicle type, technology, and fuel use to assign emissions factors. Achieving this level of granularity requires a detailed knowledge of the in-use fleet which often is not apparent in vehicle registration data and has to be generated as part of the study.

There are several methods that can be used to do this using sales data, field samples and other sources, which will be discussed in Chapter 10. Other factors that need to be taken into account include: local ambient conditions, trip length, engine soak time, and emissions deterioration with vehicle age and usage.

### *What does TAMT consist of? What does it do?*

Usually a lot of work is required to transform field data into a structure that allows it to be used in transport planning or emissions models and each step in the process is prone to adding errors and uncertainty in the data. Historically, project implementers have not had at their disposal a structured database management tool that gives consistency to this processing. The TAMT Appliance delivers this and makes it easy to process data for an unlimited number of road tags in the study region.

The TAMT framework for the assessment of transport emissions is designed to:

- Provide a simplified standardized approach to data collection and processing that can be performed by a diverse group of people and institutions in many countries.
- Allow distinct output datasets to be generated as required to run different transport planning and emissions models.



- Develop a knowledge base built from the M&E of different projects in diverse metropolitan areas that allows this open source publically available framework to be constantly refined
- Encourage local institutions to become involved both in extending the framework to cover specific local requirements and conditions and in its continual development.
- Facilitate the use of this knowledge base in improving decisions in future projects

TAMT does not calculate the emissions factors for this process, it is a toolkit that is designed to facilitate vehicle activity data gathering and management.

TAMT consists of the following elements:

1. This Practitioners' guide (TAMT Practitioners' Guide)  
The objective of this guide is to give practical assistance to the project proponent in defining: what to measure, where to measure, how to measure, and how many to measure, in order to define with an adequate levels of uncertainty the fuel consumption, global [CO<sub>2</sub> emissions] and local pollutants from on road vehicles in the study area. The practitioners guide also includes formats that can be used to record field data as required by the measurement campaign.

TAMT also includes open source software tools within a relational database (TAMT Appliance) designed to facilitate this process:

2. A study region and road hierarchy assignment tool (The Tag module)  
This Google maps-based GIS package allows the project proponent to draw out on Google's map or satellite view the study **Region** that will be used, together with the traces of the principal **Roads** (main streets, avenues, and restricted access highways) within the study region. The study region can be subdivided into three **Zone** types [residential, commercial, and industrial]. Road are grouped by **Tags** where the road links in each Tag have similar or homogeneous traffic flows. All secondary streets are tagged by default by their zone type.
3. A GPS processing tool (The Import/Assign module)  
This module enables GPS second-by-second road speed data that has been collected throughout the region to be imported into the relational database. The module assigns each second-by-second record to the corresponding road tag by day of week and hour of day. Data gaps (between hours and between the week days) are filled by interpolation.
4. A vehicle flow processing tool (Part of the Analysis module)  
This module allows vehicle flow data (in the form of vehicle counts over a time period) to be entered for each tag by day of week and hour of day for each of nine categories of vehicle types as shown below:

Two-wheeler (W2)	Taxi (TX)	Heavy-duty commercial (HDC)
Three-wheeler (W3)	Pickups, vans, SUVs (LDV)	Medium-duty minibuses (MDB)
Passenger car (PC)	Light-duty commercial (LDC)	Heavy-duty buses (HDB)

A default vehicle flow can be defined for each vehicle type of those hours of the day with little traffic (for example from midnight to 5 AM) and the program fills any data gaps by interpolation.

5. An analysis and output tool (Part of the Analysis module)  
This module processes. The analysis module also calculates trip lengths and the engine soak times (which is the time the vehicle speed and vehicle flow data by tag, by day of week, and hour of day; calculates the road length of each tag; and outputs annual vehicle kilometers traveled for each of the vehicle types in 5 km speed bin intervals in a format that can be used as input for distinct emissions factor models for which the engine is shut off between trips); data which is required to estimate the evaporative emissions from the vehicles.
6. A reporting tool (The Export module)  
This module generates and outputs the reports and produces backups the data sets that can be easily imported in other instances of the TAMT toolkit.

### *TAMT Software Design and Installation*

#### *Software architecture*

TAMT is open source and runs in Oracle's VirtualBox that enables it to be used on PC and Mac computers. It includes its own integrated development environment (IDE) to enable the user to easily generate other output reports as required. Source code is housed on Google's code page; a development wiki is published; and it is expected that a growing community will support developers that decide to modify this software.

#### **The TAMT System**

The TAMT system requires a user to download and install the Oracle [VirtualBox](#) client software and the TAMT Appliance (described below). The overall system deployment looks like this:

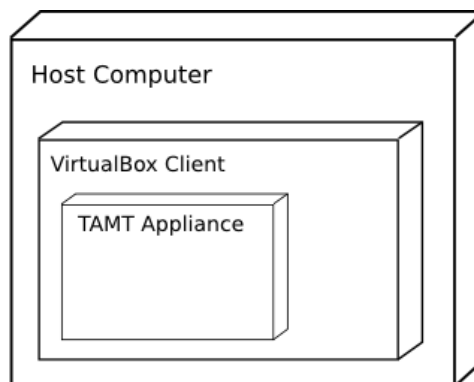


Figure 12 - The TAMT system

#### **TAMT Appliance**

The TAMT Appliance is a virtual machine packaged as a single file and deployed on client computers.

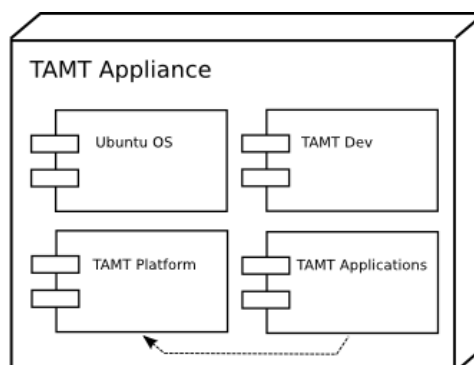


Figure 13 - The TAMT Appliance

The TAMT Appliance is a virtual machine created with [VirtualBox](#). It is a single disk image containing the Ubuntu operating system pre-installed with all of the open-source packages and libraries required to support the TAMT Platform software, including:

- Operating system: Ubuntu 10.04
- Database: PostgreSQL with PostGIS extensions and PL/Java for stored procedures; pgAdmin3 as database administration user interface
- Web Container: Apache Tomcat 6.0 - HTTP server and Servlet container supporting Java Servlet 2.5 and JavaServer Pages (JSP) 2.1.
- Software development kits: Java 1.5
- Integrated development environments: Eclipse 3.5.1 with Google Plugin for Eclipse
- Internet browsers: Google Chrome, Mozilla Firefox

## Appliance Development

There is no software "development" required for the TAMT Appliance. It is an instance of a virtual operating system created with [VirtualBox](#) (which is itself an open-source software project). For architecture, design and defect issues relating to TAMT Appliance, we are referring to pre-packaged software installation and configuration, not software development.

Therefore, the issue tracker below is not tracking issues with the development of the [VirtualBox](#) software, but it is tracking installation and configuration issues within the TAMT Appliance (for example, the installation of the TAMT Platform, PostgreSQL, PostGIS, etc.)

It is anticipated once the TAMT Platform is successfully integrated in the TAMT Appliance, the only requirement for the end-user is to download the TAMT Appliance, import the virtual machine to the [VirtualBox](#) client on the host computer, and then within the VM run the TAMT Platform Applications (which are all pre-installed).

## TAMT Platform

The TAMT Platform is an open-source stack to support the TAMT Applications suite and the TAMT Dev tools.

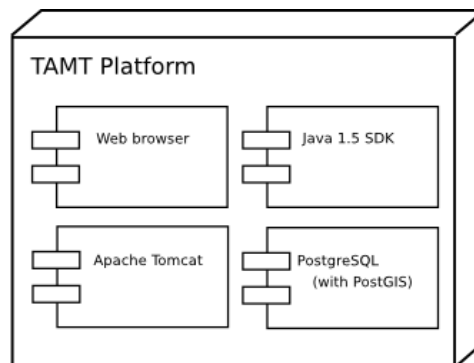


Figure 14 - The TAMT Platform

- Web browsers: Google Chrome, Mozilla Firefox
- Java 1.5 SDK
- Apache Tomcat
- PostgreSQL with PostGIS

## TAMT Dev Tools

The TAMT Dev Tools are included in the TAMT Appliance so future development is supported right in the virtual machine.

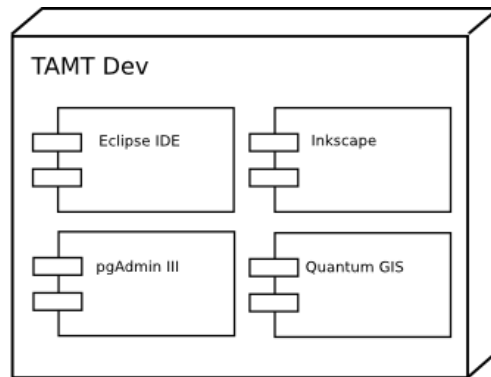


Figure 15 - The TAMT Dev Tools

- Eclipse 3.5 IDE (configured with Mercurial plugin to TAMT source repository at Google Code)
- Inkscape - vector illustration package for design diagrams
- OpenOffice.org suite for document editing
- pgAdmin III for administering the PostgreSQL database
- Quantum GIS for viewing / manipulating GIS files

## TAMT Applications

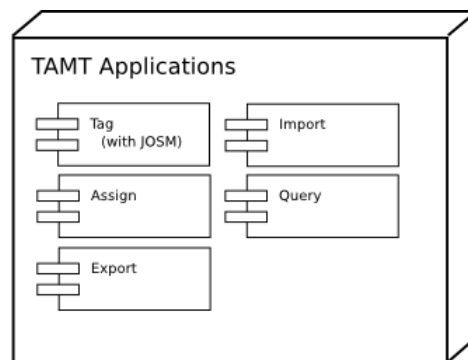


Figure 16 - TAMT Applications

- [Tag](#) allows a user to define and classify a study zone, subzones and a road network.
- [Import](#) allows a user to import GPS data from the field.
- [Assign](#) allows a user to trigger a long-running task to assign each GPS data point to its nearest road network, and assume the attributes of that network segment.
- [Analysis](#) allows a user to capture vehicle flow data for each tag by day of week and hour of day. It processes the vehicle speed and flow data and calculates annual vehicle kilometers traveled for each of the vehicle types in 5 km speed bin intervals.
- [Export](#) allows a user to export queried data for use in any greenhouse gas emissions model.

## How to install and run TAMT

The TAMT Appliance is a 3.5GB VirtualBox virtual machine.

### Download TAMT

For ease of download the 3.5GB file is split into approximately 30 segments with names such as:

<http://tamt.googlecode.com/files/tamt-beta-1.0.ova.001> (125MB)

<http://tamt.googlecode.com/files/tamt-beta-1.0.ova.002> (125MB)

First download each of the files from <http://code.google.com/p/tamt/downloads/list>. If there are several versions, download the version with the most recent "Uploaded" date, then join them using the HJSplit application. Save each file to the same folder. Please confirm that all files have downloaded correctly by comparing the file sizes. They should all be identical except for the last file. If there are any differences please download that file segment again.

### Download HJSplit

To join the segments, you must use the HJSplit application found at <http://www.freebyte.com/hjsplit/>. There are several Windows, Linux and Java versions available; choose the version that's best for you.

### Join the files

Start HJSplit. Select "Join". Use the file selector to choose the first file (tamt-beta-1.0.ova.001 in this example). The rest will be found automatically if they are in the same folder. For the output file, choose the same name (for example tamt-beta-1.0.ova) in a new folder. You will need 3.5GB of space for this file. The .ova file is the file you will import into VirtualBox .

### Download VirtualBox

Obtain the latest version of VirtualBox (currently 4.04) at <http://www.virtualbox.org/wiki/Downloads>. Download and install a version compatible with your computer, which will be the "host" for the TAMT Appliance.

### Start VirtualBox and import the TAMT appliance

Select *File > Import Appliance > Choose...* and select the tamt-beta-1.0.ova file from the directory in which you joined the files. Select *Next* and select *Finish*.

### Start the TAMT appliance

Start the TAMT Appliance from VirtualBox

Once booted, log in with username "tamt" and password "tamt"

### Install VirtualBox Guest Additions

The VirtualBox Guest Additions can then be installed to provide closer integration between host and guest and improving the interactive performance of guest systems. The Guest Additions are designed to be installed *inside* a virtual machine after the guest operating system has been installed. They consist of device drivers and system applications that optimize the guest operating system for better performance and usability. The VirtualBox Guest Additions for all supported guest operating systems are provided as a single CD-ROM image file which is called VBoxGuestAdditions.iso. This image file is located in the installation directory of VirtualBox. To install the Guest Additions for a particular VM, you mount this ISO file in your VM as a virtual CD-ROM and install from there with *Devices > Install Guest Additions*.

### Setup a Shared Folder

Having a shared folder allows you easily import GPS files from your Host into your Guest System. First create a folder to be shared in your Host system.

*In the host system (Windows)*

If you are using Windows, you might create a folder called TAMT in Documents (for example C:\Users\John\Documents\TAMT).

Then you have to set the sharing permissions in Windows for this folder. Right-click on the folder and choose *Properties*. On the *Sharing* Tab you will see in the "Network File and Folder Sharing" section that the folder "TAMT" is shared with a network path similar to \\GRIFFIN\Users\John\Documents\TAMT. Click on the "Advanced Sharing" button. Put a check mark in "Share this folder". Click on the "Permissions" button, select "Everyone" and put a check mark in "Full Control" and click both "OK" buttons. Now you should see in the "Network File and Folder Sharing" section that the folder "TAMT" is shared with a network path similar to \\Griffin\tamt. Click "Close".

#### *In VirtualBox*

In *Devices > Shared Folders*, add the shared folder (C:\Users\John\Documents\TAMT) with *Auto-mount* and *Make Permanent* both checked.

#### *In the guest system (Ubuntu)*

In Ubuntu get a terminal window at *Applications > Accessories > Terminal* and type:

```
sharename="TAMT";  
sudo mkdir /mnt/$sharename  
sudo chmod 777 /mnt/$sharename  
sudo mount -t vboxsf -o uid=1000,gid=1000 $sharename /mnt/$sharename  
ln -s /mnt/$sharename $HOME/Desktop/$sharename
```

When asked for a password, use "tamt" (without " ")

This make a shared folder named "TAMT" in the *mnt* directory with a quick access on the desktop.

On restarting VirtualBox or Ubuntu it is only necessary to reconnect to the shared folder by by opening a Terminal and inputting:

```
sudo mount -t vboxsf -o uid=1000,gid=1000 TAMT /mnt/TAMT
```

#### **Start the TAMT application**

On log in, double-click on the "TAMT" application with the World Bank icon on the middle of the screen (see Figure 18). It will launch a web browser and take you to the home page of the TAMT application at: <http://127.0.0.1:8080>.

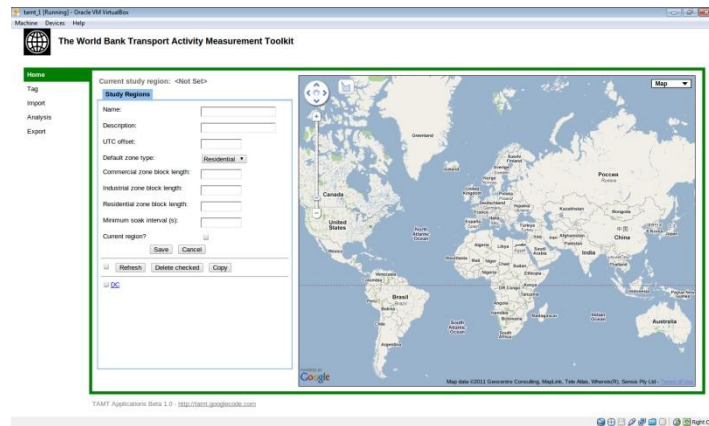


Figure 17 - TMT Home Page

## End the TMT application

To shut-down TMT select the button in the top-right hand corner of the screen and choose "Shut Down" (see Figure 19).

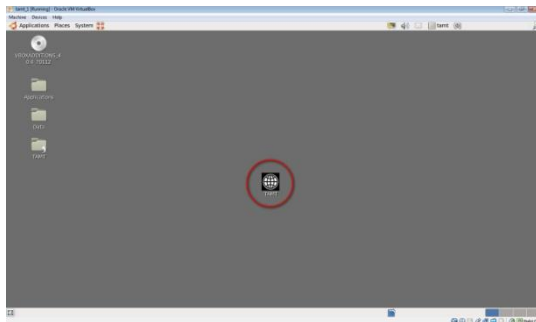


Figure 18 - Double-click to start TMT

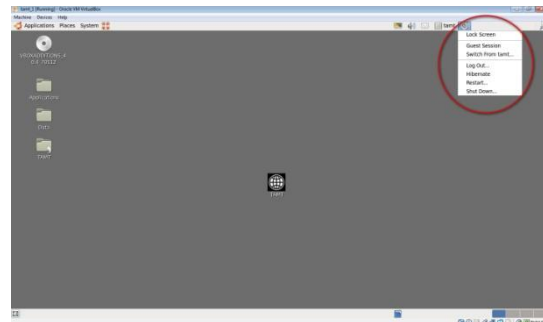


Figure 19 - Select this button to end TMT



### *How to define zones*

The first step in any link-based activity measurement, whether it uses the TAMT Appliance or not, is to define the geographical boundaries of the study zone in which measurements will be made.

### *Why is this important?*

The project boundary has to be carefully defined based on the objectives of the study since all vehicular activity within this boundary should be captured by the field measurements and calculations. There are no limitations on the size of the study zone (it could be for a complete country), however, it is important not to include an area that is un-necessarily large, since that can make it more difficult to detect changes in emissions caused by policy implementations, since the differences will be relatively smaller when compared to the (larger) total and can be hidden within the measurement and modeling uncertainties. In this case more measurements may be required to reduce the measurement uncertainties and be able to detect the change.

If the project consists of infrastructure changes on a highway, for example, great care should be taken in selecting which other streets to include in the study area. The guiding principal should be to define the boundary to capture all the changes but exclude as much extraneous vehicle movement as possible.

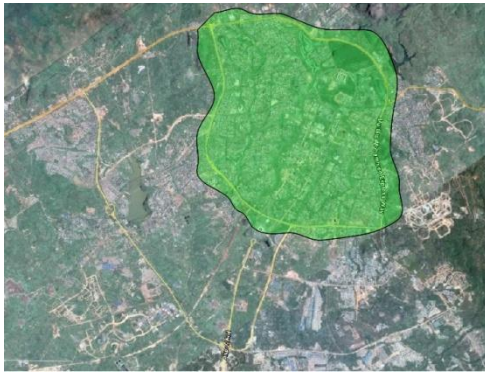
### *Defining the study zone (project boundary)*

A boundary that follows the political or geographical limits of a Metropolitan area is adequate for a study that pretends to determine the emissions or fuel consumption of on-road vehicles within the metropolis, but would be typically too large to evaluate the change in emissions due to the implementation of say a BRT corridor. For this latter case, it would be preferable to draw the boundaries closely around the corridor itself. However, if it is desirable to include the change in traffic caused by feeder routes into the BRT corridor, then the boundary should include these too.

This is illustrated in Figure 20 to Figure 23. Figure 20 shows a project boundary that includes the ring-road and all development within, but does not include urban areas that have extended beyond the ring-road. For these to be included, the boundary would have to be extended (for example, Figure 21). However a highway development project could do better to use a more tightly defined boundary (as in Figure 22) that highlights the fuel consumption and emissions on the road by excluding other areas. Figure 23 shows a similar situation where a boundary is tightly defined around a BRT corridor.

It is important to remember that the value of conducting link-based activity measurements lies in the ability to measure change over time. When defining the project boundary, care

must be taken to envisage future growth and development patterns such that the same boundary may be considered valid in other measurement campaigns at a future date.



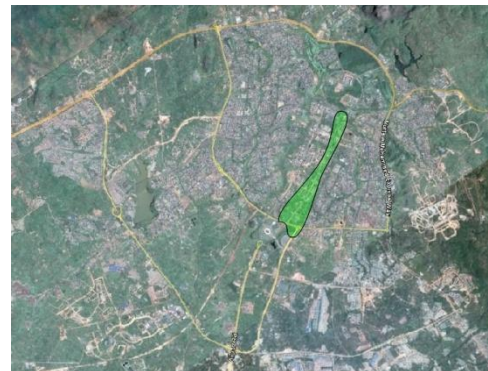
*Figure 20 - Urban Area*



*Figure 21 - Extended Urban Area*



*Figure 22 - Highway Development*



*Figure 23 - BRT Project*

## *Defining the default usage in the study zone*

In all link-based activity measurement--whether it uses the TAMT Appliance or not—it is useful to define the usage of the included area within the boundary because vehicle usage patterns can vary considerably and the land-use density may be notably different between Residential, Commercial, and Industrial zones.

The TAMT Appliance considers up to three types of zone; Residential, Commercial, and Industrial. It is useful to use these to identify different areas within the project boundary where the vehicle usage patterns vary considerably or the land-use density is notably different. To do this, the study zone is assigned a default type (often Residential) and specific sub-zones are drawn within the project boundary to specifically assign the other two types.

## Defining sub-zones

Typically, in an Industrial zone the plots of land are larger and peak traffic is driven by the manufacturing plant operating hours. In Commercial zones heavy traffic is often seen later in the day even on side streets. In Residential, side street traffic is often less and plots of land (and hence block size) are smaller.

Figure 24 gives an example of how two Industrial zones (red hatch) and one Commercial zone (yellow) could be defined. One, two, or all three land use types may be specified in any specific project in as many areas as required. However for many projects it is not necessary to use more than one. Each sub-area may be assigned to only one zone type; for example in Figure 24 the yellow area has been assigned as Commercial and thus the underlying default Residential status does not apply to this area.



Figure 24 - Industrial and Commercial zones

## Defining average block size

When defining zones, the TAMT Appliance will request the "Average block size" in each zone type. These can be most easily defined using Google Earth in satellite image view by using its ruler to measure the width and length of a "typical" block (including its corresponding road space) and taking the average of the two.

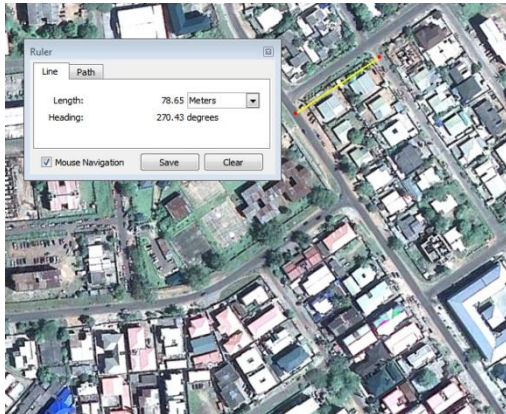


Figure 25 - Measuring Block Width

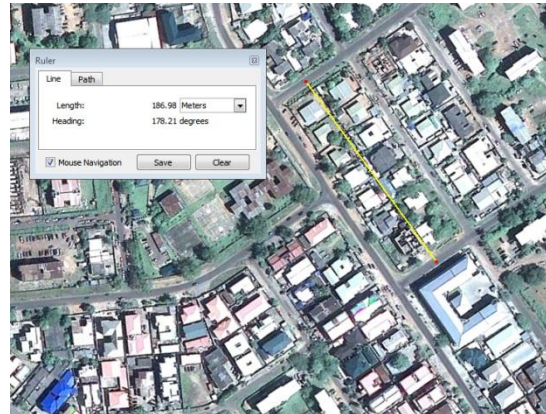


Figure 26 - Measuring Block Length

In this example Figure 25 shows a block width of 79 meters and Figure 26 shows a block length of 187 meters, giving an average of 133 meters. This data is used by TAMT to estimate the length of secondary roads within the area. With an average block size of 133 meters, which is 0.133 km, TAMT assigns  $1/0.133 = 7.5$  km of secondary road to each square kilometer of land area in the specified zone. If the length of secondary roads within the area is known, the equivalent average block size can be calculated as being the area of the zone divided by the length of secondary roads within that zone.



Please be careful to enter the average block size into the TAMT Appliance in meters.

## *How to define the Study Zone in the TAMT Appliance*

### **First, prepare the information you will need**

- **Name:** The name to be given to the study zone (for example "Accra City Center")
- **Description:** Optional description
- **UTC offset:** This is needed to correct the timestamp of GPS logs to local time. The current UTC offset for most cities can be found at:  
<http://www.timeanddate.com/worldclock/city.html?n=4>
- **Default zone type:** Commercial, Industrial, or Residential
- **Commercial zone block length:** Average block size in meters as shown above
- **Industrial zone block length:** Average block size in meters as shown above
- **Residential zone block length:** Average block size in meters as shown above
- **Minimum soak interval (s):** This will be fully explained in Chapter 12.
  - a. If a vehicle is stationary for less than this time, it is assumed that the engine will still be running.
  - b. If a vehicle is stationary for more than this time, it is assumed that the engine will be turned off.

This affects the fuel consumption and emissions calculations and also the calculation of the soak time (which is the time that the engine is turned off between consecutive trips). The time that is chosen will depend on local conditions and is often between 10 minutes (600 s) and 30 minutes (1800 s).

### **Define the Study Zone**

1. Go to the Home page in TAMT and make sure that no other zone is selected. To do this remove the check mark from current region and save. The top of the page should now show "*Current Study Region: <Not Set>*".
2. Navigate in the map to locate the new study region (in this example Accra, Ghana). Choose the highest map magnification that allows all the study region to be visible on screen. You can use Map, Satellite or Hybrid view.
3. With the Polygon tool mark the study area. On closing the polygon, a box will appear asking for the name of this region. Enter the name you have chosen (for this example Accra) and click "OK".
4. Fill in the other requested data.
5. Click the update button

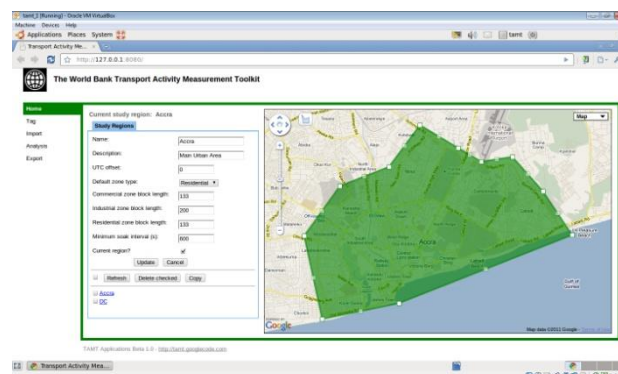


Figure 27 - Defining the Study Zone in TAMT

## Modify the Study Zone

The study zone configuration and other data can be modified after creation.

It is useful to first broadly draw-out the study region, click the update button to fix this, and then zoom in for a closer look to fine-tune the borders of the study region by moving each handle.

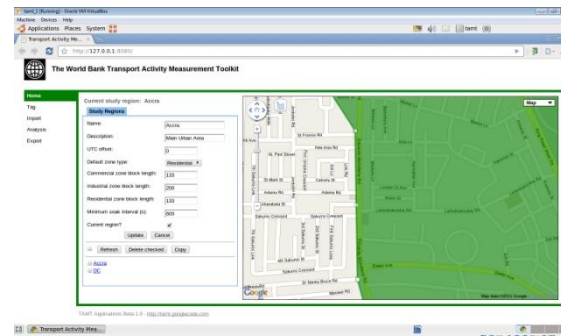


Figure 28 - Fine-tuning the Study Zone in TMT

It is recommended that you save your changes frequently (by clicking the update button).

## Copying the Study Zone in the TMT Appliance

The home page also gives to you the ability to copy the study zone. As can be seen in Figure 29 you have to first select, with a check mark, the zone that you wish to copy and then click on the copy button. This copies into a different zone name the configuration of the zone including subzones and all the roads defined in the road hierarchy as explained in the following chapter.

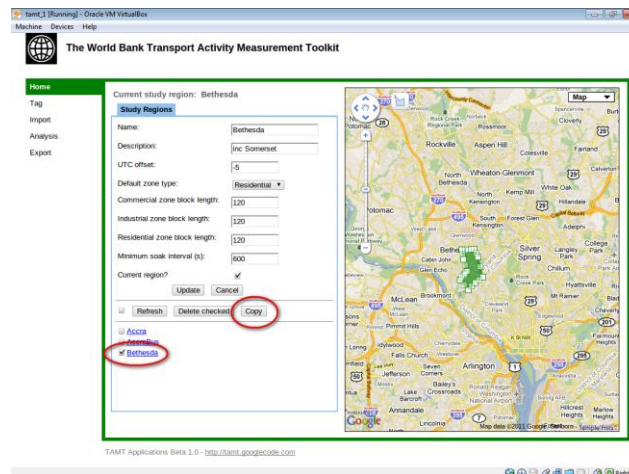


Figure 29 - Copying the study zone in TMT

## Why would you want to do this?

The purpose of this function is to allow different GPS speed traces to be used for some of the vehicles operating in the study area. For example, if the fuel consumption of buses is to be determined by their drive cycle operation then it would be necessary to generate different GPS trace information for buses than that used for other vehicles operating in this area.

To allow this, a copy of the study area can be made using this "Copy" button on the home page and the vehicle counts for buses with their corresponding GPS traces can be handled separately from all other vehicles. When the copy of the area is made by this means, none of

the vehicle specific data (such as GPS traces or vehicle counts) are copied; only the physical configuration of the zone, subzones and routes are copied over. Under most circumstances, it is recommended that the study area is not copied until all the roads and subzones have been defined.

### *How to define the road hierarchy and sub-zones*

#### *Why is this important?*

Link-based activity measurement relies on knowing the vehicle flow and speed on every link (or section of road) within the study area. Since it is impossible to measure this on each link, roads are grouped into Tags and the vehicle flow and traffic speed that is measured at one or more points of each tag are applied to all the roads that have that same tag. Thus you can see that the more tags you have, the more measurements you have to make. This applies whether or not you use the TAMT Appliance.

TAMT allows an unlimited number of roads and tags within each study area. However you should be very careful in deciding how many tags you define; each Tag should group together road sections that have homogeneous—or very similar—traffic flows and speed conditions, thus having more tags does give finer control but evidently you need to do traffic count and speed measurements on each Tag.

Usually projects will have at least three tags (major urban connectors, arterials and secondary roads) although many projects use a multiplicity of Tags.

#### *What you need to know about roads, tags, and sub-zones*

Road segments—or links—are often classified into three general groupings.

- The first group represents roads that are major urban connectors joining one urban area to another. These are typically characterized by the highest travel speed in free-flow traffic with minimal stops from cross-flow traffic. They often have a central divide, use bridges and flyovers, and are commonly known as highways or freeways.
- The second group consists of roads that connect sections of an urban area or provide an important connection within a section of the urban area. These usually do not have a central divide, often have traffic lights, and are typically referred to as arterials.
- The third group represents the streets that take people to their homes or small commercial sections of an urban area, or within the industrial area giving access to individual buildings. They are usually one- or two-lane roadways with a relatively lower average speed and frequent intersections. These roads are typically referred to as secondary streets.

In the TAMT Appliance each of the roads in the first two groups has to be individually drawn on the map and tagged. This includes all highways, freeways, main arterial roads, and routes of specific interest (such as sections of a BRT corridor) even though they fall in the category of secondary streets.

Secondary roads (the third group)—and other than the above-- do not have to be individually drawn and tagged in the TAMT Appliance by the user. The length of these roads is defined by the area of the commercial, residential, and industrial zones that have been drawn on the map within the study area. All secondary roads within each commercial, residential, and industrial zone are automatically assigned to #COM, #RES, and #IND tags.

All secondary roads within, for example, an industrial zone are assumed to have a density (expressed as kilometers of secondary road per square kilometer of zonal area) that is determined by the average block length in the industrial zone. Whilst traffic flow on secondary roads is usually far less than on primary roads, they usually have a cumulative length that is far greater, highlighting their importance to vehicle mobility and in accounting for vehicle emissions.

It is common practice in emissions inventory studies, for example, over a city-wide or metropolitan area to use at least three tag types (highway, arterial and secondary), however the use of more tags will give finer control and more detailed information on the vehicle movement and their emissions. The German MOBILEV mobile source emissions program routinely uses nine and more tag types. It is good practice to define different Tag types in each of the commercial, residential, and industrial zones.

Some specific projects, like a bus rapid transit (BRT) corridor will require a more precise measurement of vehicle activity on specific sections of road. A BRT corridor may even need to be divided into different sections of homogeneous traffic speed and flow, with measurements on each to enable more precise calculations to be made. Each of these specific corridors or road sections would require additional tags to the general citywide classification already mentioned.

There could even be some projects where road tags are not required. For a university campus for example, if all of the streets have similar traffic flows and speeds than it could be sufficient to define the total road length through the zone type and not specifically highlight any particular roadway with a tag. In this case, any vehicle flow and speed measurements that are made would be assumed as valid for all the roads within the campus.

Remember, you would only be able to desegregate results down to the specific tag level. If several roads share the same tag, you will not be able to discern differences between the activity and emissions on each of these roads. On the other hand, the more tags you have the more measurements you will need to make so it is important to define a good balance. Each tag must have vehicle flow and traffic speed measurements over at least one 24-hour period. For more precise evaluations vehicle flow and traffic speed measurements may be required on specific tags for up to a three or more week-period.

Local knowledge is needed to be able to adequately define the study area and the tags, roads and sub-zones that it contains.

## *Defining Tags in the TAMT Appliance*

Before you can select and draw the representative roads, you need to define the different tags. Each tag is a collection of different roads, or segments of roads, that have homogeneous, or similar, traffic flow and traffic flow conditions.



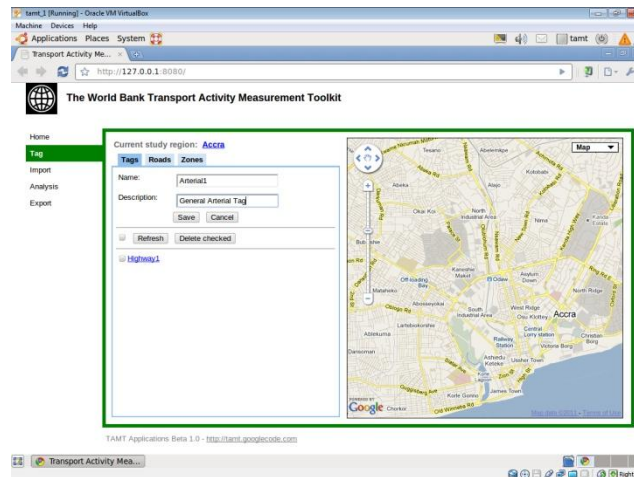


Figure 30 - Defining Tags in TAMT

In TAMT go to the Tag page (as shown in Figure 30) and define each of the Tags. These will appear in a list at the bottom of the screen. It is good practice to define all the tags that you might need, although you can go back and add to, or delete from, this list later. You will find it useful if you can keep the name of each tag relatively short.

### *Defining principal roads in the TAMT Appliance*

Once you have a selection of tags defined, you need to go to the road page to be able to select and assign the principal roads in the study area. Each road trace has to be sufficiently accurate so that the GPS data is correctly assigned to the right road. TAMT includes a default tolerance of 50 meters however when half the average block length in the default zone is greater than 50 meters, then this larger value is used.

If the average block length in the default zone were to be 120 meters, then  $T_{TOT}$  would have to be less than 60 meters where:

$$T_{TOT} = T_{GPS} + T_{TRACE} + T_{WIDTH}$$

$T_{GPS}$  = The tolerance of the GPS signal. Whilst this is often better than 3 meters, when high buildings or foliage interrupt the view of the sky and the signal from the GPS satellites, this circle of uncertainty can increase considerably<sup>5</sup>.

$T_{TRACE}$  The tolerance of the road trace. This depends on the care that was taken in matching the trace to the center-line of the road in the Google Map image.

$T_{WIDTH}$  The width of the road. The vehicles traveling in the low speed lane can be a considerable distance from the road centerline, particularly on dual-carriageway roads.

<sup>5</sup> Please note that the NMEA \$GPRMC Sentence used in the GPS log contains a navigation receiver warning A = Valid position, V = Warning (see appendix C for more details). TAMT only utilizes GPS second-by-second data that has the "A" attribute.

Thus it can be seen for example in a dual carriageway road in which the road edges are 30 meters from the centerline and where the GPS signal uncertainty is 6 meters, the maximum tolerance in tracing the road would be 24 meters, when the total tolerance is 60 meters.



Figure 31 - Example of road-trace error in TAMT

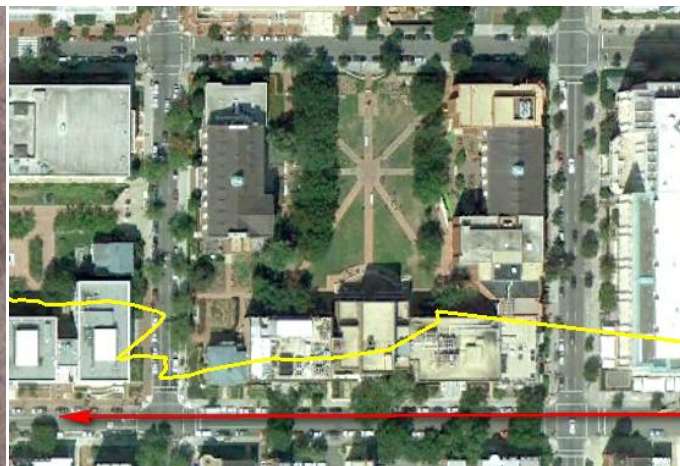


Figure 32 - Example of GPS signal error

In Figure 31, which shows a satellite view of a dual carriageway and where the blue line shows the road trace in TAMT, it can be seen that the north-bound traffic would not be mapped to that road and would be assigned by the program to the secondary roads in that zone.

Figure 32 gives an example of GPS signal error. In this example, the vehicle traveled along the road shown by the red line however the GPS signal, due to reflections off high buildings is offset to the north (yellow line). Provided that the sum of the GPS errors ( $T_{TOT}$ ) is less than 50 meters this travel would continue to be assigned to the correct tag. In this particular case as it is a secondary road, GPS signal would be correctly assigned (to the sub-zone Tag).

Although for all roads it is critical to take the time to adjust the road trace as best as possible to Google's satellite view, the additional problem of dual carriageways may be solved by defining two road traces, one in each direction. In these cases it is better to align the road trace with the slow lane (where most traffic is) rather than with the road centerline. The two traces will normally be assigned to the same tag (which will make them appear as one in the calculations), but can be assigned to a different tag if there is a reason to analyze separately, for example, north- and south-flowing traffic.

For a highway construction project this can be simplified by using the default zone Tag type to tag the main road that you're interested in<sup>6</sup>. In this case you would draw the study zone very closely around the route you are interested in and only tag other roads in the zone.

<sup>6</sup> If the study zone is set to a default of Residential and no main roads are specifically tagged then all traffic movements within the study zone will be assigned automatically to the #RES tag.

## How to define roads in TAMT

1. Choose the Tag > Roads page of TAMT
2. Choose the largest magnification that allows the whole road length to appear in the window.
3. Use the line tool to carefully mark the first road of interest
4. On double-clicking the last point a box will appear requesting the name of the road. Enter and click "OK".
5. Enter a description for the road and one of the previously defined tags. You can choose the tags by typing the first letters of its name. Click Save.

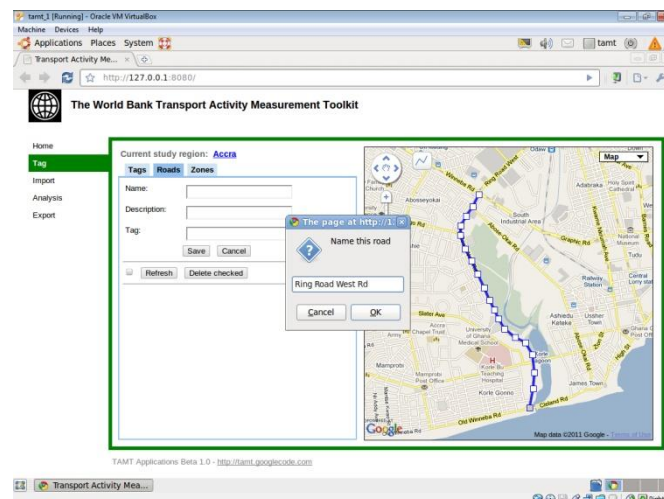


Figure 33 - Naming a Road in TAMT

6. Repeat this to include all the highways, freeways, main arterial roads, and routes of specific interest in the study area. Consider twin-traces for dual carriageways.
7. Then, for each of these roads, go to a higher magnification on the map to closely adjust the road trace to the road. You can select the Map, Satellite, or Hybrid view to do this, however sometimes the road trace on the Map view does not overlay the road as seen in the Satellite view. For these, it is preferable to use the satellite view. When adjusting a road trace, whenever you click on an anchor point an additional anchor point will be created so that it is easy to fine-tune the road trace to curves and corners.
8. Check back periodically to make sure that all the critical roads in the study zone have been included. It is good practice to make sure that the road traces cross the zone boundaries and do not just butt-up to them.

This process can take time, since it needs to be done with care. It is made easier by using a large, high-resolution monitor and using the "Host-F" command in VirtualBox to make available as much screen real-estate as possible. Save frequently.

## *Defining secondary roads in the TAMT Appliance*

Secondary roads are defined in TAMT by defining the Commercial, Industrial, and Residential areas of the study region. When drawing the main study area, one of these three classification must be selected (see Chapter 4). This is the default classification in the main study zone. The others may be drawn where necessary using the Tag > Zones page.

The process is similar to defining roads:

1. Choose the Tag > Zones page of TAMT
2. Choose the largest magnification that allows the whole sub-zone that will be traced to appear in the window.
3. Use the polygon tool to carefully mark the first zone
4. On double-clicking the last point a box will appear requesting the name of the zone. Enter and click "OK".
5. Enter a description for the zone and one of the type tags (Commercial, Industrial, and Residential) from the drop-down. Click Save.

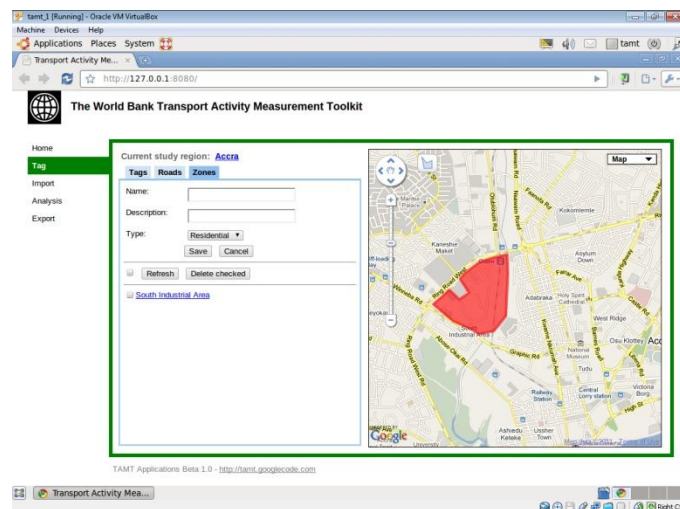


Figure 34 - Selecting sub-zones in TAMT

9. Repeat this to include all the zones, as necessary, in the study area. Remember that if the study zone was assigned a default "Residential" tag, there will be no need to define "Residential" sub-zones. In many projects (such as an inter-city highway), there is no need to define sub-zones.
10. Then, for each of these zones, go to a higher magnification on the map to fine-tune the trace, as necessary. You can select the Map, Satellite, or Hybrid view to do this. The zones should be a close fit but there is no need to achieve the sort of accuracy that is required for roads. It is important to ensure that the sub-zones do not overlap each other or overlap the study boundary.

### *How to measure vehicle flows*

#### *What are we trying to do?*

The transport activity measurement toolkit (TAMT) is designed around the concept of link-based emissions measurements. Link-based emissions measurements, uses a logic of measuring vehicle flow on a road (vehicles per hour), and by knowing the length of that road to determine vehicle kilometers traveled (VKT) in that hour. This VKT is then multiplied by an appropriate emissions factor to determine the emissions on that road during the hour.

If you could do this for every road in the study region, during every hour of the year and for each vehicle type, you would be able to aggregate the total emissions for the year by simply adding up the emissions from each type of vehicle. However, since this is not feasible, roads with homogeneous traffic flows are grouped together in "Tags" and vehicle flows are sampled on each "Tag" during different hours of the day. A simple study may consider only three tag types (highway, arterial, and secondary roads) and traffic flow measurements over the period of a few days to maybe a week, whilst a more complex study may involve more Tags and statistically significant sampling of the vehicle flows on each tag over longer period of time.

#### *Why is this important?*

This activity determination involves all vehicles that operate on the roads within the study region irrespective of where they are registered or domiciled, and irrespective of where they bought their fuel. Thus it is able to generate a true emissions "picture" from on-road transport by eliminating most of the boundary effects that plague other methods, particularly in smaller study areas. It also allows emissions to be accurately assigned to specific vehicle types and specific routes and thus is useful in determining the emissions change that can be achieved through different policy interventions.

#### *What level of detail is required by vehicle type?*

To be able to assign emissions factors to vehicles, a fine level of granularity is required. Figure 85 to Figure 89<sup>7</sup> show the approximately 250 subcategories of vehicles into which the active vehicle fleet has to be broken down to accurately assign emissions factors. This involves determining the fractional mix of the active in-use fleet, within each category of vehicle; by technology, fuel type, engine and vehicle size. It is not possible to visually identify each of these subcategories when realizing a traffic count on the road. Usually the vehicle flow count is separated into nine categories of motorized vehicles, and each of these is later subdivided into their corresponding fractional subcategories as will be shown in later section of this guide.

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<sup>7</sup> in **Appendix B** - Level of disaggregation needed for emissions factor determination

The usual categories of motorized vehicle that are counted are shown in Table 2:

Additionally for some projects non-motorized flow (such as bicycles and pedestrians) should also be counted. An example would be a bike lane project in which it is necessary to determine the modal shift from different forms of motorized transport to bikes to be able to calculate the GHG mitigation impact of the investment.

### *When are vehicle counts required?*

Most calculations look to determine the annual impact of a policy intervention or project investment on vehicle emissions. Often this annual figure is then projected over a modeling period under different sets of assumptions. This requires that the traffic flow be known, or estimated over the 24 hours of each day and 365 days of the year. Since this would be an impossibly and unnecessarily large dataset, sampling is used to achieve adequate estimation of the traffic volume at the required level of uncertainty and within reasonable time and cost bounds.

### **Which days?**

Great care must be taken to ensure the days on which traffic sampling is performed are representative of the traffic flow over the total year. Normally days that fall on school holidays or close to special events (such as a football match) are avoided as the traffic on these days may be totally unrepresentative of that which normally occurs. If the sample is small, Mondays and Fridays are also often avoided since they may not be typical of the overall traffic during the working week. However it is recommended that whatever possible the sample size be sufficiently large to encompass all the days of the week and, if a low level of uncertainty (high level of precision) is required, over several weeks. This enables an estimation of the uncertainty to be made from the differences in traffic flow over different days.

Vehicle flow measurement is usually conducted in one of two ways:

- By measuring vehicle flow over week-days only. This defines an average week-day flow by hour of day (for each of the nine vehicle categories). By applying a multiplier these are extended to cover the complete year.

Here is an example of the calculation:

If the traffic on Saturdays is found to be typically 80% of the week-day average and the traffic on Sundays and festive days is 60% of the week-day average and there are 7 festive days in the year (not counting Saturdays and Sundays), the multiplier could be 331, calculated as follows:

$$\begin{aligned} &0.6 \times (52+7) \text{ Sundays and festive days} + \\ &0.8 \times (52) \text{ Saturdays} + \\ &(365-52-59) \text{ Weekdays} \end{aligned}$$

- By measuring vehicle flows over three different groups of days; week-days, Saturdays, Sundays and festive days. The average in each of these groups is then multiplied by the corresponding number of days in the year to get the annual total.

The second of these methods is evidently more exact when a large sample is applied but for smaller samples the first can be preferred. However it is good practice to measure at a few representative sites the traffic flows on weekends and weekdays to be able to accurately determine the annual multiplier that should be used.

### **What hours?**

The traffic flow can vary considerably by hour-of-day and hence vehicle counts have to be conducted on an hourly basis to measure these differences in flow. It is not sufficient to only



measure peak traffic as this data by itself would not be representative of the 24-hours. However there is often an off-peak time period in which traffic movement is low. This may happen between, for example 11 PM and 5 AM and a default traffic flow can be used to facilitate the field campaign. This default hourly traffic flow by type of vehicle has to be determined by limited sampling in one or two strategic locations.

In many cities whilst passenger car flow is low at night, heavy-duty goods vehicle traffic may be higher due to local regulations limiting their ability to circulate during daylight hours. In these cases, you would need to obtain detailed traffic counts for heavy-duty goods vehicles at night with a low default value being used during the day, whilst for other vehicles the opposite will be true.

If you use the TAMT Appliance, you will need to clone a separate study zone for goods vehicles (than that used for other vehicles) so that the default traffic flow during the off-peak hours can be applied on a different schedule.

To simplify the measurement campaign, it is common practice to not count the vehicles during the whole hour but rather to apply a sampling technique of often between 10 and 15 min. per hour. This reduces the complexity and costs of data gathering considerably and this subject will be treated in greater detail in Chapter 14.

When you decide to sample, it is good practice to validate with an “experiment” what additional uncertainty is introduced into the calculation due to sampling error. A statistical analysis has to be performed at one or two sites in the study region to determine the additional uncertainty that is associated with using a small sample size. Using too short a sampling period can introduce huge errors and the threshold for this varies from city to city. Consider the case of sampling traffic flow immediately downstream from a traffic light; when the traffic light is in *Red*, no vehicle will pass the sampling point but when it changes to *Green*, a platoon of vehicles arrives together resulting in a very high traffic count. If the sampling period is too short, you can easily get more *Reds* than *Greens* in the sample which could result in a very low, or a very high flow being reported.

For this statistical analysis, a continuous count of traffic should be made over an extended period, recording (writing down) the vehicle count in 5 minute intervals. Since it is continuous the total count over the period is known. Multiple random samples are then taken from this selection of 5 minute records and used to project the total flow over the chosen time period. The relationship between each projection and the measured total flow is an indication of the uncertainty associated with using that sample duration. Often a sample period of 15 minutes adds a sampling uncertainty of less than 3 percent. However if this additional uncertainty can be achieved and statistically demonstrated in your study area for a shorter sample it could have a major impact on study manning and costs.

### *How to enter day-type and days per year in the TAMT Appliance*

Depending on the specific study, the user has to choose and define whether to measure vehicle flow over week-days only or over the three different groups of days; week-days, Saturdays, Sundays and festive days.

This is done in TAMT on the Analysis > Vehicle Flow > Day Type per year page (see Figure 35) where either Option 1 or Option 2 needs to be selected as the active option and the appropriate multiplier captured for the active option only.

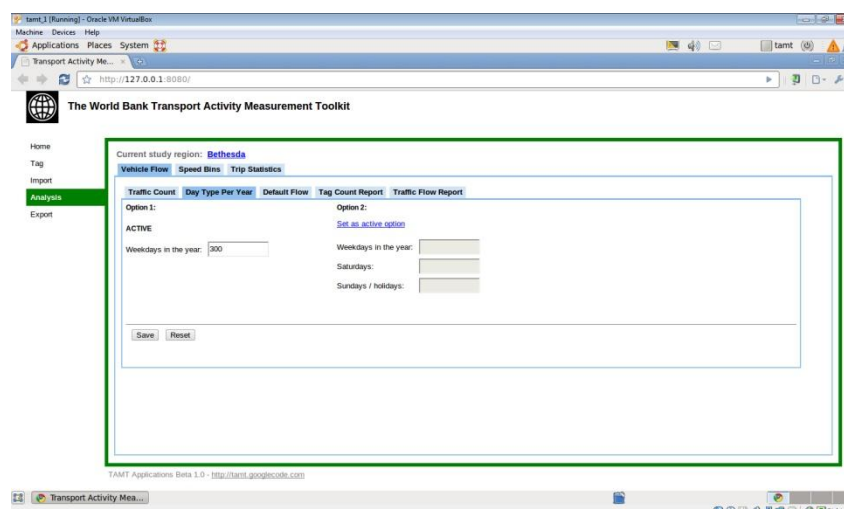


Figure 35 -Definition of Day-Type per year in TAMT

### *Where should vehicles be counted?*

Whether you are using the TAMT Appliance or not, you will need to count traffic flows at least at one location for each group of homogeneous road sections (that we refer to as “Tags”). This includes the traffic on residential, commercial, and industrial secondary roads.

In most studies you should consider performing vehicle counts at several locations within each homogeneous group of road sections for a very good reason: if you count at only one location, you will never know, nor be able to demonstrate, that this location is truly representative of the traffic on that Tag. By having several counts and comparing them considerable rigor can be added to the measurement campaign.

The locations selected should be the most representative of the set of road-links in each Tag. Since these vehicle counts need to be repeated periodically to be able to measure changes, it is good practice to have some locations that are used in all fieldwork campaigns and other additional locations within the same tags that change from period to period. This allows traffic flow consistency to be evaluated and lets you validate that the main locations selected are in fact representative of each set of set of road-links.

In an extended sample, it is good practice to use several locations on each Tag and to calculate the variance in traffic flow between these locations (for the same tab) as an estimate of the measurement uncertainty associated with the sample site location.

It is recommended that sample sites are distributed among areas with different levels of economic activity. These should include areas that are representative of the lower half of the income and the upper half of the income bracket within the study zone. Sites should not be in the absolute poorest or richest part of the zone, but rather in areas that have the greatest representation. This should include the main commercial area--if there is one within the study zone. Due to their much greater knowledge of their own city, it is an important task of the local institutions to play a primary role in the selection of the sampling locations within the study area.



Sampling sites should also be legal and secure. If a field team is to be deployed to count vehicles or operate videos then consideration should be given to finding representative intersections where one team sampling 10-15 mins per hour is able to monitor four traffic flows (in both directions on two intersecting streets) since this drastically reduces the cost and complexity of obtaining data. Other sites will be chosen because of specific facilities that they can offer, such as already installed video cameras, for example, or a police presence that adds security.

### *How to count vehicle flows*

In general, there are three ways of getting vehicle counts. These can be used separately or in combination:

- Manual counts
- Video recordings
- Automatic counts

#### **Manual counts**

The simplest way is to deploy trained field personnel to count vehicles at a pre-defined sampling point on that stretch of road. For a low-flow road, one person can count all vehicle categories, but more personnel will be required for higher traffic flows and multi-lane roadways. Usually these traffic counts are recorded on paper forms and in many cases to use of mechanical counting boards with multiple push button counters can be of great assistance. This subject will be treated in greater detail in Chapter 14.

This method of collecting traffic flow data, whilst simple and apparently low cost in many situations, is not the preferred method because it does not generate an audit trail that allows an auditor to recheck the flow calculation (and traffic counts) at a later date. This is particularly critical for low uncertainty (high precision) studies such as Clean Development Mechanism (CDM) in which strict field supervision and additional traffic counts by supervisory staff would be needed to demonstrate the field work is being correctly carried out. Chapter 14 looks at this quality assurance/quality control requirement (QA/QC).

#### **Video recordings**

These may be pre-installed for traffic monitoring or for a different purpose. Before deploying staff and cameras for traffic-count duty, it is very worthwhile investigating what options may be available using existing resources since these can reduce costs and lower uncertainties by allowing traffic monitoring over a longer period. Figure 36 shows cameras installed on a BRT station in Mexico City. In other parts of the city, agreement was obtained to program police surveillance cameras to specifically record real-time traffic flow for 15 minutes per hour over a four week period (except when a security incident required differently). Be careful though, that the recorded frame-rate is high enough to record all the vehicles that pass the camera. Figure 37 shows a camera that was specifically set-up by the study team on an overpass bridge in Sao Paulo, Brazil for the traffic count field work. Figure 38 and Figure 39 also show typical scenes where trained field personnel are using video cameras to record traffic flow.



*Figure 36 - Cameras installed on BRT station in Mexico City*



*Figure 37 - Camera located on an overpass bridge in Sao Paulo, Brazil*



*Figure 38 - Filming traffic on a secondary street*



*Figure 39 - Camera operator, support person and police protection*

These video recordings are later used by a different team to establish counts of vehicles by type (passenger car, small bus, taxi, truck, etc.) back at the office.

It is best if the camera can be located on an overpass or in some other elevated position so that vehicles in the lane closest to the camera do not obscure the vehicles in the other lanes. From such a location, the camera should be zoomed into the appropriate frame size that will capture the entire roadway in one direction.

Usually the same team can sample traffic flows in different directions (for example by filming at an intersection with 15 mins per hour sample in each four directions (both directions on two streets)). Here it is critical that the camera operator starts each film sequence with a 5 sec recording of a card that shows the name of location, route designation, direction of travel, date, hourly period, and camera designation. This helps to avoid the filmed data from being assigned to an incorrect location/time in the event the digital recording medium is mistakenly put into the wrong case. In all cases, the camera should continually record the day and time stamp.

When the filming is performed by the study team, the cameras used are standard consumer digital cameras with automatic focus and flash memory. It is recommended that units are selected with low light capability and that enough recording medium and spare batteries are procured for two days operation. It is good practice to download the recordings to a computer hard drive on a daily basis. This drive must be backed-up daily. When pre-installed cameras are used, a multi-channel digital video recorder can allow up to 16 feeds to be recorded continuously to a high capacity hard drive. Once a disc or flash memory is recorded, it must be protected so that it will not be accidentally erased.

### Analysis of the recordings

The digital media will be reviewed by personnel trained to correctly classify vehicles on a large screen TV or computer monitor. The system should allow videos to be stopped, run in slow motion, or backed up to help produce accurate vehicle counts. In high traffic flow situations it is helpful to have several people simultaneously reviewing the video, either counting traffic in different lanes or each counting different vehicle types. Equipping them with hand tally mechanical push button clicker counters is good practice. The reviewers look at the video, stopping it, and putting it into slow motion as needed to count each vehicle type. They must record the date, road designation and starting and ending times of each video section with care. A template is provided with this document.

### Automatic counts

There are many automatic traffic counters in use. Some can generate very detailed information, such as the automatic license plate readers (see Figure 41) use in congestion charge zones and toll roads, whilst others produce more basic data (see Figure 40) that even so, nicely complement other manual or video traffic counts. Whilst some may not separate the count by vehicle type, producing only a total figure, this can be disaggregated using detailed data from other methods.



Figure 40 - Pneumatic tube counter



Figure 41 - Automatic License Plate Reader

It is good practice to investigate which automatic traffic counters are installed in the study region before defining a sampling plan, and make a concerted effort to obtain data from them.

### *How to capture vehicle counts in the TAMT Appliance*

You should at this stage have multiple traffic counts over most of the 24-hour period for several days on each Tag. Each of these counts need to be entered into TAMT. This is performed using the Analysis > Vehicle Flow > Traffic Count page as shown in Figure 42.

Note that the date is selected from the calendar and that the times are to be entered in a hh:mm format (for example 13:25). The Tag name is captured from the drop-down list and the traffic counts should be the number of vehicles counted between the start- and end-times, for each vehicle category as shown in Table 2. Only those vehicle categories with vehicle counts need to be entered.

Table 2 - Categories of motorized vehicles

Code	Categories of motorized vehicles
2W	2-wheelers
3W	3-wheelers
TX	Taxis
PC	Passenger cars (other than taxis)
LDV	Light-duty passenger vehicles (other than cars and taxis)
LDC	Light-duty commercial (goods) vehicles
MDB	Medium-duty minibuses
HDB	Heavy-duty buses
HDC	Heavy-duty trucks

TAMT uses the physical vehicle counts (for example 147 passenger cars) over the actual measured periods (for example between 11:20 and 11:35) to determine average hourly traffic flows for the day of week and tag selected. Thus If the start and end times are in different hours (for example 13:50 to 14:20) then TAMT splits the count proportionally.

Figure 42 - Traffic Count Data Entry Page in TAMT

### *How to enter default traffic flows in the TAMT Appliance*

Default traffic flows for low-traffic hours are entered using the Analysis > Vehicle Flow > Default Flow page as shown in Figure 43. These have to be entered only for the day type option of (i) week-days only or (ii); week-days, Saturdays, Sundays and festive days as selected in Figure 35. TAMT uses these default data for contiguous off-peak (often night-time) hours with little traffic where traffic count data has not been entered (see Figure 42). If there are gaps in the traffic count hours for a Tag giving hours with no data, TAMT estimates this by interpolation.

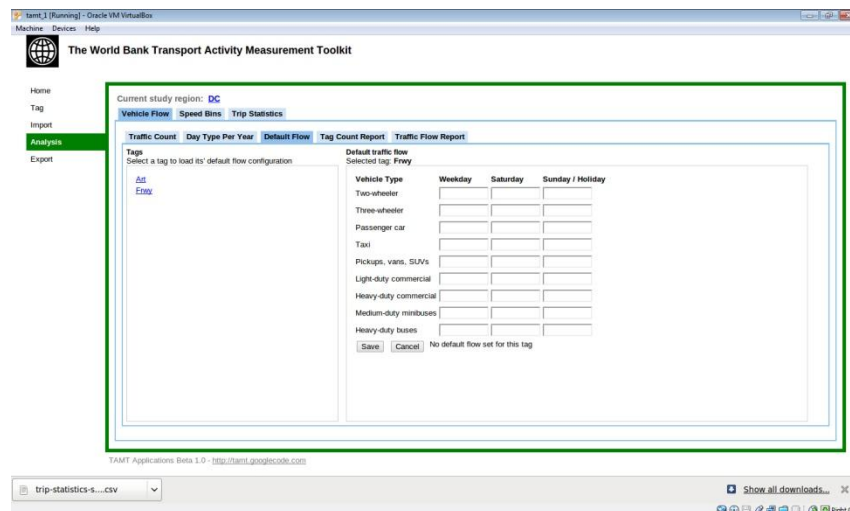


Figure 43 - Default Traffic Flow Data Entry Page in TAMT

## How to detect where more traffic counts are needed in TAMT

The Tag Count report that is found at Analysis > Vehicle Flow > Tag Count report page (see Figure 44) is a useful tool to be able to easily see where vehicle count data is missing. The report shows each Tag individually (by clicking on the Tag name) over the 24 hour period and the daytype that was captured when the vehicle counts were entered into the system. This report does not include the default data and gaps filled by interpolation; only traffic count data.

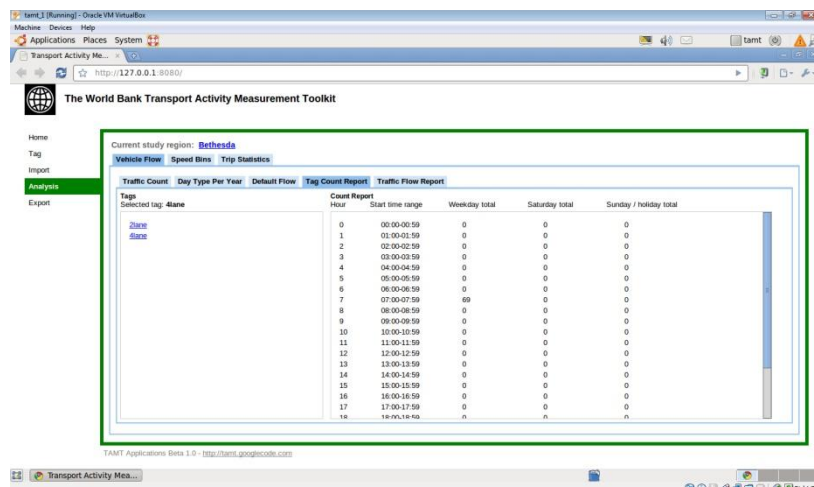


Figure 44 - Tag Count Report in TAMT

## The traffic flow report from the TAMT Appliance

A different and more detailed report is to be found on the Analysis > Vehicle Flow > Traffic flow report page (see Figure 45). This has to be generated by clicking on the "Create Report" button. This report shows separately for each Tag and Day-type, the hourly vehicle flow by hour of day for each vehicle category. This report includes the default data and gaps filled by interpolation.

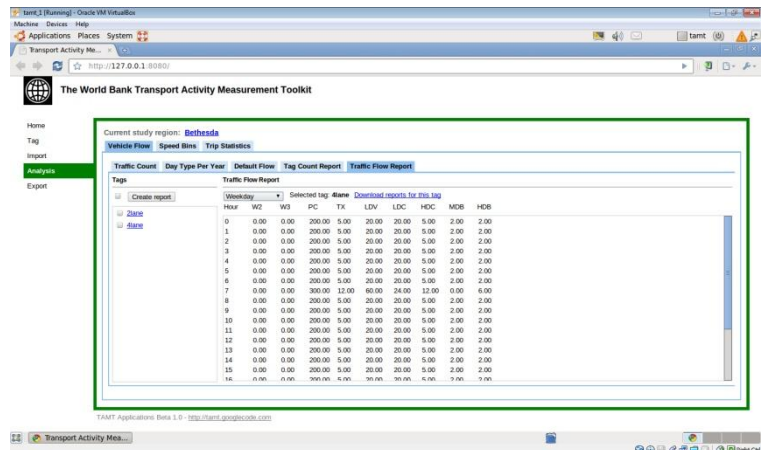


Figure 45 - Traffic Flow Report in TAMT

This report can be downloaded as a csv file.



## How to measure driving speed and drive cycle

### Why is this important?

Vehicle fuel consumption and emissions are not only dependant on the type and technology of the vehicle, they are also on many other factors such vehicle speed, acceleration, the number and length of idle periods, and driving style (or driver aggressiveness), etc. Although emission factors are expressed as a grams per kilometer value, this figure will be different for different driving conditions, and varies over quite a large range. Under laboratory conditions, vehicle fuel consumption and emissions are measured on different drive cycles, each representative of different driving conditions.

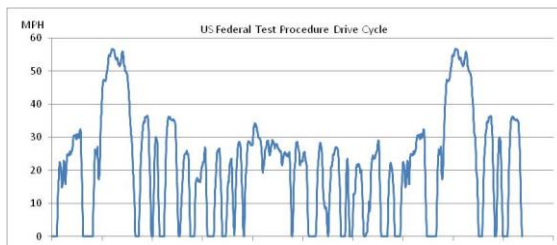


Figure 46 - Federal Test Procedure Drive Cycle

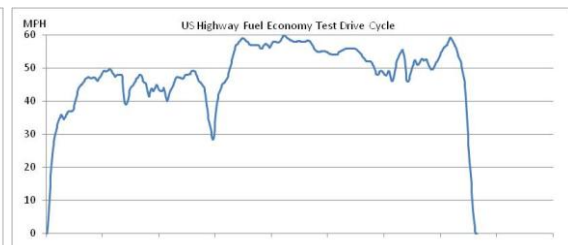


Figure 47 - Highway Fuel Economy Drive Cycle

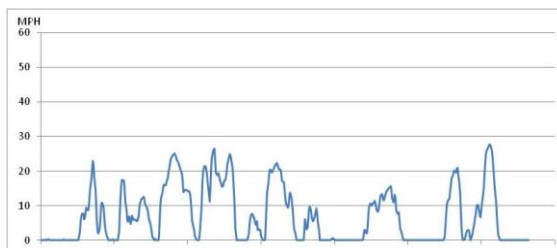


Figure 48 - New York City Drive Cycle

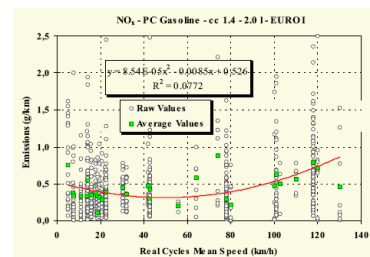


Figure 49 - COPERT Speed-dependant Curve

Figure 46, Figure 47, and Figure 48 show respectively the typical driving conditions represented by: the US Federal Test Procedure Drive Cycle, the US Highway Fuel Economy Drive Cycle and the US New York City Drive Cycle. It can be seen that the speeds and accelerations are totally different in each, and as an outcome the recorded fuel consumption and emissions also vary considerably.

By combining the results of thousands of empirical tests on different drive cycles, it is possible to develop a mathematical relationship that allows the fuel consumption and emissions to be predicted under different conditions. Figure 49 shows a typical speed-sensitive emissions factor curve developed under COPERT. In MOVES, similar relationships have been developed that are both speed and engine stress related. Since any two nominally identical models vehicles will often have differences in their emissions test results due to variations in manufacturing tolerances and, more importantly, their current maintenance status, these speed-sensitive curves are constructed by taking an "average" of a large sample of tests. COPERT reports the  $R^2$  "curve fit-factor" for the speed sensitive emissions curves which allows variability to be taken into account.

These resultant curves are often more valid than local emissions measurements based on very small sample sizes, no matter how sophisticated the testing equipment might be, because of such variability and the impossibility of demonstrating that the tested vehicle was in fact representative of the in-use fleet.

One basic point which must be reinforced is that such speed-related emission factors take into account the constant fluctuations in acceleration, deceleration and idle period that occur in normal driving. As such, each factor is an estimate of the grams of pollutant emitted per kilometer from a vehicle traveling in a traffic stream with a given average travel time (mins/km) which is often expressed as an **average** speed. It is **not** a measure of the emission rate of a vehicle when it is actually traveling at that constant speed.

Figure 50 is an example of how CO<sub>2</sub> emissions (and by reference, fuel consumption) from passenger cars vary over a range of 5:1 as a function of average vehicle speed in MOVES.

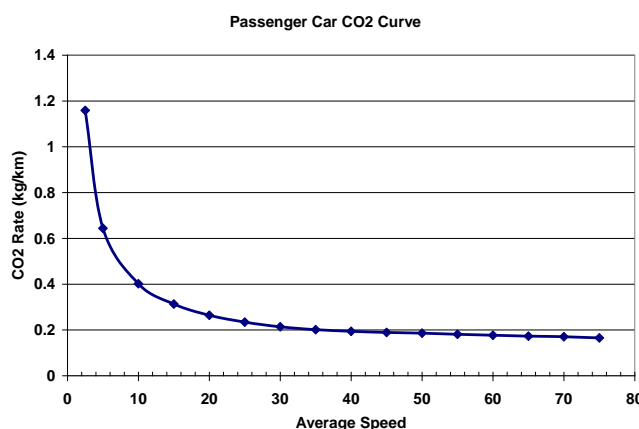


Figure 50 - EPA speed correction factors for CO<sub>2</sub> emissions for passenger cars

The shape of this curve is different for different technology vehicles and for each pollutant and clearly illustrates why the measurement of speed is important to fuel consumption and emissions determination.

## *Methods used to determine driving speed*

There are several methods that can be used to determine driving speed. Some as outlined below will give the average travel speed over a length of road (a link) whilst others deliver second-by-second data that allows a more precise determination of the emissions factors by binning travel into different speed bins.

A quick illustration based on Figure 50 can show why binning is more accurate:

Consider the case of a passenger car that travels one kilometer; half at 5 kph and the other half at 15 kph.

- The average speed of this car is 10 kph. Figure 50 shows that its CO<sub>2</sub> emissions could be expected to be 0.4 kg/km. This gives an emission of 0.4 kg over the kilometer.

However if we calculate each speed separately we obtain:

- at 5 kph for 500 mt. Figure 50 shows CO<sub>2</sub> emissions of 0.65 kg/km.
- at 15 kph for 500 mt. Figure 50 shows CO<sub>2</sub> emissions of 0.33 kg/km.



This gives an emission of 0.49 kg over the kilometer. A difference of over 20%!

Commonly used methods include:

1. The moving vehicle observer technique
  - a. Using a driver's log
  - b. Using GPS
2. Using Cameras
3. Recording normal trips using GPS
4. Using traffic modeling
5. Accessing existing data

Often these can be used in combination.

TAMT is specifically designed to manage and use GPS-generated data.

### **Moving vehicle observer (MVO) surveys**

These involve driving a vehicle around a pre-defined and representative schedule of routes, recording time and distance travelled. Such surveys have been undertaken regularly in many major cities. In London, for example, moving car observer surveys have been used since the 1950s, and have been stepped-up considerably within and around the charging zone since 2002 to provide a greater level of detail. The charging zone, Inner Ring Road, and key radial routes approaching the zone are monitored continuously (on a two-monthly cycle), while elsewhere, where congestion effects are predicted to be minimal, i.e. the rest of inner London and outer London, the networks are surveyed at one and three year intervals respectively.

Care has to be taken to ensure that the MVO travels at the average traffic speed. This is achieved when the same number of vehicles overtake the MVO as are overtaken by the MVO on each stretch of the route. Achieving this requires practice. If the MVO is continually in the fast lane or in the slow lane of a route, then the results will not be representative of overall traffic speed.

In many urban environments, it can be assumed that the travel speed will be similar for most vehicles, with the exception of buses, taxis and possibly 2-wheelers. However on inter-city routes it may be necessary to track travel times separately for different classes of vehicle. This will involve the MVO closely matching the travel patterns of the vehicle class that it is recording.

This same technique can be used on other modes of transport such as NMT - cyclists and pedestrians.

There are two ways of getting travel time information from a MVO survey:

#### *Using a Driver's Log*

The first involves a driver's log in which the time of day (including seconds) is recorded on passing specified landmarks (usually intersections). It is good practice to record additionally the time in seconds that the vehicle is stationary at each traffic light. Also it is important to pre-define if the timestamp should be recorded at arrival at the intersection or on leaving the intersection to ensure consistency.

If the vehicle's driver is to record these timestamps then it is useful to fix a large digital clock in his field of view. If a passenger records the data, stopwatches can be used.

This will generate average travel times over specific links or sections of road, which can then be applied to all other sections of road associated with the same tag.

### *Using GPS*

A better way is to equip the MVO with a GPS logger and record second-by-second his position, time, and speed. There are many low-cost, high-sensitivity GPS loggers on the market that have the capacity to record over 100,000 GPS points thus allowing continuous recording for more than 24 hours. After this period, the data has to be downloaded to a computer and the logger's battery recharged, or exchanged. More sophisticated loggers (that are also more expensive) can transmit the data back to a server whilst they are in operation, or have higher capacity.

These devices are usually self-powered and can easily be carried by a bus-passenger or mounted on the helmet of a motorcyclist.

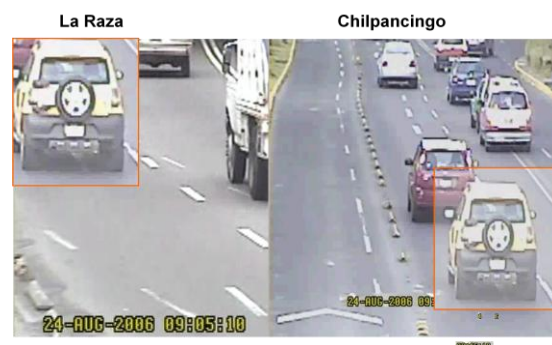
Using GPS reduces the demand on the driver to record, but it is still useful for him to register the arrival time at distinct landmarks as a means of control and to more easily find travel traces for specific parts of the route.

### **Using Cameras**

Cameras can record the travel time of vehicles by using a process of by matching sample observations of the same vehicle between pairs of cameras. In cities where enforcement and monitoring camera sites are equipped with automatic number-plate readers (ANPR) this can be done automatically by mining the associated database (using a process of anonymisation to protect privacy as necessary).



*Figure 51 - Cameras installed on BRT station*



*Figure 52 - Time-stamping sample vehicles*

Even without ANPR this is a useful technique. Mexico City decided to install video cameras on the stations of a pilot BRT corridor along Insurgentes (as seen in Figure 51) at a cost of approx US\$17,000 for 10 cameras and recorders including installation. These allowed continuous recording of traffic that was used for vehicle flow counts and to determine average traffic speed over the 24 hour period. Sufficient, easily-identifiable vehicles were found (see Figure 52) to measure the travel speed between consecutive cameras with a relative standard daily error of less than 1%.

Care had to be taken to ensure that the clocks of each recorder were synchronized and that any deviation was noted in the calculations.

### Recording normal trips using GPS

Since low-cost, high-sensitivity GPS loggers can be bought for US\$50-80 dollars each, it is feasible to have a number on hand and "lend" them to normal local people going about their daily business. These provide multiple record of real trips, as opposed to artificially defined trips around a pre-defined and representative schedule of routes. These loggers can be setup to record only when the vehicle is in motion, so provided that they can be connected to a cigarette lighter socket in the vehicle they can be retrieved every two weeks for data download (assuming an average of less than 2 hours travel per day) and swap to another vehicle. Used in this way, 50 loggers could generate up to 10 million second-by-second data points per month, giving a precise representation of travel in the study area.

This quantity of data could easily overwhelm many analytical techniques, however TAMT has been specifically designed to manage and use high volumes of GPS data. In a MVO survey, it is easy to assign second-by-second data points to specific routes since these are known by design, beforehand. When recording normal trips, however, the software has to allocate each second-by-second data point to its corresponding route and this task would be extremely time consuming to do by hand because each trip can be different. The TAMT Appliance performs this analysis automatically with no practical limit on the number of points.

### Using traffic modeling

All traffic models are able to estimate average vehicle speeds per link from the measured or estimated vehicle flows (vehicles per hour) and the characteristics of the link. This is particularly useful in ex-ante estimations but may not truly represent real driving conditions "on the ground".

A variant of this approach is to measure and calibrate vehicle travel time vs flow using GPS or driver logs on specific sections of road (an example of which is shown in Figure 53 for one section of the Mexico City Insurgentes corridor). This can then be used to estimate the travel time on this section of road under different vehicle flow conditions, assuming that no other changes are made that affect traffic flow.

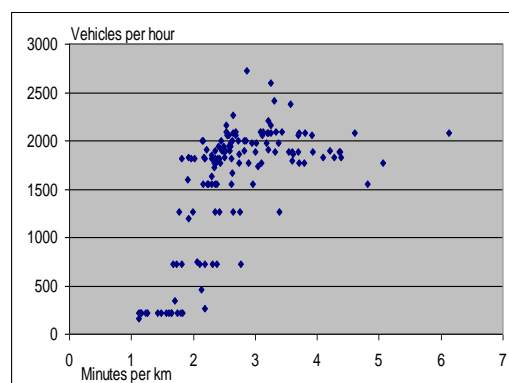


Figure 53 - Empirically measured traffic speed-flow relationships

Such analysis can be useful to isolate the impact of say a traffic light synchronization scheme. A travel time vs flow analysis could be conducted before implementing the traffic light synchronization and used to evaluate the differences against speed and flow measurements performed after implementation. Such an analysis involves the statistical treatment of variance to determine the measurement uncertainties.

### Accessing existing data

Existing sources of travel time data should not be overlooked. These can include:

- **Police and other security cameras.** In Mexico City access to recordings from police security cameras provided vehicle count data and vehicle speed data.
- **Automatic traffic flow counters.** Some, such as radar based units can also provide speed information
- **Congestion zone and toll road ANPRs and gantries**
- **Fleets.** Many fleets of vehicles already use GPS or on-board speed recorders. These include bus fleets, long-distance trucks and some delivery vehicles.

Whilst these may not cover your complete data needs, they may provide important complementary information.

### *Binning for accuracy*

As seen above, greater accuracy can be achieved in the calculations if vehicle travel can be split amongst various bins and the emissions, or fuel consumption calculations performed separately on each bin. The smaller each bin, the better the final estimation. TAMT currently accumulates the fraction of vehicle travel, by type of vehicle, into five-kilometer-per-hour speed bins, based on the instantaneous speed of the vehicle as reported by the GPS logger, starting in zero and up to the maximum speed registered (0-5kph, 5.1-10kph, 10.1-15 kph, etc).

An Emissions Factor model can use this output from TAMT to determine the corresponding emissions factors covering local pollutants, CO<sub>2</sub>, and fuel consumption for each bin. By multiplying these emissions factors by the vehicle activity that corresponds to each bin, the total emissions or fuel consumption can be determined.

Some models such as MOVES and IVEM also bin vehicle travel, but in addition to speed use vehicle specific power. The description of these methodologies is outside the scope of this practitioner's guide but could be easily added to TAMT in a future release.

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## Chapter 8

### *Using GPS loggers with TAMT*

#### *GPS Loggers*

The equipment used in the methodology on which TAMT is based consists of GPS loggers that are able to collect global positioning data on the location of the device on a second-by-second basis. This allows them to calculate and store the speed, location, and direction of travel, of the vehicle (or person) carrying the device. Because the GPS signal can also provide second-by-second data on the elevation of the antenna, the slope (grade) of the roadway being traveled can also be reported. Changes in speed from one second to the next allow rates of acceleration and deceleration of the vehicle to be calculated, and this when combined with the slope of the road and the speed of the vehicle allows a determination of the vehicle specific power (or workload).



*Figure 54 - Typical GPS loggers*

There are many models on the market (see Table 3) in an approximate price range of US\$50-90 dollars that can be used for this purpose. When selecting, it is useful to have 51-66 channels with high receiving sensitivity with AGPS capability. They are commonly based on the MTK / MTK II chipsets.

*Table 3 - Partial list of GPS loggers*

BL-99 (seen on <a href="http://www.etek.com.tw">www.etek.com.tw</a> )	i-Blue ( <a href="http://www.transystem.com.tw">http://www.transystem.com.tw</a> );;
Bluenext ( <a href="http://www.bluenext.co.uk">http://www.bluenext.co.uk</a> )	iTrek z1 ( <a href="http://www.itrekgps.com">http://www.itrekgps.com</a> );
Blumax ( <a href="http://www.blumax.eu">http://www.blumax.eu</a> or <a href="http://www.eurotronic.net/">http://www.eurotronic.net/</a> )	Konet ( <a href="http://www.konet-sys.com">http://www.konet-sys.com</a> );
EBON ( <a href="http://www.ebontek.com">http://www.ebontek.com</a> )	NCS-NAVI + ( <a href="http://www.ncsnavi.com">www.ncsnavi.com</a> )
GISTEQ	Pentagram ( <a href="http://www.pentagram.pl">pentagram.pl</a> )
( <a href="http://www.wondeproud.com">www.wondeproud.com</a> , <a href="http://www.gisteq.com">www.gisteq.com</a> ),	Photomate ( <a href="http://www.transystem.com.tw">http://www.transystem.com.tw</a> );
Gosget;	Qstarz ( <a href="http://www.qstarz.com">http://www.qstarz.com</a> );
Holux ( <a href="http://www.holux.com">www.holux.com</a> )	Sanav ( <a href="http://www.sanav.com">sanav.com</a> , <a href="#">report</a> )
	Visiontac VGPS-900 ( <a href="http://www.visiontac.com">http://www.visiontac.com</a> )

These loggers typically include an antenna; have on-board power for over 24 hour operation, and the capacity to record at least 100,000 waypoints. They should be capable of outputting a NMEA-0183 - GGA, GSA, GSV, RMC data set at a second-by-second rate with an accuracy of better than 3m (unaided). It is useful if they can be setup to record only when motion has been detected and that they come equipped with a car charger and USB download port.

## Data Logger Software

Often these units come with a PC-based software that allows them to be configured. However, the open source BT747 Data Logger Software (<http://www.bt747.org>) is an excellent choice for setting up most loggers, downloading data and converting data files between different formats. It can be installed within the VirtualBox (on UBUNTU) or on the Windows 32 & 64 bit, MacOSX, or Linux Host systems, and will be used as an example in this Guide.

## Configuring the GPS Logger

Before putting the GPS logger into service, previous log files have to be downloaded and it has to be configured. Figure 55 shows the main configuration page.

The logger should be configured to record at a minimum the NMEA RMC sentence. This is the recommended minimum specific GPS/TRANSIT data giving UTC Date of fix, Time of fix, Latitude, Longitude, Speed over ground in Knots, and Course Made Good in degrees true. It also contains an indicator of whether it was a valid fix and the Magnetic variation. If the Antenna altitude above mean-sea-level is required the NMEA GGA sentence should also be recorded.

The minimum configuration is shown in Figure 55, If any of this data is missing the TAMT Appliance will not be able to process the GPS log files. If more data is included, it will not get in the way, but will reduce the number of seconds of data that can be recorded and stored in the logger.

Figure 56 shows how the logger can be configured by NMEA sentence type to record only the RMC sentence.

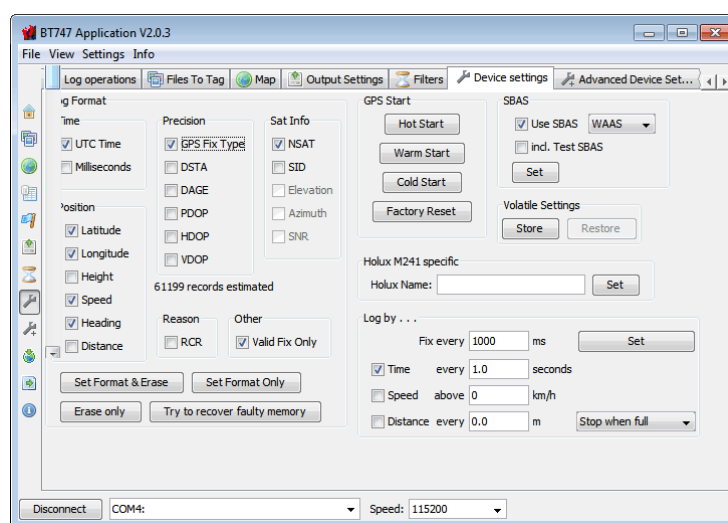


Figure 55 - Configuring the GPS Logger with BT747

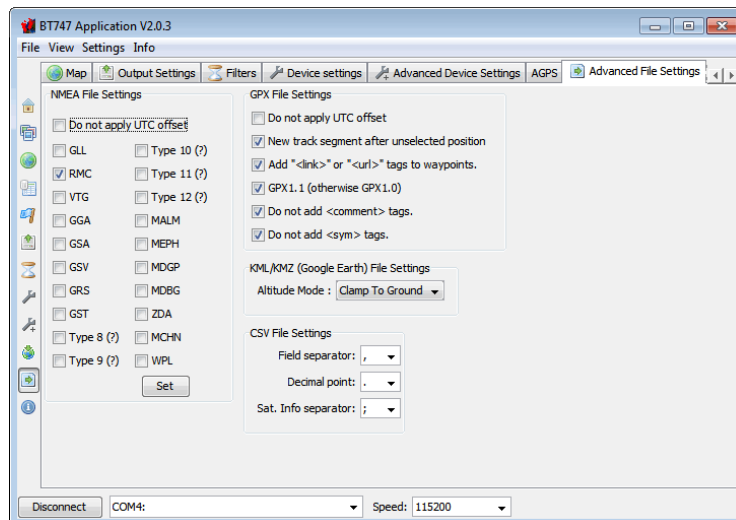


Figure 56 - Configuring the GPS Logger by NMEA sentence type

There are two additional decisions to be made at the time of configuring the logger:

1. Setting the logger to continuously record second-by-second data or setting the logger to record second-by-second data above 10 kph
2. To overwrite when full or to stop recording

The advantage of setting the logger to record second-by-second data above 10 kph is ease of administration. If the logger can be installed in a vehicle using its car charger, a capacity of 110,000 way points would allow up to 30 hours of in-use operation spread over several days. This could require someone collecting the logger and downloading data every fortnight or more, but if it is installed to record continuously, the logger would need to be collected and the data downloaded almost daily. However, setting the logger to record second-by-second data only above 10 kph, means that you will not collect data on the idling time at traffic lights and due to congested traffic and thus will under-estimate both fuel consumption and emissions.

A solution to the problem could be to have some loggers operating in each mode. Then loggers in vehicles that are difficult to contact can serviced every fortnight whilst the others (in continuous recording) can generate data on the fraction of vehicle use in the lowest two bins (0-5 kph, and 5-10 kph) accumulating this fraction to the GPS logs from the other vehicles.

The setting to overwrite the GPS memory when full or to stop recording is also a choice that requires thought. The preference is to stop when full (no overwrite) since it generates a continuous log of the vehicle travel whereas overwriting can divide the journey into two trips. However overwriting can generate more recent data.

Please note the TAMT requires the logger to generate the NMEA RMC sentence. Most of loggers can be configured to generate more information than this but please note that by configuring them to do so the capacity of logger for storing data points is proportionally reduced.

## *Installing the GPS logger*

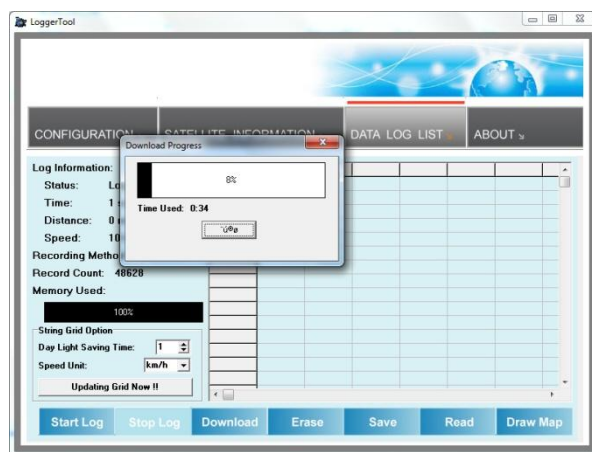
Upon installing the GPS unit in the vehicle and turning on, a small red light will come on. At this point, the red light simply indicates that the GPS module is receiving power from the battery. Once the GPS module begins to receive signals from sufficient satellites for a reading, the light will begin to blink. In order for the GPS unit to be collecting data, the light must periodically blink. If this does not occur, a different location for the unit, allowing a stronger signal from the satellites should be found.

While traveling the assigned route, the driver should periodically check the GPS unit to make sure that the light is still blinking. Sometimes the signal will be lost because of tall buildings or foliage etc but if this happen excessively it could indicate a problem. It is important to detect such problems early on and not after a fortnight of field work.

It is good practice to log a short run with the logger configured to ensure that all the settings are correct before embarking on a complex field survey campaign.

## *Downloading GPS Data*

How to download GPS data depends on the specific unit you have and it is important to follow the specific instructions given by its manufacturer.



*Figure 57 - Data download in progress*

In all cases the raw data should be downloaded (Figure 57) and carefully labeled to indicate the date, vehicle type, usage, and route. This can then be converted to the specific NMEA format using BT747 (see Figure 58).

## *Converting GPS Data to NMEA format*

The converted log files must be text files in a specific NMEA format. TAMT requires users to configure BT747 so that it records and outputs the NMEA RMC sentence. If it additionally records other NMEA sentences, TAMT in its current form, will ignore them. A sample of a log file containing RMC and GGA sentences is provided in Figure 59.



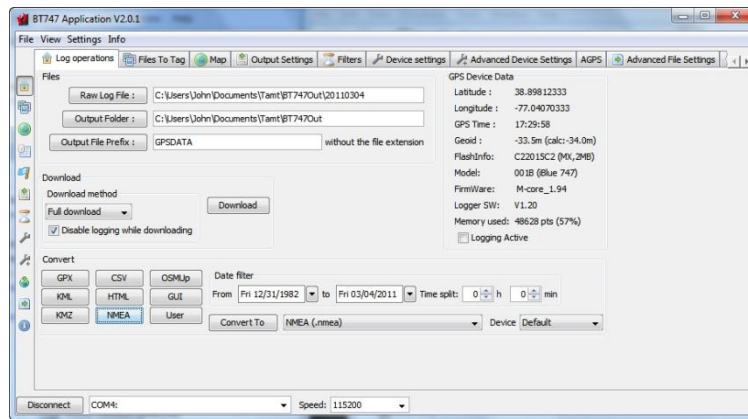


Figure 58 - Converting GPS data to NMEA format

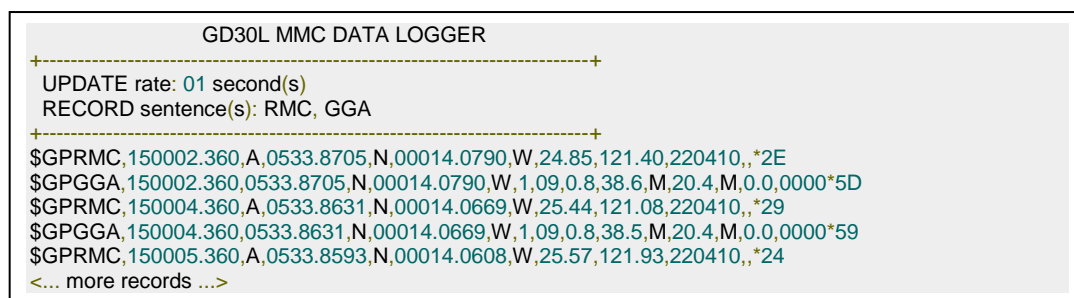


Figure 59 - Example of a log file in which only the \$GPRMC sentences will be used by TAMT

A single GPS point in TAMT is derived from each \$GPRMC line in the log file. \$GPRMC provides date, time, latitude, longitude, bearing and speed. The line following each \$GPRMC entry in Figure 59 is the \$GPGGA sentence, which provides altitude.

If the RMC sentence does not have valid data in every field, processing the records may fail. It is good practice to open some of the converted files in a text file editor to make sure that they have this format.

## Checking the NMEA file data for errors

### File names, headers and footers

The converted text file that contains the NMEA sentences may be given any name and name extension. Within this file, there may be several lines of text before the first RMC sentence (as seen in Figure 59); this will not affect operation in any way. There may be empty lines between each RMC sentence and even additional NMEA sentences. Additionally at the end of the file that may be several lines of text. None of these affect operation.

### NMEA Encoding

An NMEA sentence consists of a start delimiter, followed by a comma-separated sequence of fields, followed by the character '\\*' (ASCII 42), followed by a CRC32 checksum expressed as two hexadecimal digits, followed by an end-of-line marker.

The start delimiter is normally '\$' (ASCII 36). and TAMT expects the following two characters to be "GP".

## RMC sentence structure<sup>8</sup>

The RMC sentence is the recommended minimum specific GPS/TRANSIT data.

```

=== RMC - Recommended Minimum Navigation Information ===

-----
      1           2 3           4 5           6 7 8 9           10 11 12 13
      |           | |           | |           | | | |           | | | |
$--RMC,hhmmss.ss,A,llll.ll,a,yyyy.yy,a,x.x,x.x,xxxx,x.x,a,m,*hh<CR><LF>
-----

```

Figure 60 - RMC Sentence structure

Figure 60 shows the expected structure of the RMC sentence. Practical examples of this include:

eg1.

```
$GPRMC,081836,A,3751.65,S,14507.36,E,000.0,360.0,130998,011.3,E*62
```

eg2.

```
$GPRMC,225446,A,4916.45,N,12311.12,W,000.5,054.7,191194,020.3,E*68
```

**The fields that are used by TAMT and must exist in the sentence are shown in Table 4. None of these fields may be blank.**

Table 4 - RMC Sentence structure

Index	Name	Example Data	Description	Used by TAMT
	Sentence Identifier	\$GPRMC	Global Positioning System Fix Data	✓
1	Time	225446	22:54:46 UTC	✓
2	Navigation receiver warning	A	A = Valid position, V = Warning (Invalid)	
3,4	Latitude	4916.45,N	Latitude 49 deg. 16.45 min. North	✓
5,6	Longitude	12311.12,W	Longitude 123 deg. 11.12 min. West	✓
7	Speed over ground (knots)	000.5	0.5 knots	✓
8	Course Made Good, degrees true	054.7	54.7 degrees	✓
9	UTC Date of fix	191194	19 November 1994	✓
10, 11	Magnetic variation	020.3,E	20.3 deg. East	
12	FAA mode indicator (NMEA 2.3 and later)		A=Autonomous, D=Differential, E=Estimated, N=Data not valid	
13	Checksum	*68	Used by program to check for transmission errors	

In NMEA 2.3, several sentences (including the RMC sentence) received a new last field carrying the signal integrity information needed by the FAA. The values in the GGA mode field were extended to carry this information as well. TAMT operates perfectly with this

<sup>8</sup> (from <http://home.mira.net/~gnb/gps/nmea.html#gprmc>)

NMEA 2.3 and later sentence structure as well as with the previous versions in which this added field may be empty.

## Visualizing the NMEA file data

The easiest way to visualize the NMEA data before uploading it to TAMT is by using Google Earth. After installing Google Earth (<http://www.google.com/earth/index.html>), you can use the Open menu to load the \*.nmea track file as you can see in Figure 61. You have to select the option of "all file types" to be able to find and upload this file. Figure 62 shows several tracks uploaded and you will see how Google Earth provides a scrollbar that allows you to travel along the uploaded traces by time of day.

Another good option is to use the BT747 application to view the log data. This uses OpenStreetMaps, which may not have a complete roadset for the study location.

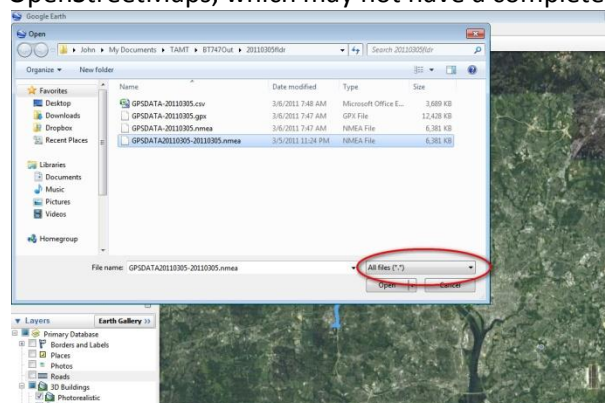


Figure 61 - Opening the NMEA track in Google Earth

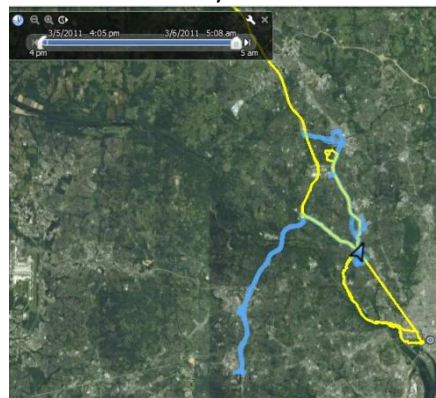


Figure 62 - Visualizing the NMEA track in Google Earth

## Importing GPS Data into the TAMT Appliance

Any number of GPS log files can be included in a compressed ZIP file. These ZIP files are imported into the PostGIS database in TAMT with the following attributes:

- The ZIP file is stored directly in the database with an ID and date created field
- The GPS trace meta data (name, description) are stored in a separate table.

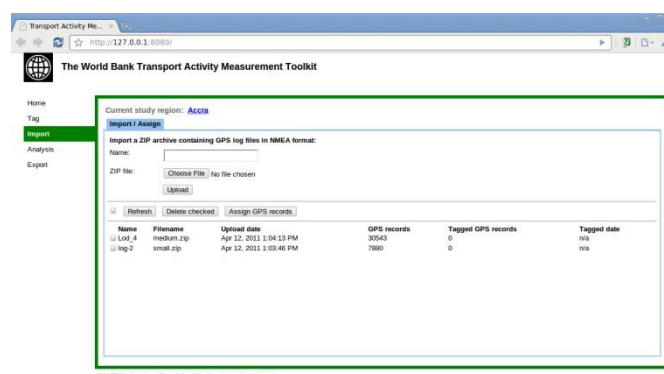


Figure 63 - Importing GPS zip files into TAMT

To import, the ZIP file is located on disc (with the "choose file" button) and given a unique name then the "Upload" button is clicked.

After successful upload, the ZIP file is processed, creating individual records for each GPS second-by-second waypoint. These points have latitude, longitude, bearing, speed, and altitude, and are related to the GPS trace information provided during the upload process.

The import page (see Figure 63) shows which files have been imported, the number of valid GPS second-by-second waypoints each contained, and how many of these were assigned to the tagged roads. This page also allows you to delete ZIP files that were previously uploaded.

### *Assigning GPS points in the TAMT Appliance*

Once the Zip files that contain the GPS traces have been imported, the next step is to assign each of these GPS points to the corresponding tag (tagged roads and subzones). This is done by selecting each of files (with a check mark next to his name) and picking the "Assign GPS points" button (see Figure 63). The assign process can be performed on a file by file basis, or several uploaded Zip files may be processed together. If the file has already been assigned, reprocessing will supersede previous assignments. This process can take a while if the selected files have a lot of data since the database has to locate the tag that each of the points the GPS waypoint lies on.

If the appropriate button is used to delete a Zip file, all the GPS points that it contains and their assignment to road and zone tags will be removed.

### *How are the GPS points processed in TAMT?*

Each GPS second-by-second data point contains information on its location, day of week, time of day, altitude, speed and heading. In the above-mentioned "Assign" process each GPS second-by-second data point in each Zip file is processed into different "bins" according to the following order and logic.

TAMT takes all the GPS data for each tag type and subdivides it into different groups based on the day of week and time of day in which it was obtained. It then assigns each point into a speed bin based on the speed data that it contains.

#### **Tag assignment**

First TAMT assigns each of the second-by-second GPS data points to its appropriate Tag that corresponds to the road and zone on which the vehicle was operating. This takes into account the assignment tolerance mentioned in Chapter 5. Where a GPS point is located near an intersection, the program takes the direction of travel into account to assign that point to the correct road.

#### **Day of week assignment**

For the day of week assignment, TAMT operates in two modes that can be selected by the user on the "Analysis > Day Type by year" page. Option one, when active, takes only the GPS data that is being obtained during the week (Monday to Friday) and handles this as one group. In option two, the GPS data is divided into three groups; Weekdays, Saturdays, and Sundays and Festive days based on the date stamp that each second-by-second point contains.

#### **Hour of day assignment**

For the hour of day assignment, TAMT takes all the GPS data in each of the day of week assignments and assigns it to a corresponding hour of day bin labeled from bin "0" (from

midnight to 0:59:59) to bin "23" ( from 11:00:00 to 11:59:59) based on the time stamp that each second-by-second point contains.

### **Speed bin assignment**

Last but not least, TAMT assigns the GPS data in each of these day-of-week and hour-of-day assignments into 5 km/h speed bins where the first bin is from 0 to 5 km/h and these continue to cover the maximum speed registered by the GPS traces.

This can produce a very large number of individual bins.

Consider the following example for a study zone with:

- 6 tags consisting of 3 road types (Highway, Arterial and Secondary) and 3 zone types (Residential as default, Commercial and Industrial)
- 3 day types (Option 2 consisting of Weekdays, Saturdays, and Sundays plus Festive days)
- 24 hour types
- 20 speed bins (each of 5 km/h) to cover 0 - 100 km/h.

In this example a total of 8640 bins will be created, consisting of 432 tag-day-hour bins each subdivided into 20 speed bins.

Each of these 8640 bins at this stage of the analysis contains a count of the number of second-by-second data points that it contains. These are then re-processed to determine the fraction of the time for each of the 432 tag-day-hour bins that the traffic flow spends in each speed bin.

Unless the data collection effort was large enough to generate enough GPS second-by-second data to fill each bin, TAMT then "fills the gaps" by using data from other similar bins in which enough was collected.

The next stage of the process is to aggregate these bins into the smaller number of bins used in the emissions calculating models. For speed sensitive emissions factors such programs may typically look for the vehicle kilometers travelled per year, by type of vehicle in each of 20 x 5km/h or 10 x 10km/h speed bins. Figure 64 shows a typical data output table. To obtain this weighted averages have to be used to take into account the differences in the number of vehicles that correspond to each driving condition (that is to each on the 432 tag-day-hour bins in the above example).

	Annual Vehicle-km travelled within each speed bin									
	0 to 9.9 km/h	10 to 19.9 km/h	20 to 29.9 km/h	30 to 39.9 km/h	40 to 49.9 km/h	50 to 59.9 km/h	60 to 69.9 km/h	70 to 79.9 km/h	80 to 89.9 km/h	90 km/h and above
Two-wheeler (2W)										
Three-wheeler (3W)										
Passenger Car (PC)										
Taxi (Taxi)										
Pickups, Vans, and SUV <i>people-movers</i> (LDV)										
Light Duty Commercial vehicles <i>freight-movers</i> (LDC)										
Heavy Duty Commercial vehicles (HDC)										
Medium Duty minibuses (MDB)										
Heavy Duty Buses (HDB)										

Figure 64 - Typical data output table

This requires vehicle flow data to be obtained and entered into TAMT. The following chapter will look in depth at how vehicle flows can be measured to generate this required data.

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## Chapter 9

### *Output Reports from the TAMT Appliance*

Once all the traffic counts and GPS log files have been inputted into the TAMT Appliance the next step is to generate and output data on vehicle activity from TAMT for use in other programs. TAMT currently emits two groups of reports:

- Speed Bins; and
- Trip statistics

Each of these has to be generated by clicking the appropriate "Create Report" button. All reports can be viewed on screen and exported as a download.

#### **Speed bin reports**

##### **i. Speed Distribution**

This gives the travel distribution on each Tag in terms of:

- time (s),
- distance (m)
- average speed (m/s)
- percent time
- percent distance

by Day Type, Speed Bin, Hour Bin

##### **ii. Speed Distribution by Traffic Flow**

This includes vehicle type information to give the travel distribution on each Tag in terms of:

- Day Type,
- Vehicle Type,
- Speed Bin,
- time (s)
- distance (m)
- average speed m/s,
- percent time
- percent distance

##### **iii. Aggregate by Day-type**

This aggregates to an annual level by vehicle type to give the travel distribution on each Tag for each day type in terms of:

- Vehicle Type
- Speed Bin
- time (s)
- distance (m)
- Average m/s



#### **iv. Aggregate by Tag**

This aggregates the data to an annual level by vehicle type. It generates formatted output for each day type in terms of:

- Vehicle Type
- Speed Bin
- time (h)
- distance (km)
- Average km/h

### **Trip statistics reports**

#### **v. Trip Bin**

This report generates a distribution of trips by trip length. It gives the number of trips in each trip-length bin and the average distance and speed of the trips in each bin.:

- Trip bin
- Trip count
- Average distance
- Average speed

#### **vi. Engine Soak times**

This report generates a distribution of time between trips, binned by time:

- Trip bin
- Trip count

### ***Generating New Reports***

This software (TAMT) is issued under the Apache License, Version 2.0 which is, compatible with version 3 of the GPL. As such, you have the freedom to run the program, for any purpose; the freedom to study how the program works, and change it to make it do what you wish; the freedom to redistribute copies so you can help your neighbor; and the freedom to distribute copies of your modified versions to others.

The Appliance includes all the tools you might need to be able to extend and modify the software and particularly, to generate new output reports. By incorporating your changes and extensions into the <http://code.google.com/p/tamt/> site you can give the whole community a chance to benefit from your changes.

### *How to determine the in-use vehicle fleet characteristics*

#### *Why do we need to determine this?*

Vehicle emission factors (specific fuel consumption and emissions per kilometer of CO<sub>2</sub>, CO, HC, NO<sub>x</sub> and PM) vary due to:

- (i) Intrinsic vehicle characteristics; and
- (ii) The conditions of use.

**Conditions of use** include ambient temperature, travel speed, biofuel components, road grade, vehicle load (particularly for heavy duty vehicles), and the presence of an effective vehicle inspection and maintenance program that can lead to improved maintenance.

**Vehicle characteristics** include vehicle type, subtype, technology, Gross vehicle weight (GVW), accumulated mileage, engine displacement, and fuel used.

When we measure vehicle activity using a link-based method, we count the flow of in-use vehicles along a stretch of road. Often we will count separately up to nine categories of motorized vehicles as seen in Table 2:

- 2-wheelers
- 3-wheelers
- Taxis
- Passenger cars (other than taxis)
- Light-duty passenger vehicles
- Light-duty commercial (goods) vehicles
- Medium-duty minibuses
- Heavy-duty trucks
- Heavy-duty buses

However this is not a sufficient detail to be able to assign the corresponding emissions factor to each vehicle type. The in-use population of each of the above nine types of vehicle needs to be disaggregated or sub-divided into finer categories, and each forecast independently.

The emissions per kilometer of a low technology, high mileage passenger car with a gasoline V8 engine will be totally different than those from a more modern, higher technology and smaller diesel powered passenger car. In total there are some 250 important combinations of motorized vehicle type, sub-type, fuel use, engine displacement, vehicle size, and emission technology and it is impossible to visually separate and count each one on the street.

Most cities do not have all combinations of vehicles, but even so it is not practical to attempt to count each separately. Remember that improved vehicle emission technology is usually introduced when emissions standards come into effect. So there is often a direct link

between this and vehicle model year, which makes it far easier to decide which options really need to be taken into account.

### *What exactly are we trying to do?*

The objective is to subdivide each of the categories of vehicles for which we can measure vehicle activity (that is count the flow per hour) into fine-enough groupings that we can assign an emissions factor to each. This involves characterizing the in-use vehicle fleet into type, sub-type, fuel use, engine displacement, vehicle size, and emission technology groups.

We do need to differentiate between “static fleet” data; this is based on the number of on-road vehicles independently of their amount of use, and “dynamic fleet” data where this is weighted by the kilometers of use of each vehicle. Typically, older vehicles are driven less than new vehicles; also older vehicles often have higher emissions factors than new vehicles. Thus using a static fleet configuration will often result in higher total emissions than if we use a dynamic fleet configuration.

Our objective hence is to define the dynamic fleet configuration.

The needed level of detail required depends on how the emissions factors are defined. This in turn depends on the technology standards being used by the country. Most new-vehicle technology standards are derived from US (EPA), European (EURO) or Japanese standards. Since more developing countries use EURO-standard vehicles, or have defined their national standards based on these, the rest of the discussion will take EURO as the example.

This guideline builds on, and slightly adapts the EURO emissions factors included in their COPERT-4 model. The main motorized vehicle types considered in this guide are separated in two groups, as follows:

- Group 1:
  - Motorcycle
  - 3-wheeler
  - Passenger car (inc Taxis)
  - Light-duty vehicles
- Group 2:
  - Medium- and Heavy-duty truck
  - Medium- and Heavy-duty bus

The sub-classification of these takes into account the attributes shown in Table 5 for Group 1 vehicles (2-3 wheelers, passenger cars and light duty vehicles) and Table 6 for Group 2 vehicles (heavy-duty trucks and buses)<sup>9</sup>. In total there are around 250 possible combinations but most countries will only have a sub-set of these.

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<sup>9</sup>for more information see Appendix B - Level of disaggregation needed for emissions factor determination

Table 5 - Vehicle classification for Group 1: 2-3 wheelers, passenger cars and light duty vehicles

Type	Sub-type	Fuel used	Sub-subtype (engine displacement)	Emission technology
2 wheeler  22 possible combinations	2 stroke	Petrol	Up to 50 cc Over 50 cc	Conventional Euro 1, Euro 2, Euro 3
	4 stroke	Petrol	Up to 250 cc Over 250 and up to 750 cc Over 750 cc	Conventional Euro 1, Euro 2, Euro 3
	Electric		Up to 750W Over 750 W	
3 wheeler  13 possible combinations	2 stroke	Petrol	No engine displacement limitation	Carburated, Conventional Carburated, improved conventional Carburated, high technology Fuel injected, Conventional
	4 stroke	Petrol CNG	No engine displacement limitation	Carburated, Conventional Carburated, improved conventional Carburated, high technology Carburated, catalyst Fuel injected, catalyst
Passenger car  64 possible combinations	Private car Taxi	Petrol	Up to 1.4 litre Over 1.4 and up to 2.0 litre Over 2.0 litre	Conventional Improved conventional Open Loop Euro 1, Euro 2, Euro 3, Euro 4, Euro 5, Euro 6 Euro 3 + GDI
		Diesel	Up to 2.0 litre Over 2.0 litre	Conventional Euro 1, Euro 2, Euro 3, Euro 4, Euro 5, Euro 6 Euro 3 + DPF
		LPG CNG	Up to 1.4 litre Over 1.4 and up to 2.0 litre Over 2.0 litre	Conventional Euro 1, Euro 2, Euro 3, Euro 4
		Hybrid		
		Electric		
Light duty  29 possible combinations	Up to 3.5t GVW	Petrol Diesel	No engine displacement limitation	Conventional Euro 1, Euro 2, Euro 3, Euro 4, Euro 5, Euro 6
	Up to 2.5t GVW	LPG CNG	Up to 1.4 litre Over 1.4 and up to 2.0 litre Over 2.0 litre	Conventional Euro 1, Euro 2, Euro 3, Euro 4

Table 6 - Vehicle classification for Group 2: heavy-duty trucks and buses

Type	Sub-type	Fuel used	Sub-subtype (GVW or GCW)	Emission technology
Medium and Heavy-duty truck  91 possible combinations	Rigid truck	Diesel	Rigid Truck <=7.5t Rigid Truck >7.5-12t Rigid Truck >12-14t Rigid Truck >14-20t Rigid Truck >20-26t Rigid Truck >26-28t Rigid Truck >28-32t Rigid Truck >32t	Conventional Euro 1 Euro 2 Euro 3 Euro 4 Euro 5
	Articulated truck	Diesel	Tractor-Trailer/Articulated Truck >14-20t Tractor-Trailer/Articulated Truck >20-28t Tractor-Trailer/Articulated Truck >28-34t Tractor-Trailer/Articulated Truck >34-40t Tractor-Trailer/Articulated Truck >40-50t Tractor-Trailer/Articulated Truck >50-60t	Conventional Euro 1 Euro 2 Euro 3 Euro 4 Euro 5
Medium and Heavy-duty bus  34 possible combinations	Over 3.5t GWV	Petrol	No weight limitation	Conventional Euro 1, Euro 2, Euro 3, Euro 4, Euro 5, Euro 6
	Long distance bus	Diesel	Coach Standard <=18t Coach 3-Axles >18t	Conventional Euro 1, Euro 2, Euro 3, Euro 4, Euro 5
	Urban bus	Diesel	Urban bus Midi <=15t Urban bus Std >15-18t Urban bus Articulated >18t	Conventional Euro 1, Euro 2, Euro 3, Euro 4, Euro 5
		LPG CNG	No weight limitation	Conventional Euro 1, Euro 2, Euro 3 Enhanced Environmental Vehicle

## *Choosing the best approach*

There are several approaches that you can use depending on the availability of reliable data. Often a combination of these produces the best results; using one, say, for passenger cars and a different one for heavy trucks.

Wherever possible try and use existing data. If there is an existing database (e.g. vehicle registrations, or an obligatory Inspection and Maintenance (I&M) program) that **reliably** establishes the distribution of vehicle technologies on the road it is likely to be the least expensive approach. However be careful and selective; many vehicle registration databases do not contain the technical data we need and do not reliably de-register vehicles that are scrapped or go out of service – this gives too many old vehicles. Voluntary I&M programs often skew the data towards new vehicles because old vehicles that need repair are not voluntarily taken in for testing.

If a significant portion of the vehicles on the road is registered in a different jurisdiction, then taking registered vehicles of the entity in one jurisdiction only may also skew the data.

Vehicle retail sales data is usually collected by vehicle manufacturers and often available from manufacturers associations. This is usually reliable, contains all the technical detail that is needed, and can be used to construct an in-use fleet classification.

Surveys are a very effective way of collecting information but care should be taken that the data collected properly represents the fleet under study. Surveys require more time and are more costly than using existing databases, however for fleets of vehicles, such as urban buses, a survey of the fleet operators can be the most effective way to go.

Combinations of the above techniques can be very successful. Where existing databases do not have all the information we need, they can be complemented through surveys.

This chapter will guide the selection process of an appropriate methodology. The following three sections will discuss:

- Using existing vehicle fleet data
- Using vehicle sales data
- Conducting a vehicle survey

## *Using existing fleet composition data*

There are four manners of using existing fleet composition data. These are:

- From registration databases, obligatory I&M programs and from fleet records
- Using license plate data to obtain information from the vehicle registration or I&M database
- Using the complete vehicle registration, or I&M database; and
- Using fleet-specific records

These may be used separately or in combination as described briefly below:

### **From registration databases, obligatory I&M programs and from fleet records**

In some countries the vehicle registration database is one of the most useful sources of information for the analysis of vehicle technology distribution. However, since it is usually established for tax collection purposes, in many countries these data sets may not include all the fields required for a comprehensive technology distribution analysis.

In such cases, complementing registration data with other sources such as inspection & maintenance information or surveys can be a good cost effective alternative for a complete analysis.

Videotaping in-use vehicles can allow license plate numbers to be captured as a means to identify specific vehicle technologies for the passenger vehicles, trucks, buses, and other types of vehicles that are operating on the streets. This can produce a good evaluation of the dynamic in-use vehicle fleet.

### **Using license plate data to obtain information from the vehicle registration or I&M database**

In the USA and many other countries, license plate data is reliably linked to vehicle characteristics through the Vehicle Identification number (VIN), which is included in the vehicle registration database. License plate numbers can be captured by videotaping vehicles driving in the study area. The local authority can enable these to be accessed in the license plate database giving the VIN and full vehicle characteristics right down to the vehicle dress code level. This directly gives the desired dynamic fleet composition data and can be used for most types of vehicle (motorbikes, cars, light duty vehicles, medium and heavy duty trucks).

For example: In Sao Paulo, Brazil the license plates of trucks were videotaped. These numbers were supplied to the motor vehicle authority, which had records on the technology of the truck. Since the licenses were recorded on urban roads the distribution that was observed should be consistent with the dynamic fleet.

In other developing countries the vehicle registration database is not kept up-to-date or does not contain any useful link to vehicle specifications, but there can be other sources of this data, such as an obligatory I&M program. The Mexico City Metropolitan Area is covered by an obligatory vehicle Inspection and Maintenance program. License plate numbers can be captured by videotaping vehicles driving in the study area and the local authority (with some insistence) can enable these to be accessed in the I&M database to give the vehicle characteristics. This can give the dynamic fleet composition data for cars and light duty vehicles, but care must be taken when two or more local authorities are involved in the study area. If one has less stringent I&M controls



than the other, then it can be expected that the older, more polluting fraction of the fleet will gravitate towards that local authority and unless the full set of databases are available (from all participating local authorities) the vehicle fleet mix can be skewed. Voluntary I&M programs that cover only a portion of the vehicle fleet are typically highly skewed towards less polluting vehicles.

Before you expend energy on this technique, check with the local authorities to ensure that they will allow access to the vehicle registration or I&M data.

### **Using the complete database**

The complete vehicle registration, or I&M database, when available can be used to disaggregate the static fleet configuration. For this it is not necessary to have the license plate of each vehicle in the database. Care must be taken when using the complete database, however. Many vehicle registration databases do not reliably de-register vehicles that are scrapped, go out of service, or move from the area – this gives too many old vehicles which skews the distribution to give higher emissions factors. Voluntary I&M programs often have the opposite effect; they skew the data towards new vehicles because old vehicles that need repair are not voluntarily taken in for testing.

Additional usage information will be needed to convert this static fleet composition data to dynamic fleet data so that the fleet is disaggregated by age and technology in the proportion of how they are driven on the street. Weighting factors of use against age, derived from odometer readings in the database, surveys, or other sources (such as insurance data) may be used. In many databases, particularly I&M, odometer readings are notoriously error prone and must be treated with great care.

Table 7 shows the relationship between the age of the vehicle and its annual mileage (in kms) that was found for vehicle in India. Here it can be seen that business vehicles start with a considerably higher annual mileage than private vehicles, but after a number of years get sold into private usage, equalizing their annual usage. Using data from this table it can be seen that a small passenger car in India in private usage can be expected to drive after 20 years of use (5000 kms) only one quarter of the annual mileage when it was new (20,000 kms). Thus the weighting factor for this vehicle after 20 years will be 25% and the equivalent dynamic population mix will be achieved by multiplying past model year sales, each by their equivalent weighting factors. Information on EU country vehicle fleets can be found in EuroStat.

Table 7 - Kms per year per vehicle type in India

Type	Segment	Purpose	1st year	5th year	10th year	15th year	20th year
PC	mini	business	25,000	25,000	10,000	10,000	5,000
PC	mini	private	15,000	15,000	10,000	10,000	5,000
PC	small	business	50,000	15,000	10,000	5,000	5,000
PC	small	private	20,000	15,000	10,000	5,000	5,000
PC	low er medi	business	30,000	10,000	10,000	5,000	5,000
PC	low er medi	private	15,000	10,000	10,000	5,000	5,000
PC	upper medi	business	30,000	30,000	5,000	5,000	2,500
PC	upper medi	private	10,000	10,000	5,000	5,000	2,500
PC	luxury	business	20,000	20,000	5,000	2,500	2,500
PC	luxury	private	10,000	5,000	5,000	2,500	2,500
PC	SUV	business	30,000	10,000	10,000	2,500	2,500
PC	SUV	private	10,000	10,000	10,000	2,500	2,500
LCV	AUV/MUV	business	50,000	30,000	20,000	10,000	10,000
LCV	AUV/MUV	private	20,000	20,000	10,000	10,000	10,000
LCV	mini van	business	40,000	40,000	30,000	10,000	10,000
LCV	mini van	private	15,000	15,000	15,000	10,000	10,000
LCV	van	business	50,000	50,000	20,000	10,000	10,000
LCV	pick-up	light	30,000	30,000	10,000	10,000	10,000
LCV	pick-up	heavy	80,000	30,000	10,000	10,000	10,000
HCV	light bus	light	25,000	25,000	10,000	10,000	10,000
HCV	light bus	heavy	50,000	30,000	10,000	10,000	10,000
HCV	medium bus	light	80,000	80,000	20,000	20,000	20,000
HCV	medium bus	heavy	150,000	150,000	100,000	100,000	20,000
HCV	light truck	light	40,000	40,000	20,000	20,000	10,000
HCV	light truck	heavy	80,000	80,000	20,000	20,000	10,000
HCV	medium truck	light	60,000	60,000	20,000	20,000	10,000
HCV	medium truck	heavy	180,000	180,000	80,000	20,000	10,000
HCV	heavy truck	heavy	180,000	180,000	80,000	80,000	20,000
HCV	prime mover	heavy	180,000	180,000	80,000	80,000	20,000
MC	tw o-w heeler	commuting	15,000	10,000	10,000	2,000	2,000
MC	tw o-w heeler	business	40,000	10,000	10,000	2,000	2,000
3W	three-w heeler	commercial	30,000	30,000	15,000	5,000	5,000

### Using fleet-specific records

Fleet records can be particularly useful to identify the technology mix and usage of specific classes of vehicles operating in the study area, such as public transport or freight vehicles.

If the area is urban, bus data can often be obtained from the operating fleet. In Pune, India the bus companies were contacted, and it was found that they had very accurate records on their buses including engine technology, size, and exact driving amounts. In Mexico, competing private bus operators on the same route were found to have very similar technology buses and knew the length of the route and how many round-trips each was making per-day. In Santiago, Chile, the Inspection/Maintenance data for buses was used. Data for other municipal vehicles, such as garbage collection, can be obtained in the same way.

If the study area is a highway outside of the urban area than it is more important to obtain fleet-specific data from trucking companies and long distance buses. Usually these fleets monitor closely vehicle usage and fuel consumption and can provide a wealth of data if approached correctly.

In Beijing, China, trucking companies provided data concerning the technologies in their heavy-duty vehicles.

### *Using vehicle sales data*

Reliable vehicle sales data is often available with the level of detail that we need to identify the combinations shown in Table 5 and Table 6. All vehicle manufacturers are interested in monitoring their market position and usually share this retail sales data with each other through their vehicle manufacturers associations or sales associations in each market. If this sales data can be obtained for the last 20 or more years then there are two techniques to use it to develop a reliable technology distribution for each class of vehicle.

The population of vehicles in any one-year will be the same as that in the previous year plus new vehicles entering the market minus old vehicles leaving the market in that year. Thus, since we know vehicle sales, if we can determine the number of vehicles that leave the active fleet per year, we can calculate the size and distribution of the active fleet.

The two methods of constructing the dynamic fleet from this data are:

- Using a model-year survey
- Using a mortality analysis

### **Using a model-year survey**

It is very easy and quick to conduct a model year survey for each type of vehicle at traffic lights or filling stations. The objective is to determine what percentages of the sales of vehicles in each model year are still in use.

The following types of vehicle are visually easy for the interviewer to identify:

- Motorcycle
- 3-wheeler
- Passenger car
- Taxis
- Light-duty vehicle
- Medium- and Heavy-duty truck
- Medium- and Heavy-duty bus

In some markets it is important to separately register data for some sub-categories such as Pickups, SUVs and Vans and for mini- or micro-buses.

For each of these that enter the filling station, or stop at the traffic light, the interviewer records the vehicle type and asks the vehicle's driver what model-year is his/her vehicle.

For each type of vehicle, the percent of the total number of vehicles surveyed that corresponds to each model year is calculated. This is compared to the total percent of vehicle sales (for each type of vehicle) each model year to determine a survival ratio for each model year. This ratio is then applied to the retail sales to get the active dynamic population. Figure 65 shows the relationship that was found in this manner between the retail sales of passenger cars by model year in Monterrey, Mexico and the surviving fraction of the dynamic vehicle fleet.

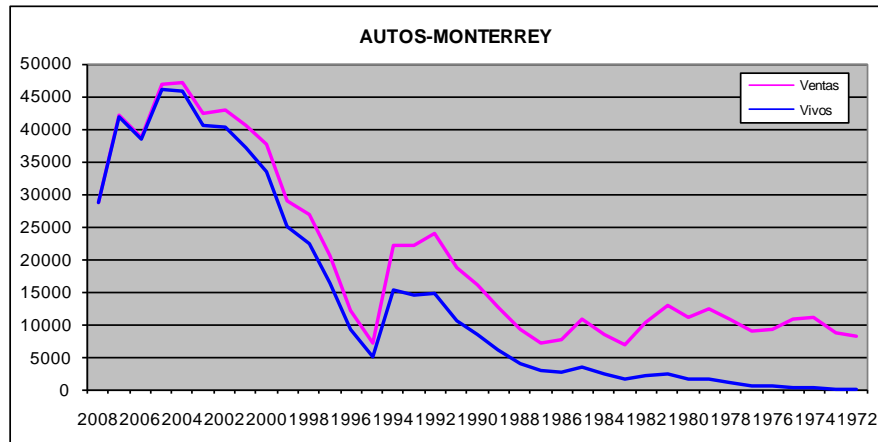


Figure 65 - Sales and surviving cars in Monterrey Mexico

In some cities there is an important influx of used vehicles from elsewhere. This is the case for cities along the border in Mexico where vehicles that were locally sold when new have the corresponding State license plates, whilst vehicles from elsewhere (typically from the US) have different license plates. Here the interviewer additionally notes if the vehicle is local or from elsewhere. The above calculation is performed for local vehicles only – looking to obtain the relationship between retail sales and existing in-use vehicles. This determines the population of local vehicles. The population of vehicles from elsewhere is then determined according to the relationship between these, and local vehicles in the sample.

### Using a mortality analysis

Vehicle population is disaggregated by using the historic vehicle sales through a mortality model. The sales data is needed (as above) at the level of detail shown in Table 5 and Table 6, specifying vehicle type, subtype, engine displacement, technology, GVW, and fuel.

Vehicle mortality is calculated using a modified Winfrey S3 survival curve as shown in Equation 4, where mortality<sub>i,t</sub> is defined as the percentage of the park of vehicle type *i* that needs to be replaced in year *T*. The curve is adjusted to add “*s*” years of zero mortality at the beginning of the vehicles in-use service. *t* = *T* - *s* where *t* is always greater or equal to zero, *m* = 3 and *a* is adjusted

such that  $\left(1 - \frac{Y_t^2}{a^2}\right)^m$  gives 50 percent when *t* is equal to the average age of retirement of vehicle type *i*.

$$mortality_{i,t} = \left(1 - \frac{Y_{t-1}^2}{a^2}\right)^m - \left(1 - \frac{Y_t^2}{a^2}\right)^m \quad (4)$$

Figure 66 shows the form of typical Winfrey S3 survival curves for average operation life of 6, 12 and 22 years.

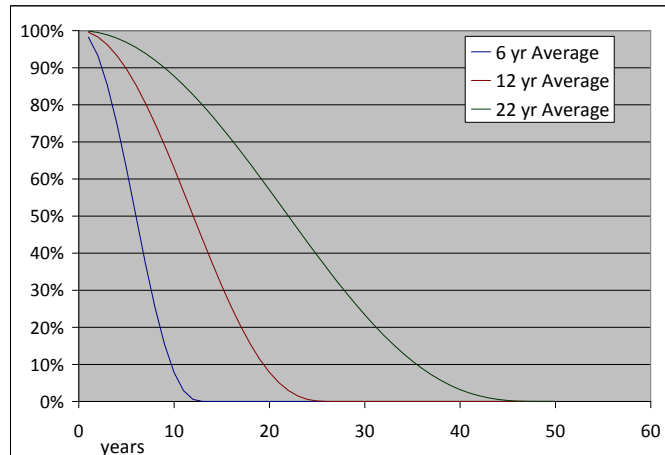


Figure 66 - Typical Winfrey S3 Survival Curves

The values for “s” and average age of 50% retirement that matched field data in India are shown in Table 8.

Table 8 - Typical values for s and average age of 50% retirement in India

Vehicle type	Value for s	Age of 50% retirement (yrs)
2-wheelers	2	7
3-wheelers	1	7
Passenger cars	1	Small, Mini 8 Medium 9 Large, Luxury, SUV 10
Commercial vehicles	0	12

Vehicle mortality is calculated separately for each year’s historic sales of each vehicle type. When using the mortality model to forecast vehicle static population, this average vehicle life may be modified periodically to take into account changes in vehicle build quality and other factors.

The dynamic population is calculated by applying usage-weighting factors to each model year obtained from kilometers per year per vehicle type information as in Table 7.

### Conducting a technology survey

Because of the wide variation in types of passenger vehicles, trucks, and buses that operate on the roadway, it is necessary to determine the percentage of vehicles that use gasoline or diesel, those that have catalysts, specific engine control technology, and other parameters to support vehicle emissions estimates. If this information cannot be determined through existing databases and sales data cannot be located, then on-site surveys should be carried out.

In such parking-lot surveys, a local mechanic physically inspects a sample of vehicles and determines the technological characteristics of each one (i.e. model year, emission and engine control technologies, odometer reading, presence of air conditioning, etc). Experienced local mechanics are often very knowledgeable about identifying engine technology, model year and

such. They can also be knowledgeable about catalyst technology but care should be taken to insure this fact. The data is daily recorded on paper and then onto a computer.

In order to collect the technology distribution from different vehicle categories, different survey locations should be selected. This selection is divided between vehicle types belonging to group 1 (two-three wheelers, passenger cars, taxis and light duty vehicles) and group 2 (heavy-duty trucks and buses).

### **Survey location**

It is important that the locations in which data are collected are representative of the fleet that operates in the region. Three areas or zones should be identified within the area of interest, related to the specific transport intervention. These areas should be the same for the other activity parameters taken into consideration on this guideline. For example, if the project is area-based with urban coverage it is recommendable to select a low-income area, high-income area and a commercial area. The locations where the surveys will be carried out should be inside the designated zones, with specific characteristics depending on the type of vehicle, as it is explained below.

### **Passenger cars, two wheelers and light-duty vehicles**

Vehicle surveys can consist of two types. One way to collect this information is to survey unoccupied vehicles on-street parking and parking lots. In the other case, drivers are sought out as they enter grocery stores, businesses, or shopping areas and submitted to a short survey.

Vehicles are parked on the street in commercial areas in the proportion that they are driven. Thus, the distribution of vehicle technologies identified in a parking lot study is applicable to vehicle emissions modeling. Residential streets are avoided because residents tend to park their oldest vehicles on the street and newer vehicles in the garage. On residential streets, cars and 2-wheelers can remain on the street out of proportion to how they are driven. Business centers are avoided because they tend to only have newer vehicles. Use of a lot of this data would bias the sample.

An indication of the technology mix for private vehicles can be obtained from a parking lot survey, whilst they are in use. Grocery stores, businesses, shopping areas, and filling stations are good in-use activity indicators, however care must be taken in their selection; if only middle class families shop at supermarkets in your city than sampling only at supermarkets will undoubtedly skew the sample. You should also be careful not to use sampling sites where vehicles are parked “at home” since these will give an indication of the static fleet configuration, not the dynamic in-use fleet. Caution is employed to select a variety of parking lots that contain a proportionate mixture of cars. For example, shopping malls or grocery stores or gas stations in several different areas of the metropolitan region, housing vehicles involved in daily commuting are the best places to collect data.

Depending upon the location, 2-wheelers are used in essentially the same manner as passenger vehicles for commuting. In other cases, 2-wheelers are used more for deliveries. In this latter case, contact with the delivery companies, brief interview with operators, or other approaches similar to those used for trucks, buses, and taxis may prove valuable.

**Taxis and 3-wheelers**

Taxis and 3-wheel vehicles tend to congregate at certain locations. Thus, the best way to collect their information is to go to several of these taxi stops (driver interview) or depots (company interview) and collect appropriate local technology data.

There can be a tendency for taxi drivers to disconnect odometers and thus produce erroneous readings and, in the case of 3-wheelers, there may or may not be an odometer. Many taxi drivers seem to know how much they drive per day, which can be useful information; although we have found that they remember their best days more than their bad days. Thus, care should be taken in interpreting their driving estimates.

**Buses**

In some cases, the bus companies themselves keep accurate records, which can be valuable. Most buses are diesel and the variety of technologies is small so that there are not a lot of technologies to consider thus a process tailored to the local situation can be used which typically includes surveying bus stops in lieu of parking lots.

**Trucks**

The determination of on-road technologies for trucks can be very difficult. It is often not possible to do parking lot surveys for these vehicles because they are not parked typically in accessible places. However stations where trucks stop to pay fees and filling stations can be used successfully. This was done in Pune, India, where trucks were inspected and the drivers were quizzed to develop a database of truck technologies that is indicative of the distribution of on-road operations.



### *How to calibrate emissions and fuel consumption factors to local conditions*

The international vehicle emissions factor models, such as US-EPA MOVES and the EU COPERT have derived equations to determine the emissions in g/km of each pollutant and fuel consumption under varying conditions of speed and load based on empirical data obtained during thousands of vehicle tests. These consider that vehicles that meet the same specification in different countries will be technically similar and that any differences that can be measured in their emissions will be basically due to the differences in operating conditions including ambient temperature, vehicle drive cycle etc. which are taken into account in these emissions factor models when calculating the g/km.

However, it is clear that there are other factors that may not be so well compensated. For example, the same COPERT 4 vehicle/engine classification can be used in different sub-types of vehicle. For example, EURO-2 fuel-injected gasoline engines of less than 1.4 L engine displacement are used in India in both Mini and Small cars with different vehicle weights and clearly the fuel economy should be different in each of these classifications. Additionally, fuel consumption differences – in addition to the speed sensitive fuel economy change due to road speed conditions -- can be expected between, for example, Asian cities and the EU due to differences in maintenance habits, driver aggressiveness, and other factors.

One solution to this dilemma could be to measure the emissions factors independently for vehicles in each country but this is not an option under normal circumstances because of the exorbitant expense and time required, with:

- Up to around 250 types/technologies/fuel combinations to test
- The need for statistically significant sample sizes for each vehicle type/subtype combination since there is no practical means of demonstrating that a small sample is truly representative of an un-tested in-use fleet.

The other option is to use internationally derived emissions factors adjusted to local conditions using limited information on a small number of popular vehicle types - and in which it is assumed that other vehicles will require the same fractional adjustment as those tested.

In some countries this has been done through testing vehicles for CO and/or HC emissions and calculating an adjustment factor that would need to be applied to the output of international emissions factor models to get the same result. The derived adjustment factor is applied to all vehicles. This was done for example, in Brazil and Mexico with great success but needs specialized equipment and technical skills to get comparable results.

Another technique that is easier to perform (and needs no specialized measuring equipment) involves deriving an adjustment factor based on fuel consumption. Fuel consumption data on popular makes and models of vehicle are obtained from various sources in the study area and surroundings. Sources that are used include:

- **Motoring magazines;**

Many countries have motoring magazines that test and report on popular vehicles including their fuel consumption under real world city and highway driving conditions. Back issues of these magazines will provide data on those vehicles that currently make-up a significant fraction of the in-use vehicle fleet.

- **Fleets;**  
Many fleets have large numbers of similar vehicles and can report the average fuel consumption of these under local operating conditions.
- **Private vehicle owners;**  
Last but not least, data is obtained from private owners to fill any gaps.

It is important to mention that most modern cars with computers do report average fuel consumption. Since the computer is tracking fuel use and mileage, this is a reliable source of data. Manufacturers reported fuel consumption data is normally not used, since in most markets it tends to be overly optimistic when compared to real-life measurements.

The method used in determining this correction factor is as follows:

- a) The most popular vehicle sub-type (and model years) in the active vehicle fleet are identified using local knowledge
- b) For each of these, practical examples of their in-use fuel consumption in the study area are obtained from published reviews (Motoring magazines), fleet interviews and from private owners. In some cases limited testing is required by filling up a vehicles tank, allowing it to operate all day with a GPS logger installed and recording how much fuel is needed to re-fill the tank at the end of the day.
- c) Using an international emissions factor model for each popular vehicle sub-types, the VKT weighted fuel economy (of the in-use vehicles) can be calculated for liquid fuels whilst correctly applying local data on driving conditions, temperature etc.
- d) A correction factor is derived--this being the fractional difference of (b) and (c)
- e) This correction factor is then applied to all the emissions factors for local pollutants, CO<sub>2</sub> emissions and fuel consumption derived from the international emissions factor model.

## What are cold start emissions?

Cold start emissions are those emissions that occur in the first minutes of vehicle operation that are in excess of those that would have been emitted by the vehicle if it had made the same trip with the engine and emissions controls fully warmed up. The extra emissions that occur during a start-up can be significant. These emissions depend upon the starting temperature of the catalyst and the engine. The starting engine and catalyst temperatures depend upon the ambient temperature of course, but the temperature of the catalyst and engine are normally well above ambient if the vehicle has been operated in the recent past. Thus, ambient temperature can be less important as an indicator of the amount of start-up emissions compared to the “soak time” of the vehicle which is the amount of time that a vehicle has been sitting without the engine operating.

Figure 67 illustrates this point. It shows cumulative dimensionless excess emission (ratio of absolute excess cold start emission to total absolute excess cold start emission) as a function of the distance (km) for the short Inrets free-flow urban cycle and represents the correction calculation of ECE-15 cycle for CO from gasoline cars without a catalyst. Excess cold start emissions are only calculated for gasoline engines since they are not significant for diesel.

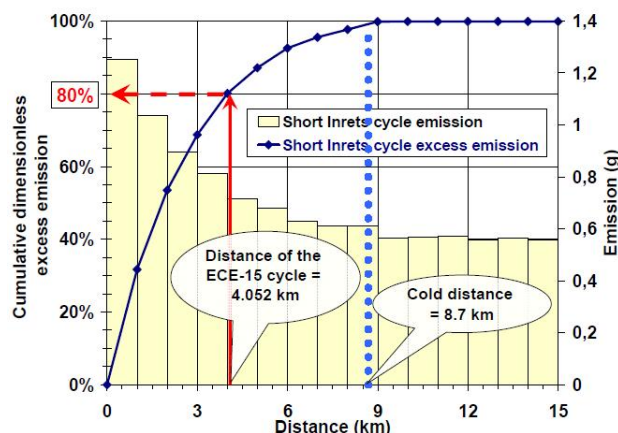


Figure 67 - Typical cold start excess emission ratio as a function of distance<sup>10</sup>

Figure 67 shows on the left-hand axis that 80 percent of these excess emissions due to cold start occur during the first 4.06 km of operation and virtually all of these excess emissions occur during the first 8.7 km of operation.

Using the right-hand axis it can be seen that whilst this test vehicle when warm emits around 0.58 g CO/km. Its emission level increases to an average of around 1.3 g CO/km –twice the hot emissions—during the first kilometer, and over 1.0 1.3 g CO/km during the second kilometer.

<sup>10</sup> from INRETS report LTE 0509 April 2005

On average, vehicle owners start their vehicles between 6 and 8 times per day. The soak times associated with these starts will vary from just a few minutes to more than 12 hours. The engine is typically the coldest for the morning start, but the starts that might occur at lunch and then to return home in the evening also include a relatively cool engine and catalyst. Other potential starts are to pick up passengers or to stop at the store or for refueling.

Inventories of cold-start emissions are calculated as the product of start emission factors, expressed as excess grams of each pollutant emitted per start, and the total number of starts per day for the vehicle fleet. As can be expected, a vehicle will on average emit more on shorter trips than if it were used in long trips under the same operating conditions.

## *How to derive cold start information*

There are several approaches that can be used to measure soak time:

- Driver log
- Voltage monitor
- GPS

For these to accurately represent the driving habits within the study zone it is important that the information is collected from a representative sample of ordinary people going about their daily business. Recording data from professional drivers contracted for the data collection process may generate data, but this is unlikely to be representative.

### **Driver log**

The simplest approach to collecting data on vehicle starts is to ask drivers to carry a notebook and to record the times when they start their engine and then stop their engine. This should be carried out for a one to two week period. The problem with this approach is that drivers often forget to note that they stopped their vehicle and turned the engine off. This leaves gaps in the data and leads to an underestimation of vehicle start-ups. If this approach is taken then care should be taken to make the drivers aware of the importance of the data and the need to be accurate.

### **Voltage Monitor**

A better method is to use a monitor that can measure and record variations of the vehicle's voltage against time. The alternator in a vehicle produces typically 13-14 volts when it is operating. The battery is typically between 11-12 volts when the engine is turned off. This difference in voltage can be used to determine if the vehicle is operating or not. Also, in many cases, the voltage to the cigarette lighter in a vehicle is turned off when the vehicle engine is not running. In this case, the voltage in the cigarette lighter will go from 0 to 13-14 volts when the vehicle is operating. This provides a large signal to determine when the vehicle engine starts. Figure 68 shows the voltage recorders used by the University of California - Riverside for this purpose.



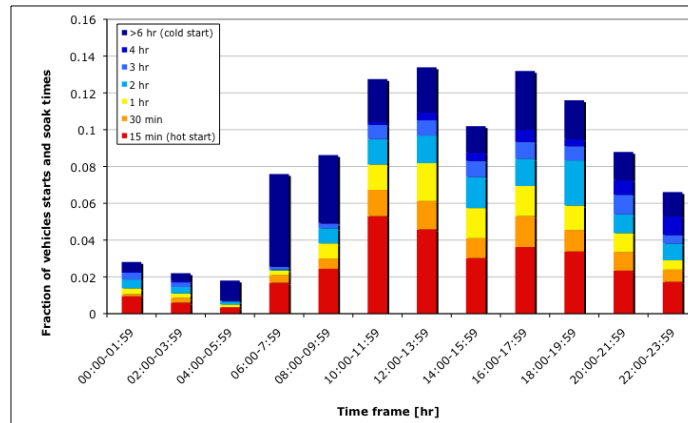
Figure 68 - VOCE unit from ISSRC

## GPS

This is the method used by TAMT. Since a GPS is being use to record driving patterns, the same device can be use to estimate the starts patterns. In this case a criteria must be defined for when to consider a start, for example if the vehicle stop for more than 10 minutes.

In TAMT this criteria is input on the "Home" page as minimum soak interval in seconds. The engine soak time report can be found on the Analysis > Trip Statistics > Engine Soak times report page. You have to click the "create report" button for TAMT to generate this.

City	Number of Starts	Year Measured
Almaty, Kazakhstan	7.5	2003
Beijing, China	6.7	2004
Istanbul, Turkey	5.8	2006
Lima, Peru	5.6	2003
Los Angeles, California	6.8	US EPA Estimate
Mexico City, Mexico	5.6	2004
Pune, India	7.0	2003
Santiago, Chile	6.0	2002
Sao Paulo, Brazil	6.1	2004
Shanghai, China	5.2	2004



*Start Patterns for Sao Paulo, Brazil*

*Figure 69 - Number of Starts for different cities (ISSRC)*

## *Trip length report*

The criteria that is defined in TAMT for when to consider a vehicle start, for example after the vehicle has been stationary for more than 10 minutes, also allows the trip length of each trip and the average speed of each trip to be calculated from the GPS log files.

The trip length report can be found on the Analysis > Trip Statistics > Trip Bin report page. You have to click the "create report" button for TAMT to generate this.

### *How to get passenger and freight movement from vehicle activity*

In many traditional transport models, vehicle activity is derived from passenger and freight movements. This is reflected in the box "Methodological Approach - The ASIF Decomposition" in Chapter 1. However, it is often easier to work the other way round and derive the on-road transport of passengers and freight from vehicle activity combined with surveys of occupancy (passengers) and load factor (freight) for each vehicle type.

The World Bank's EFFECT model, which is described in Appendix C, uses this approach. It takes on-road vehicle activity (by type and sub-type of vehicle) and uses occupancy and load factor surveys to determine passenger and freight movement expressed as passenger-km and freight-tonne-km. It then forecasts changes over time to the passenger-km and freight-tonne-km transported based on multiple exogenous variables including GDP, population growth, and income. These future transport needs are then used to project vehicle activity based on the expected changes in the composition of the on-road vehicle fleet, and projected changes in occupancy and load factors, together with changes in user preferences.

Thus, as can be seen, it involves a two-step process; first measure occupancy and load factor as shown below and then forecast exogenously how these might change over time. This second step involves at least three areas of complexity:

- As transport infrastructure and services improve over time, users have an incentive to travel longer distances. A new highway or rail link can allow commuters to live further from their place of work, or companies to establish offices or manufacturing facilities where land and labor is lower cost. This increases the length of trips and passenger-km and freight-tonne-km for a similar level of economic activity.
- As transport infrastructure and services improve, people have an incentive to make trips that they would otherwise not have made. Passengers may start frequenting commercial zones that before were considered too difficult to reach, or companies access markets that previously were not available to them. This increases the number of trips.
- As transport infrastructure and services improve, user preferences shift between the different modes of travel that are available, often due to other considerations, popularity, and changing habits.

These can be extremely difficult to forecast.

### *Existing Transport Master Plans and Origen-Destination surveys*

Wherever possible data from existing studies should be accessed and used to determine the average number of passengers per vehicle and freight-tonnes per vehicle to be able to relate passenger and freight movement to vehicle movement. These include locally calibrated transport models and Origen-Destination surveys. However, this data is often not recent and maybe not sufficiently focused on the study area, thus requiring additional data collection.



## *Vehicle occupancy surveys*

By determining vehicle occupation levels, passenger movement can be derived from the measured vehicle activity. This involves counting the number of passengers per vehicle in each visually identifiable category of passenger vehicle, at different locations within the study zone and periods (day, and time of day). In these counts, occupational drivers (in taxis, buses, and 2- and 3-wheelers) and other transport staff--such as fare collectors on buses--should be excluded. There are three ways of getting this data, which can often be used in combination:

### **Existing data sources**

For high occupancy vehicles such as buses and BRT, ticketing information and other company records can often be an important source of data to relate passenger movement to vehicle movement. This should be the first option that is investigated, and complemented as necessary by other means.

### **Manual counts**

The simplest way to count passengers in other vehicles is to deploy trained field personnel to sample as they drive past a sampling point on a stretch of road. This works satisfactorily for all vehicle types except high occupancy vehicles such as buses. Often this can be combined with the traffic counts, where the same person counts passengers per vehicles for 15 minutes per hour and counts vehicles for the remaining 45 minutes.

For buses it is easiest for field personal to board the bus to count the number of passengers and get off at the next stop. He can then do the same in the other direction of traffic flow returning to his original starting point.

Usually these passenger counts are recorded on paper forms. This subject will be treated in greater detail in Chapter 14.

As for traffic counts this method of collecting data, whilst simple and low cost is not the preferred method because it does not generate an audit trail that allows the count to be validated at a later date. Chapter 14 looks at this quality control/quality assurance requirement (QA/QC).

### **Video recordings**

For all vehicle types other than high occupancy buses it is possible to count the number of passengers per vehicle from a street-side video-recording. For this, it is best if the camera can be located at street level and zoomed into the appropriate frame size that will capture the entire roadway in one direction. The process is very similar to that of videoing vehicle counts (see Chapter 8) and provides an audit trail that enables supervisors or external auditors to validate the counts obtained. The digital media must be correctly identified by the camera operator, starting each film sequence with a 5 sec recording of a card that shows the name of location, route designation, direction of travel, date, hourly period, and camera designation. The recordings will be reviewed by personnel trained to correctly classify vehicles on a large screen TV or computer monitor.

## *Freight load-factor surveys*

As with passengers, by determining freight vehicle loading levels, freight movement can be derived from the measured vehicle activity. Since freight movement is usually expressed in terms

of freight tonne-kilometer it is necessary to determine the average weight of the load transported by each vehicle.

### **Existing data sources**

Goods vehicle fleets offer an important source of information from their waybill data and other company records. This should be the first option that is investigated, and complemented as necessary by other means. Weigh-stations also can offer excellent data, where they exist.

### **Sampling**

A trained observer can however distinguish on medium and heavy duty goods vehicles approximately how loaded the vehicle is by the position and shape of the vehicle's springs. This can be reported in the form of 0, 25, 50, or 100 percent etc. However, it is difficult to obtain more detailed data from a road-side observer because:

- i. it is difficult to estimate the weight by looking at the load. For some products such as steel sheet the vehicle may appear almost empty and yet be at its maximum weight, whilst for others such as deliveries to retail stores, the vehicle may appear full but in reality be lightly loaded.
- ii. Another other problem is that in many countries closed trucks are used in which it is virtually impossible to see from the roadside what they contain and how full they are.
- iii. Often trucks are not identified with the brand of merchandise they are carrying, since signage for high values brands (TVs electronics etc) can incite greater theft.

### **Cross country comparison**

Data that is published for other similar countries may be used if all else fails. Eurostat<sup>11</sup>, for example, publishes freight loading data for all EU member countries, and how this has changed over time.

## ***Passenger or goods-transport modal choice and on-route Origin-Destination (O-D) surveys***

Additional modal choice information is often required (i) to be able to determine how the traveler (passenger or freight) would have reacted in the absence of a specific project and (ii) to have a basis for projecting changes in mode choice for future years.

An example of the first case is a mass-transit project (such as a BRT) in which it is necessary to estimate the reduction in GHG emissions and fuel consumption that the project has caused. Here riders on the mass-transit can be interviewed to determine the length, timing and configuration of their trip and what mode (or modes) they would have used if the BRT had not been available. The fraction that would have used each alternative travel mode—including more energy-, or emissions-intensive travel modes such as private automobiles—can be determined from this and the overall difference in fuel consumption and emissions calculated. Such a survey can also identify travelers that would not have made the trip in the absence of this mode; so-called induced traffic.

Forecasting changes in mode choice in future years is a complex business. In traditional economic analysis of consumer decisions, acts and outcomes are treated as real variables. This is the case for

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<sup>11</sup> See <http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home>

example for the demanded quantities of most generic consumables. However, decision problems in other social sciences often lead to acts or outcomes that are bounded by a finite number of options and these are termed qualitative or quantal response problems. Examples include the ownership and brand of consumer durables (such as cars), household and work or shopping locations, and travel mode. In travel, individuals (and freight) are faced with a finite number of modal choice alternatives, each with different attributes (for example: speed, comfort, security, cost, and accessibility) and each with different selection probabilities.

How these can be analyzed is outside the scope of this guide. Revealed preference in conventional consumer demand analysis loses validity for options that the interviewee has not previously experienced. However even in these cases, modal choice and on-route O-D surveys may need to be conducted.

The simplest way to conduct a modal choice and on-route O-D survey is to deploy trained field personnel to interview passengers in transit as they pass a sampling point on-board their vehicles, walking, biking or waiting to board. A stratified proportional sample can be constructed to include several travel modes.

For mass transit it is easiest for field personal to interview people waiting to board the vehicle. Alternatively they can interview passengers that are on-board but this of course requires the consent of the bus or train line.

For private vehicles, soliciting police support to randomly select and stop vehicles for interview is the most effective for all vehicle types except high occupancy vehicles such as buses. Often this field work can be combined with the traffic counts and usually these passenger surveys are recorded on paper forms. Interview content usually focuses on defining:

- Demographics and modal choice
- Modal choice by trip type<sup>12</sup> (local, intercity, long distance, international)
- Modal choice by trip purpose
- Modal choice by trip distance
- Modal choice by day of week and time of day
- Modal choice by geography
- Trips using different modes in combination including access and egress from origin and to destination

This subject will be treated in greater detail together with the quality control/quality assurance requirement in Chapter 14.

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<sup>12</sup> This concept is independent of trip segment length. Intercity bus travelers are more likely to walk to their destination or use public transportation than international travelers even on the same segment.

### *Fieldwork*

The overall design of the fieldwork campaign can have a major impact on the quality of the data generated and on the costs involved. This chapter is designed to guide the user on the practical aspects of field survey work and help him to determine the extent of the work in terms of duration and costs and how to adjust these to keep within budget limitations.

#### *Field Surveys*

Field surveys are used to gather data on:

- a) Vehicle flow rates (via traffic counts on a sample of streets)
- b) Vehicle speed, driving cycles, start patterns and soak times (primarily from GPS loggers)
- c) Vehicle occupation levels (via sampling the number of passengers per vehicle)
- d) Vehicle usage surveys (focused origin-destination surveys)
- e) Vehicle fuel consumption calibration surveys
- f) Travel preference surveys
- g) Fleet composition surveys (Vehicle technology distribution)

In all these cases, the data obtained will depend greatly on where and when it was collected and great care is needed in the design of the field survey campaign to ensure that the results are representative of the location and for the entire year.

The objective of the following sections is to assist in this process.

#### *Sample size and measurement uncertainty*

One of the most important concepts in the design of any fieldwork campaign is the evaluation and understanding of measurement uncertainty since this defines the size of the samples that are needed.

In measuring transport activity, we have seen that it is impossible to measure every trip made by every vehicle that is operating within the study region. Sampling is needed to get data for the traffic counts, and GPS samples are used to get traffic speeds and drive cycles. Additionally any emissions factors used, from COPERT, MOVES, or locally measured emissions, are also based on a sample of vehicles.

The driving patterns of no two vehicles will be identical and thus their emissions will also differ. If the samples are small, then the risk of their results being different from the total population of vehicle-trips also may increase. Using larger samples may diminish this risk, but at the same time increase cost and so getting the “right” size for the samples is a delicate matter.

Appendix D: “Guidelines for Evaluating and Expressing the Uncertainty of Measurement Results” gives a detailed guide on how to determine and calculate the measurement uncertainty. It is recommended that you read it carefully.

There are two ways to define the size of the samples to be used in the field measurement campaign, which are usually used in combination by providing answers to the following questions:

### **How “accurate” do I need the final results to be?**

The answer to this question will depend on the usage that will be given to the results. Some usages, such as International Verification, intrinsically require low measurement uncertainties whilst for others a “directional indication” of tendencies may be sufficient. The desired level of “accuracy” may come from specifications<sup>13</sup> or from the need to be able to detect and evaluate a change. If the implementation of a project is likely to cause for example a reduction in local emissions from traffic of say 10 percent, then sample uncertainties would have to be sufficiently controlled and small enough to detect such a difference. Examples of this are given in Appendix D

It is important to spell out and share with the project stakeholders the proposed expanded uncertainty level of the final results before starting to collect data. It is critical that all are aware of what the uncertainty goals are, particularly when there are physical limitations that would not allow the measurement campaign to be later extended to improve results. It is also critical to weigh the importance of other uses for the field data that will be collected.

If for example data is being collected for a vehicle activity baseline on a corridor where the road layout will be changed once the project starts (a BRT may remove lane-space for normal traffic, for example) then once project construction is initiated it may be impossible to collect more baseline data. In this case it will be critical to achieve low-enough uncertainties for all significant future uses of this data.

### **How much can I afford to spend on measurements?**

The other side of this coin is keeping within funding limitations. This requires careful thought on where the biggest “bang-for-the-buck” in terms of reducing overall expanded uncertainty can be achieved for each additional dollar spent. There is little point in striving to achieve extremely low uncertainties in one variable if this will be more than offset by extremely large uncertainties in another.

### **Ex-ante estimation of the uncertainty budget**

To develop such an uncertainty budget before starting the field work requires the uncertainties associated with each variable to be estimated. For Type B uncertainties<sup>14</sup>, these will be the same as those used in the final calculation. Many of the Type A uncertainties come from sampling and the sample size approximations shown in Table 9 can be used as a first approximation.

The table shows the two-tailed estimated standard error of mean at different confidence intervals for an infinite population of data that conforms to a standard distribution. Under these conditions,

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<sup>13</sup> For example: The results will be reported to within a tolerance of  $\pm 15\%$  at a level of confidence of approximately 95%.

<sup>14</sup> **Type A** uncertainties are derived from the statistical analysis of series of observations whilst **Type B** uncertainties are usually based on scientific judgment using all of the relevant information available, including manufacturer's specifications, reference data from handbooks and data provided in calibration and other reports

it shows that an estimated sample size of 384 should give a standard error of mean of  $\pm 5\%$  at a level of confidence of approximately 95% but to reduce the estimated standard error of mean to  $\pm 4\%$  an additional 216 samples would be required. This allows different sampling options to be costed.

Of course, as sampling progresses, it is good practice to continually monitor the standard deviation and number of the results obtained for each variable, and to dynamically calculate the true standard error of mean that is being achieved and to adjust the sample size as needed to meet the uncertainty budget goals.

Table 9 - Sample size estimations

		Estimated standard error of the mean												
		1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	15%	20%	25%
Confidence level	60	1764	441	196	110	71	49	36	28	22	18	8	4	3
	65	2209	552	245	138	88	61	45	35	27	22	10	6	4
	70	2704	676	300	169	108	75	55	42	33	27	12	7	4
	75	3306	827	367	207	132	92	67	52	41	33	15	8	5
	80	4096	1024	455	256	164	114	84	64	51	41	18	10	7
	85	5184	1296	576	324	207	144	106	81	64	52	23	13	8
	90	6806	1702	756	425	272	189	139	106	84	68	30	17	11
	95	9604	2401	1067	600	384	267	196	150	119	96	43	24	15
	99	16384	4096	1820	1024	655	455	334	256	202	164	73	41	26

## Quality assurance and quality control (QA/QC)

### What is QA/QC?

Quality Control (QC) is a system of routine technical activities, to measure and control the quality of the transport activity measurement as it is being developed. QC activities include accuracy checks on data acquisition and calculations, and the use of documented standardized procedures for measurements, estimating uncertainties, emission calculations, archiving information and reporting. QC activities also include technical reviews of source categories, activity and emission factor data, and methods.

The QC system is needed to:

- Provide routine and consistent checks to ensure data integrity, correctness, and completeness;
- Identify and address errors and omissions;
- Document and safeguard all collected data, survey and other related material and record all QC activities.

Quality Assurance (QA) activities include a planned system of review conducted by personnel not directly involved in the transport activity measurement process. Reviews verify that data quality objectives were met, ensure that the measurement campaign represents the best possible estimates of transport activity and support the effectiveness of the QC program. These reviews, preferably by independent third parties, should be performed when a transport activity measurement campaign is finalized following the implementation of QC procedures.

## Good practice in QA/QC<sup>15</sup>

It is *good practice* to implement quality assurance and quality control (QA/QC) procedures in the development of all measurement campaigns.

### *Documentation*

As part of QC procedures, it is *good practice* to document and archive all field survey reports and data collection forms. Each should contain the date and time of the data collection and full reference to the site location. It should have the name(s) of the field personnel and supervisory staff.

QC documentation should:

- Give the assumptions and criteria for selection of all data collection sites
- Enable all activity data to be traced to the referenced source
- Give the rationale for choice of methods
- Define the methods used, including those used to estimate uncertainty
- Give information on the uncertainty associated with each variable
- Identify any changes in data inputs or methods from previous related surveys
- Identify all individuals providing expert judgment for uncertainty estimates and their qualifications to do so

### *Activities*

Table 10 gives examples of typical QC procedures that should be created and followed:

*Table 10 - Typical QC procedures*

QC Activity	Procedures
Check that assumptions and criteria for the selection of activity data and sampling sites are documented.	Cross-check descriptions of activity data with information on source categories and ensure that these are properly recorded and archived.
Check that field surveys are correctly performed	Cross-check a sample of field surveys with counts/revisions performed by third-parties
Check for transcription errors in data input and references	Cross-check a sample of input data from each source category (either measurements or parameters used in calculations) for transcription errors. Confirm that bibliographical data references are properly cited in the internal documentation.
Check that calculations are performed correctly.	Reproduce a representative sample of calculations. Selectively mimic complex model calculations with abbreviated calculations to judge relative accuracy.
Check that parameter and units are correctly recorded and that appropriate conversion factors are used.	Check that units are properly labeled in calculation sheets. Check that units are correctly carried through from beginning to end of calculations. Check that conversion factors are correct. Check that temporal and spatial adjustment factors are used correctly
Check the integrity of database files	Confirm that the appropriate data processing steps are correctly represented in the database. Confirm that data relationships are correctly represented in the database. Ensure that data fields are properly labeled and have the correct design specifications. Ensure that adequate documentation of database and model structure and operation are archived.

<sup>15</sup> This guidance establishes good practice consistent with the Revised 1996 IPCC Guidelines on Quality Assurance and Quality Control and Uncertainty Management in National Greenhouse Gas Inventories.

QC Activity	Procedures
Check for consistency in data between source categories	Identify parameters (e.g. activity data, constants) that are common to multiple source categories and confirm that there is consistency in the values used for these parameters in the calculations.
Check that the movement of data among processing steps is correct.	Check that data are correctly aggregated from lower reporting levels to higher reporting levels when preparing summaries. Check that data are correctly transcribed between different intermediate products.
Check that uncertainties are estimated or calculated correctly.	Check that qualifications of individuals providing expert judgment for uncertainty estimates are appropriate. Check that qualifications, assumptions and expert judgments are recorded. Check that calculated uncertainties are complete and calculated correctly. If necessary, duplicate error calculations or a small sample of the probability distributions used by Monte Carlo analyses.
Undertake review of internal documentation	Check that there is detailed internal documentation to support the estimates and enable duplication of the data and uncertainty estimates. Check that data and records are archived and stored to facilitate detailed review. Check integrity of any data archiving arrangements of outside organizations involved in data preparation
Check methodological and data changes resulting in recalculations	Check for temporal consistency in time series input data for each source category. Check for consistency in the algorithm/method used for calculations throughout the time series.
Undertake completeness checks.	Confirm that estimates are reported for all source categories Check that known data gaps that result in incomplete source category emissions estimates are documented.
Compare estimates to previous estimates.	For each source category, current inventory estimates should be compared to previous estimates. If there are significant changes or departures from expected trends, recheck estimates and explain any difference.

The checks in Table 10, should be applied irrespective of the type of data used or collected and are equally applicable to source categories where default values or national data are used as the basis for the estimates.

In some cases, data collection is performed by outside consultants. The principal stakeholder or contracting agency should ensure that the QC checks listed in Table 10 are communicated to the consultants. This will assist in making sure that QC procedures are performed and recorded by the consultant. The contracting agency should review these QA/QC activities.

For example, countries often use either vehicle fuel usage or kilometer (km) statistics to develop emissions estimates. The national statistics on fuel usage and kms travelled by vehicles are usually prepared by a different agency from that calculating the emissions. However, it is the responsibility of the latter to determine what QA/QC activities were implemented by the agency that prepared the original fuel usage and km statistics for vehicles. Questions that may be asked in this context are:

- Does the statistical agency have a QA/QC plan that covers the preparation of the data?
- What sampling protocol was used to estimate fuel usage or kms travelled?
- How recently was the sampling protocol reviewed?
- Has any potential bias in the data been identified by the statistical agency?
- Has the statistical agency identified and documented uncertainties in the data?
- Has the statistical agency identified and documented errors in the data?

National level activity data should be compared with previous year's data for the source category being evaluated. *Activity data* for most source categories tend to exhibit relatively consistent



changes from year to year without sharp increases or decreases. If the national activity data for any year diverge greatly from the historical trend, the activity data should be checked for errors. If the general mathematical checks do not reveal errors, the characteristics of the source category could be investigated and any change identified and documented.

Where possible, a comparison check of activity data from multiple reference sources should be undertaken. This is important for source categories that have a high level of uncertainty associated with their estimates. As part of the QC check, the agency should ascertain whether independent data have been used to derive alternative activity data sets. In some cases, the same data are treated differently by different agencies to meet varying needs. Comparisons may need to be made at a regional level or with a subset of the national data since many alternative references for such activity data have limited scope and do not cover the entire nation.

## *Deciding when and where to survey*

### **Calendar restrictions**

Traffic activity varies by day, week, year, and thus choosing the right days to measure traffic flow is critical. In a small survey, it is usually desirable to gather normal traffic activity representative of weekday behavior. In this case it is better to carry on these surveys on weekdays (Monday to Friday) and avoiding bank holidays and long school vacations. A typical weekday-to-annual multiplier is then chosen that takes into account the Saturday, Sunday and holiday traffic. This is usually determined by expressing the traffic on those days as a fraction of the typical weekday values. Table 11 gives an example of this calculation.

*Table 11 - Example of typical equivalent weekday per year calculation*

Day Type	Number per year	Fraction of weekday traffic	Equivalent Weekdays per year
Weekdays	254	1	254
Saturdays	52	0.7	36.4
Sundays	52	0.5	26
Public holidays	7	0.4	2.8
Total equivalent weekdays per year			319.2

However, in many cities, particularly those in which traffic is restricted during the week, weekend traffic flow can be very significant and it becomes more important to specifically sample these days. Additionally, it can be seen that any significant uncertainty of the real traffic flow on weekends will impact 104/365 days or 28 percent of the year whilst any significant uncertainty of the real traffic flow on public holidays will only impact 7/365 days or 2 percent of the year. Thus in studies where tighter control of uncertainties is required, it is good practice to sample Saturdays and Sundays in addition to the normal weekdays, but since the traffic flows are often different at weekends, keep this calculation separate.

Great care should be taken to keep track of, and avoid special events when planning a field survey campaign. Football matches, political rallies etc, can have a major impact on traffic congestion and flows, which may be totally atypical of normal operation. Additionally, care is needed on how to

take into account the different traffic patterns on school holidays vs the rest of the year. If the sampling period is going to be over say 3 weeks then if this is during a school holiday the annual traffic flow is likely to be underestimated. If the sampling period is extended, then consideration should be given to defining a stratified sample that proportionally includes school-holiday and non-school-holiday weekdays.

### **Time restrictions**

Traffic activity also varies by hour of day and thus choosing the right times to measure traffic flow is equally critical. Whilst it is ideal to measure traffic flow over each 24 hour period, when field personnel are involved it is often desirable to use a shorter sample in order to reduce cost (by using field personnel in two shifts rather than three per day) and reduce the security risks that can be implicit over the night-time hours.

In these cases, it is often better to carry on field survey work during hours of most movement (usually 6:00-22:00). The off-peak night traffic hours (from 22:00 to 6:00 the next day) are estimated by using default values that can be defined from one or two 24-hour vehicle counts at strategic locations. The methodology used to define these default off-peak traffic flows for each Tag-type should be fully documented in accordance with the QA/QC procedures for the study.

### **Where to sample**

As has been covered in previous chapters, in TAMT, road-links are grouped into different tags and traffic flow needs to be sampled on at least one site for each tag. When the study area is around a highway, the sampling points should be selected to best represent the homogeneous traffic flow on each Tag.

When the study area is urban, it is usual that for each tag-type, three representative sections of the city are selected for the vehicle counts. It is recommended that one of the study areas represent a generally lower income area of the city, another represent a generally upper income area of the city, and the third represent a commercial area of the city. The sections representing the upper and lower income areas of the city for study should not be the absolute poorest or richest part of the city. It is better to select areas that are representative of the lower and upper halves of income. Normally, the urban center is selected as the best commercial area to study.

Within each of the study areas, different types of streets must be analyzed to gather data on each tag-type that may be considered representative of the entire urban area. Streets are usually classified into at least three tag groupings, however in many studies more tags are used to give a finer control to the results. The first group represents streets that are major urban connectors and can connect one urban area to another. These streets are typically characterized by the highest traveling speed in free-flow traffic with minimal stops from cross-flow traffic and, are commonly referred to as highways or freeways. The second classification of streets represents streets that connect sections of an urban area. They may connect one section of an urban area with another or may provide an important connection within a section of the urban area. These streets are typically referred to as arterials. The third classification of streets represents the streets that take people to their homes or small commercial sections of an urban area, and are usually one- or two-lane roadways with a relatively lower average speed and frequent intersections. These streets are typically referred to as secondary roads.

## Sampling periods

If the traffic counts are to be made by field personnel then it is worthwhile defining a sampling period per hour instead of counting all the vehicles continually because this can considerably reduce costs and the number of field personnel involved. Care must be taken not to choose a sampling period that is too short because this can radically affect results. An example of this is where a traffic light is located upstream of the sampling position; when the light turns green a platoon of vehicles all move together past the sampling point and when the light is red, very few vehicles will come past. In this case too short a sample could radically over-estimate or under-estimate the traffic flows.

Often a sample time length of 15 minutes is sufficient to eliminate this effect but this hypothesis needs to be proven in each study area. To do this, one or more typical sites are chosen and traffic counts conducted continually over an extended day; counting and registering the number of each type of vehicle to go past the sampling point in 5-minute increments. If the total period is from 6:00 to 22:00, 192 5-minute samples will be taken. From these, multiple 15-minute samples can be randomly selected (with one 15-min period per hour) and the total flow calculated by extrapolating each 15-minute sample to the hour (ie multiply the 15-minute vehicle count by 4).

The total flow of each type of vehicle over the extended day can be calculated in this way and then compared to measured total (from all the 192 5-min counts) to determine the error involved. This can be done also for 10-minute samples and for 20-minute samples using the same data.

The advantage of using say a 15-minute sampling period is that it allows one person, situated at an intersection to count the traffic flows in all four directions but it does introduce an additional error term in the uncertainty calculation (as determined above). Often however this can be more than offset by extending the number of days over which traffic flow is counted. Using 15-minute samples over twice as many days can still reduce the personnel cost by half and often reduces the total sampling uncertainty as well. This is truly a win-win situation.

## Number of samples

### *For traffic counts*

For each sampling site and hour of day usually the number of samples varies between 3 and 10 according to the type of study and the required level of uncertainty. Quadrupling the sample number from 3 to 12 would reduce the uncertainty by half ( $\sqrt{3} = 1.73$ ,  $\sqrt{12} = 3.46$ ; see Appendix D).

The minimum of 3 samples allows unusually low or high numbers to be identified, and rectified as necessary. The minimum of 3 samples also allows their variance to be evaluated and standard error calculated. If the variance is large then consideration should be given to extend the sample and thus improve the level of uncertainty. For studies that aim to evaluate small changes in activity or emissions it is usual to consider traffic flow measurements continually over a 3 week period such that the sample contains 3 Saturdays, 3 Sundays, and 3 of each weekday.

### *For GPS logs*

As in all statistical work, the larger the sample, the better. Here it is preferable to have enough time to be able to collect GPS traces over a period of several weeks or months to allow many different drivers, routes, and driving techniques, to be included. Care must be taken to ensure that the GPS data collected covers all tags and each distributed over most of the hours of the working day. At a very minimum, the survey should look to collect 3 second-by-second traces (GPS log files) that give traffic speed and drive-cycle information for each tag over the 24-hour period. If the option to measure only weekdays is selected, then the GPS log files will be required only for weekdays; if the option to measure weekdays, Saturdays, Sundays and holidays, is selected, then the GPS log files will be required for all day types.

### *For vehicle occupation surveys*

Often these are conducted by the same personnel that perform traffic counts. If the traffic count sample period that has been chosen is 15 minutes, then an additional 15 minutes per hour should be dedicated to counting the number of people per vehicle. This does not need to be performed at every traffic count site but only at a few representative stations.

Mass transit (including bus and minibus) passenger counts are most easily performed by the field personnel boarding the vehicle, performing the count, and alighting at the following bus-stop. This requires a dedicated staff member full time.

### *Vehicle usage surveys and travel preference surveys*

If one of the objectives is to evaluate modal preference of riders who have shifted from a passenger car to mass transit for example then we may want to evaluate that shift with a standard error of no greater than  $\pm 5\%$  with a 95 percent level of certainty. According to Table 9 this would require an estimated sample size of approximately 384 but if only one in ten riders may have shifted from a passenger car to mass transit then we would need to interview 3840 passengers to accumulate 384 who could provide the answer to this question. Following this logic, vehicle usage surveys and travel preference surveys usually include sample sizes of 3000-5000. The initial estimation needs to be determined according to the uncertainty levels desired and as the survey progresses, the standard deviation of answers to key questions should be continually monitored together with the number of answers to be able to adjust the real sample size to meet these uncertainty expectations.

### *For fleet composition surveys*

Costs and time often limit how many vehicles can be surveyed. One approach is to survey enough vehicles so that vehicle populations down to the 1 percent level will show up in the survey. This implies collecting data on more than 1,200 randomly selected parked passenger cars over a 6-day study period. A single survey team consisting of a person to identify technologies and a person to record data can normally collect data on 100 to 130 vehicles per day. Thus over a 6 day period, two teams can collect data on 1,200 or up to 1,600 vehicles.

There are a much lower variety of truck, bus, 2-wheeler, and 3-wheeler technologies and even taxis tend to conform to a more limited range of vehicle types. Thus it is often sufficient to collect information on 50 to 100 of each of these classes of vehicles.

## *Personnel*

Training is crucial for all personnel. Each member needs to understand the objective of the survey and the nature of the data collection process. Care must be taken to ensure that each person fully understands his or her obligations in the QA/QC system and what is needed from them to ensure that the survey results are of high quality.

They need to be able to identify vehicle types. They must be able to enter information into the forms and also answers questions from vehicle owners, the police, and others about the purpose of the survey.

The team should include an experienced mechanic or equivalent that can identify model year of the vehicle, engine technology, control technology and all other information required on the data entry forms.

The team will need to include the following people:

- a) Field Personnel to conduct the field surveys
- b) Data entry staff to count vehicles in videos and enter field survey data into the computer
- c) Drivers if needed to conduct a Moving Vehicle Observer (MVO) survey of travel speeds and drive cycles.
- d) Administrative supervisor(s) to assign and control staff and coordinate the distribution and collection of GPS loggers. This is a lead person who selects survey locations, explains to guards or owners the nature of the data collection process and gets permission to collect data when needed.
- e) Technical QA/QC supervisor to review all survey data and conduct parallel survey samples to validate results
- f) Security staff as required to accompany the field survey personnel

### **Field personnel dress code**

Most vehicle owners will be happy to provide the researchers with information in a survey provided that he/she does not feel threatened by the experience. It is good practice to dress the researchers in bright, reflective safety hats and jackets with large visible identifications with photograph. Since no car thief would ever dress in such garb, it gives confidence to the vehicle owners. Identifying the survey location with large orange traffic cones, banners that identify the motive for the survey and police presence all help create the safe environment that the interviewees require.

### **Instruction for Moving Vehicle Observer drivers**

It is critical that the type of driving done during this study is representative of the way vehicles are normally driven in this city/area. Drivers are not judged on how fast they drive the routes or how they obey or disobey traffic signals. The most important thing is that drivers drive with the flow of traffic. This means that they are not driving faster or slower than the other vehicles on the road at that time. If the driver is being passed by a majority of the vehicles on the road, he/she is not driving fast enough. If the driver is passing the majority of the vehicles on the road, he/she is driving too fast. The trick is to pass the same number of vehicles that pass you; this means that you are travelling at the average traffic speed.

Sometimes, it is helpful to simply pick out a vehicle and then follow behind that vehicle maintaining the same distance between the two vehicles. If this approach is employed, the driver should not select a vehicle and then accelerate up to the vehicle before matching speed with it. Instead, the driver should select a vehicle, note the distance that vehicle is from his/her vehicle and try to maintain that distance during the period of time they are following it. If the vehicle pulls over to park, or leaves the route that being driven, the driver should select another vehicle that is on the assigned route and begin following it. This selection process should be varied between traffic lanes in cases where the assigned street has more than one traffic lane. In a situation where there are no other vehicles on the road, the driver should drive just as he/she normally would, given the existing road, weather, and traffic conditions.

## Forms used in the fieldwork

This Practitioners Guide is accompanied by an Excel workbook titled “Sample forms.xlsm” that contains examples of the forms that are most used in the fieldwork:

- i. Travel Time Survey
- ii. Traffic Count Survey
- iii. Vehicle turns and crossing survey
- iv. Bus Passenger Count Survey
- v. Light Duty Vehicle passenger count survey
- vi. Trip Origin-Destination and Distance Survey
- vii. Modal Choice and Preference Survey

These forms need to be adjusted or modified by the user to adapt to specific project needs. The Excel workbook is setup to allow easy translation of the forms into different languages and currently offers two versions: English and Spanish.

## How to use Sample Forms.xlsm

On opening the workbook, go to the “Index” page which lists the forms and allows languages to be switched by using the two arrow keys shown in Figure 70.

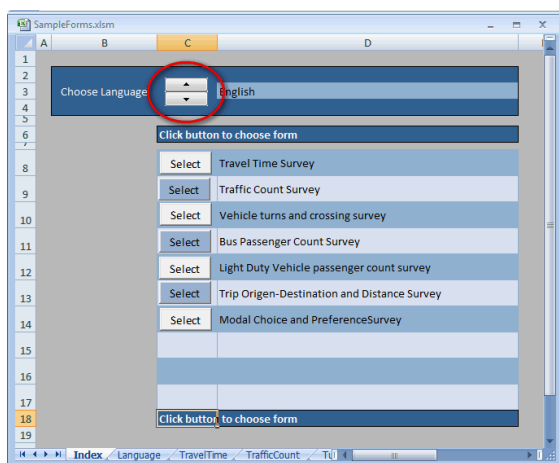


Figure 70 - Language selection keys on the Index page

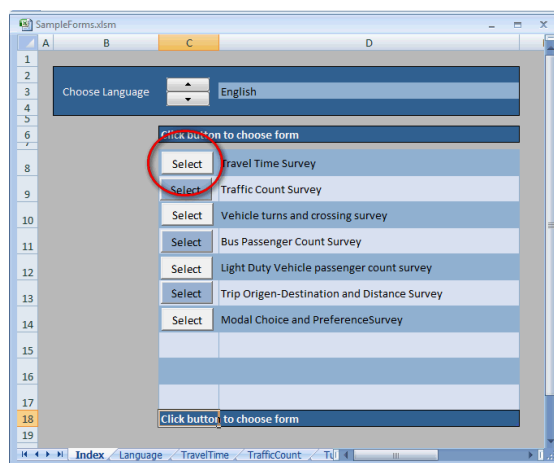


Figure 71 - Form selection keys on the Index page

This sheet also contains the buttons needed to navigate to each form as shown in Figure 71. The text for the forms is input into the “Language” page. In Figure 72 you can see how English occupies column “E”; Spanish in column “F” and other languages can be added in column “G” onwards. The text in column “C” which is copied by formula from these other columns is that which appears on each form.

Form	Active Language - English	English	Spanish	Portuguese
<b>General Fields</b>				
1	Date	Date	Fecha	
2	Date of Analysis	Date of Analysis	Fecha de Analisis	
3	Time of day	Time of day	Hora del dia	
4	Day	Day	Dia	
5	Month	Month	Mes	
6	Year	Year	Año	
7	Hrs	Hrs	Hr	
8	Min	Min	Min	
9	Sec	Sec	Seg	
10	Performed by	Performed by	Realizó	
11	Supervised by	Supervised by	Supervisó	
12	Authorized by	Authorized by	Autorizó	
13	Start	Start	Inicio	
14	End	End	Terminó	
15	Shift Start	Shift Start	Inicio Turno	
16	Shift End	Shift End	Fin Turno	
17	Hrs of Shift	Hrs of Shift	Hora del Turno	
18	Sheet 1	Sheet 1	Hoja 1	
19	Sheet 2	Sheet 2	Hoja 2	
20	Yes	Yes	Si	
21	No	No	No	
22	Description	Description	Descripción	
23	Name	Name	Observaciones	
24	Interviewed by	Interviewed by	Entrevistado por	
25	Control number	Control number	Numero de Control	
26	License Plate	License Plate	Numero de Placa	
27	Location	Location	Lugar	
28	Vehicle type	Vehicle type	Tipo de Vehículo	
<b>TravelTime</b>				
29	Travel Time Record	Travel Time Record	Registro Tiempo de Viaje	
30	Site Name_Eth1	Site Name_Eth1	Site Name_Eth1	
31	Site Name_Eth2	Site Name_Eth2	Site Name_Eth2	
32	Site Name_Eth3	Site Name_Eth3	Site Name_Eth3	
33	Site Name_Eth4	Site Name_Eth4	Site Name_Eth4	
34	Site Name_Eth5	Site Name_Eth5	Site Name_Eth5	

Figure 72 - The Language page

## How to use the forms

As covered in Chapter 14 it is important that all documentation used during field survey work be kept as a permanent register of that work in an accessible form for future revision and for use in other calculations and studies. Each form should be signed by the person that used the form to collect data in the “Performed by” box. Each form should additionally be revised and signed by the field survey supervisor, and signed by the study leader who in this way authorizes its use. Each form should contain the date and time information of its application together with all pertinent and necessary identification data.

Whilst this may seem somewhat bureaucratic it is in fact a necessary step to conserve the data trail. If for example it is later determined that one of the field personnel was inventing data and filling in his forms from the comfort of his own home, then it would be critical to be able to identify all the forms prepared by that person and ensure that only valid field results are used in the calculations.

## The Travel Time Survey Form

This form shown in Figure 73 is designed for use in a moving vehicle observer (MVO) traffic speed and travel time survey in which the driver will travel a fixed route on many separate occasions in both directions and note down on the form the time at which he passed different intersections or landmarks. The names of these should be substituted for the place-marker text that the sample form contains. The driver is expected to annotate on the form any events that occurred that increased or decreased the travel time between two points away from the normally expected time. These could be for example accidents, political demonstrations, or traffic light outages.

## The Traffic Count Survey Form

This form shown in Figure 74 can be used by field personnel counting vehicles on the side of the road or by personnel counting vehicles from a video-recording. For each sample period, which typically could be of approximately 15 minutes duration, the user should annotate on the form the exact time of the start of the sample (hours, minutes, seconds); the exact time of the end of the sample and the number of vehicles counted in each of the vehicle categories.



### **The Turns and Crossings Survey Form**

This form shown in Figure 75 can be used to evaluate the impact on cross traffic and on vehicles that need to turn off a corridor of major changes to that corridor, such as for example the inclusion of a segregated road space for a BRT which has traffic light priority.

The field personnel will sample the number of vehicles crossing and turning per traffic light change or other pertinent interval using one row for each sample to note the vehicle count by type of vehicle. As in the previous form it is important to note the time period of each sample with precision (minutes and seconds).

### **The Passenger Count: Buses Survey Form**

This form shown in Figure 76 can be used by field survey personnel when counting the number of passengers on board buses. It is expected that one person will board the bus to count the number of passengers, get off at the next stop and board another bus in the opposite direction to count passengers and return to his starting point. The names of these two locations should be substituted for the place-marker text that the sample form contains. It is important that he annotates against each sample the time of day and the route number since often multiple bus routes will coincide on the same avenue or street.

### **The Passenger Count: Light Duty Survey Form**

This form shown in Figure 77 has the same usage as the bus form but considering passengers in Light Duty Vehicles where the field survey personnel can count the number of passengers without stopping or boarding the vehicle.

### **The Trip Distance Survey Form**

This form shown in Figure 78 can be used for interviewing people in transit, by vehicle or NMT, to determine the Origin and Destination of their trip and the frequency of repetition. It additionally asks for information as to where they joined a specific route and where they finally left it. It is particularly useful for BRT corridors for example to be able to evaluate the benefits of including feeder lines at certain stations along the corridor. It can also be used in certain CDM methodologies.

### **The Modal Choice Survey Form**

This form shown in Figure 79 can be used to determine travel preferences, particularly for people traveling along a specific route such as a BRT corridor. A lot of information is collated in this survey and additional questions can be added as needed to look at New media, fare collection or any other related themes of interest.

Figure 73 - Travel time form for MVO measurements

[illegible]

Figure 74 - Traffic Count Survey form

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<b>Passenger Count: Buses</b>										Date			
										Day	Month	Year	
<b>Route</b>		<div style="display: flex; justify-content: space-between;"> <span>&lt;Start_of_route_Name_EN&gt;1 to &lt;End_of_route_Name_EN&gt;2</span> <span>&lt;End_of_route_Name_EN&gt;2 to &lt;Start_of_route_Name_EN&gt;1</span> </div>											
Hr of Shift	<b>Performed by</b>			<b>Supervised by</b>			<b>Authorized by</b>						
<b>1</b>		<b>From &lt;Start_of_route_Name_EN&gt;1 to &lt;End_of_route_Name_EN&gt;2</b>								<b>1</b> <b>From &lt;End_of_route_Name_EN&gt;2 to &lt;Start_of_route_Name_EN&gt;1</b>			
		Number of Passengers											
	Hr	Min	Route N°	HD Bus	MD Bus	LD Bus	Van/Combi						
1													
2													
3													
4													
5													
6													
7													
8													
9													
10													
<b>2</b>		<b>From &lt;Start_of_route_Name_EN&gt;1 to &lt;End_of_route_Name_EN&gt;2</b>								<b>2</b> <b>From &lt;End_of_route_Name_EN&gt;2 to &lt;Start_of_route_Name_EN&gt;1</b>			
		Number of Passengers											
	Hr	Min	Route N°	HD Bus	MD Bus	LD Bus	Van/Combi						
1													
2													
3													
4													
5													
6													
7													
8													
9													
10													
<b>3</b>		<b>From &lt;Start_of_route_Name_EN&gt;1 to &lt;End_of_route_Name_EN&gt;2</b>								<b>3</b> <b>From &lt;End_of_route_Name_EN&gt;2 to &lt;Start_of_route_Name_EN&gt;1</b>			
		Number of Passengers											
	Hr	Min	Route N°	HD Bus	MD Bus	LD Bus	Van/Combi						
1													
2													
3													
4													
5													
6													
7													
8													
9													
10													

Figure 76 - Passenger Count Buses Sample form

<b>Passenger Count: Light duty</b>					Date																																																																																																																										
					Day	Month	Year																																																																																																																								
Route	<div style="display: flex; align-items: center;"> <div style="border: 1px solid black; padding: 2px 5px; margin-right: 5px;">&lt;Start_of_route_Name_EN&gt;1</div> <div style="border: 1px solid black; width: 20px; height: 20px; margin: 0 5px;"></div> <div style="border: 1px solid black; padding: 2px 5px; margin-right: 5px;">&lt;End_of_route_Name_EN&gt;2</div> <div style="margin-left: 5px;">to</div> </div>																																																																																																																														
Hr of Shift	Performed by		Supervised by		Authorized by																																																																																																																										
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Figure 77 - Passenger Count Light Duty Sample form

Trip O-D and Distance Survey										Date						
Travel Route Name										Sampling site						
Time of Interview			Hr		Min		Traffic flow direction			N - S	S - N	E - W	W - E			
Transport mode used by the interviewee when interviewed																
Passenger Cars			Motorcycles			HD Bus			LD Bus							
Taxis			Van/Combi			MD Bus			Walking/Cycling							
Number of people travelling together										(not including driver of taxi/bus)						
Performed by				Supervised by				Authorized by								
<b>Good Morning(Afternoon) We are conducting a survey of travel distance and transport modes used that include this route</b>																
<b>1.-</b> How frequently do you travel on this route? <div style="display: flex; justify-content: space-around; margin-top: 5px;"> <span>( ) Daily</span> <span>( ) in one direction</span> </div> <div style="display: flex; justify-content: space-around; margin-top: 5px;"> <span>( ) Weekly</span> <span>( ) round trip (both directions)</span> </div> <div style="display: flex; justify-content: space-around; margin-top: 5px;"> <span>( ) Monthly</span> </div>																
<b>2.-</b> Normally, which transport modes do you use in your trip? Please give approx distance of each. (miles/km/meters) <div style="display: flex; justify-content: space-around; margin-top: 5px;"> <span>Passenger Cars</span> <span>Motorcycles</span> <span>HD Bus</span> <span>LD Bus</span> </div> <div style="display: flex; justify-content: space-around; margin-top: 5px;"> <span>Taxis</span> <span>Van/Combi</span> <span>MD Bus</span> <span>Walking/Cycling</span> </div>																
<b>3.-</b> On this trip, normally how many people travel together with you (including yourself)? <div style="border: 1px solid black; width: 50px; height: 20px; margin-top: 5px;"></div>																
<b>4.-</b> Can you tell me the start and end points (Origin and Destination) of your trip? <table border="1" style="width: 100%; margin-top: 5px;"> <thead> <tr> <th>Journey Origin</th> <th>Journey Destination</th> </tr> </thead> <tbody> <tr> <td>Map Reference</td> <td>Map Reference</td> </tr> </tbody> </table>													Journey Origin	Journey Destination	Map Reference	Map Reference
Journey Origin	Journey Destination															
Map Reference	Map Reference															
<b>5.-</b> Can you tell me where you join and where you leave this route? <table border="1" style="width: 100%; margin-top: 5px;"> <thead> <tr> <th>Where route was joined</th> <th>Where route was left</th> </tr> </thead> <tbody> <tr> <td>Map Reference</td> <td>Map Reference</td> </tr> </tbody> </table>													Where route was joined	Where route was left	Map Reference	Map Reference
Where route was joined	Where route was left															
Map Reference	Map Reference															
<b>Thank you for all your help. Goodbye</b>																

Figure 78 - Trip distance Survey Form

On-board, Modal Choice Survey										Date			
Travel Route Name										Sampling site			
Time of Interview		Hr	Min	Traffic flow direction						N - S	S - N	E - W	W - E
Number of people travelling together													
Performed by				Supervised by				Authorized by					
Good Morning(Afternoon) We are conducting a survey of travel preferences													
Can you tell me the start and end points (Origin and Destination) of your trip?													
Journey Origin						Journey Destination							
Map Reference						Map Reference							
Where are you travelling from?			Reasons for Trip (may be several)				How frequently do you travel on this route?						
Home <input type="checkbox"/> Work <input type="checkbox"/> School <input type="checkbox"/> Recreation <input type="checkbox"/> Shopping <input type="checkbox"/> Visiting Family/Friends <input type="checkbox"/> Other <input type="checkbox"/>			Work <input type="checkbox"/> School <input type="checkbox"/> Recreation <input type="checkbox"/> Shopping <input type="checkbox"/> Visiting Family/Friends <input type="checkbox"/> Other <input type="checkbox"/>				Trips <input type="checkbox"/> Daily <input type="checkbox"/> Weekly <input type="checkbox"/> Monthly One way or both ways? <input type="checkbox"/> in one direction <input type="checkbox"/> round trip (both directions)						
What transport modes did you use to reach this point?			How long did it take you to reach this point?				How long did you, or do you expect to wait for this bus?				How long do you expect this bus journey to take?		
This bus route <input type="checkbox"/> Metro <input type="checkbox"/> Passenger Cars <input type="checkbox"/> Taxis <input type="checkbox"/> Motorcycles <input type="checkbox"/> Van/Combi <input type="checkbox"/> HD Bus <input type="checkbox"/> MD Bus <input type="checkbox"/> LD Bus <input type="checkbox"/> Walking/Cycling <input type="checkbox"/>			< 5 min <input type="checkbox"/> 6 - 10 min <input type="checkbox"/> 11 - 20 min <input type="checkbox"/> 21 - 30 min <input type="checkbox"/> 31 - 45 min <input type="checkbox"/> 46 - 60 min <input type="checkbox"/> >60 min <input type="checkbox"/>				< 5 min <input type="checkbox"/> 6 - 10 min <input type="checkbox"/> 11 - 20 min <input type="checkbox"/> 21 - 30 min <input type="checkbox"/> 31 - 45 min <input type="checkbox"/> 46 - 60 min <input type="checkbox"/> >60 min <input type="checkbox"/>				< 5 min <input type="checkbox"/> 6 - 10 min <input type="checkbox"/> 11 - 20 min <input type="checkbox"/> 21 - 30 min <input type="checkbox"/> 31 - 45 min <input type="checkbox"/> 46 - 60 min <input type="checkbox"/> >60 min <input type="checkbox"/>		
Can you tell me where you join and where you leave this route?													
Where route was joined						Where route was left							
Map Reference						Map Reference							
How will you travel from this route to your final destination?			How long will it take you to travel from this route to your final destination?				Nowadays do you have a travel option distinct to this route?				Yes ( ) No ( )		
Metro <input type="checkbox"/> Passenger Cars <input type="checkbox"/> Taxis <input type="checkbox"/> Motorcycles <input type="checkbox"/> Van/Combi <input type="checkbox"/> HD Bus <input type="checkbox"/> MD Bus <input type="checkbox"/> LD Bus <input type="checkbox"/> Walking/Cycling <input type="checkbox"/>			< 5 min <input type="checkbox"/> 6 - 10 min <input type="checkbox"/> 11 - 20 min <input type="checkbox"/> 21 - 30 min <input type="checkbox"/> 31 - 45 min <input type="checkbox"/> 46 - 60 min <input type="checkbox"/> >60 min <input type="checkbox"/>				Metro <input type="checkbox"/> Passenger Cars <input type="checkbox"/> Taxis <input type="checkbox"/> Motorcycles <input type="checkbox"/> Van/Combi <input type="checkbox"/> HD Bus <input type="checkbox"/> MD Bus <input type="checkbox"/> LD Bus <input type="checkbox"/> Walking/Cycling <input type="checkbox"/>						

Figure 79 - Modal Choice Survey Form Page 1



Before this route came into operation, did you travel this way?				Yes <input type="checkbox"/>	No <input type="checkbox"/>
What mode of transport did you use?		Compared to your previous mode, this route is:		The time to reach your final destination is:	
Metro	<input type="checkbox"/>	Better	<input type="checkbox"/>	Longer	<input type="checkbox"/>
Passenger Cars	<input type="checkbox"/>	About the same	<input type="checkbox"/>	Shorter	<input type="checkbox"/>
Taxis	<input type="checkbox"/>	Worse	<input type="checkbox"/>	About the same	<input type="checkbox"/>
Motorcycles	<input type="checkbox"/>	No comment	<input type="checkbox"/>		
Van/Combi	<input type="checkbox"/>				
HD Bus	<input type="checkbox"/>			The journey cost is:	
MD Bus	<input type="checkbox"/>			Higher	<input type="checkbox"/>
LD Bus	<input type="checkbox"/>			Lower	<input type="checkbox"/>
Walking/Cycling	<input type="checkbox"/>			About the same	<input type="checkbox"/>
On a scale of 1 to 10 where 10 is best and 1 is worse, how do you rate:					
The cost of the service	Bad 1	5	10 Good	Two things you most like	
The presentation of the driver	Bad 1	5	10 Good		
Safety getting in and out of the bus	Bad 1	5	10 Good		
Bus frequency	Bad 1	5	10 Good		
Cleanliness of the bus	Bad 1	5	10 Good	Two things that most need improvement	
Comfort while travelling	Bad 1	5	10 Good		
Security and police presence	Bad 1	5	10 Good		
What is your overall score?	Bad 1	5	10 Good		
Should this service be implemented on other routes?				Yes <input type="checkbox"/>	No <input type="checkbox"/>
Could you tell me something about yourself?					
<b>Age</b>		<b>Sex</b>	<b>Education level</b>	<b>Occupation</b>	
15 - 20	<input type="checkbox"/>	Male	<input type="checkbox"/>	Employee, Public Service	
21 - 27	<input type="checkbox"/>	Female	<input type="checkbox"/>	Employee, Private company	
28 - 37	<input type="checkbox"/>		Primary	<input type="checkbox"/>	
38 - 50	<input type="checkbox"/>	<b>Civil Status</b>	Secondary	<input type="checkbox"/>	
51 - 65	<input type="checkbox"/>	Single	Technical Diploma	<input type="checkbox"/>	
>65	<input type="checkbox"/>	Married	High School	<input type="checkbox"/>	
	<input type="checkbox"/>	Widow(er)	Undergraduate	<input type="checkbox"/>	
	<input type="checkbox"/>	Divorced	Masters or higher	<input type="checkbox"/>	
	<input type="checkbox"/>	Living together		<input type="checkbox"/>	
	<input type="checkbox"/>			Formal commerce	
	<input type="checkbox"/>			Informal commerce	
	<input type="checkbox"/>			Blue collar job	
	<input type="checkbox"/>			Retired	
<b>Thank you for all your help. Goodbye</b>					

Figure 80 - Modal Choice Survey Form Page 2

### **Appendix A** - Fuel-use and Local Emissions Models

#### *Commonly used models*

The most widely used models for on-road vehicle emissions inventory work are:

1. **MOBILE**  
US-EPA Emission factor model for predicting gram per mile emissions of On-road Vehicles. Versions 5 and 6 (current) of the MOBILE model are in use in many countries.
2. **MOVES**  
US-EPA current emissions inventory model (MOVES2010) for On-road Vehicles that has replaced MOBILE
3. **COPERT**  
EEA emissions inventory model for On-road Vehicles

Each of these is briefly described in the following sections:

#### **MOBILE**

MOBILE is an emissions factor program designed by the U.S. Environmental Protection Agency. Version 6.2 was released in 2004, this was the latest in a series of MOBILE models dating back to 1978. One of the primary uses of the MOBILE model was to develop in the United States emission inventories for State Implementation Plans (SIPs) and for conformity determinations. It has since been replaced by MOVES.

MOBILE is also used in many countries for other kinds of analysis ranging from estimating the national impacts of motor vehicle emissions control strategies to estimating human exposure to pollutants at a specific intersection. The emission factors calculated by MOBILE are then multiplied by an estimate of vehicle miles traveled (VMT) to estimate total on-road emissions.

The MOBILE family of models is for On-road vehicles (a NONROAD Model covers nonroad engines, equipment, and vehicles). Designed to predict gram per mile emissions factors of Hydrocarbons (HC), Carbon Monoxide (CO), Nitrogen Oxides (NO<sub>x</sub>), Carbon Dioxide (CO<sub>2</sub>), Particulate Matter (PM), and toxics from cars, trucks, and motorcycles under various conditions.

Exhaust, evaporative, and refueling emission factors are also estimated in units of grams per mile. The last version, MOBILE6.2 is the first update which added the capability to estimate particulate matter<sup>16</sup> (PM) and mobile source air toxics emissions<sup>17</sup>. MOBILE6.2 includes carbon dioxide

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<sup>16</sup> exhaust particulate matter (which consists of several components), tire wear particulate matter, brake wear particulate matter

<sup>17</sup> sulfur dioxide (SO<sub>2</sub>), ammonia (NH<sub>3</sub>), six hazardous air pollutant (HAP)

(CO<sub>2</sub>) emission factors for gasoline-fueled and diesel highway motor vehicles, and for certain specialized vehicles such as natural-gas-fueled or electric vehicles that may replace them.

The MOBILE program estimates emission factor for 28 vehicle classes and covers:

- Vehicle Standards:- Pre-control, Tier 0, Tier 1, LEV & Tier 2. It is important to note that no non-US standards are included.
- Fuels:- Gasoline (RFG, RVP, oxygenates, sulfur) and Diesel. Natural and LP gas are also considered.
- Driving Conditions:- Speed, A/C, off-cycle, Temperature
- I&M:- Impact of distinct Inspection & Maintenance programs
- Model Year:- 1955 – 2050 model years

### MOBILE6 emissions predictions

MOBILE6 emissions predictions are in general higher in the past and lower in the future than the previous version, MOBILE5 as illustrated in Figure 81 to Figure 83.

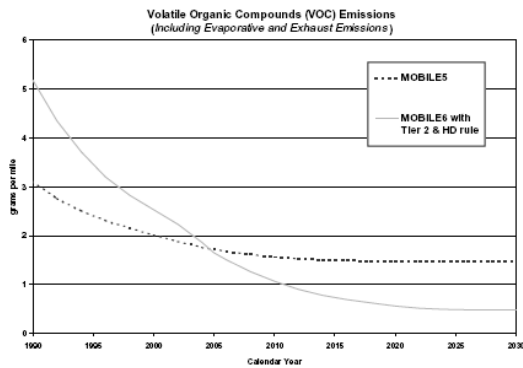


Figure 81 – VOC Mobile 6 vs Mobile 5 comparison

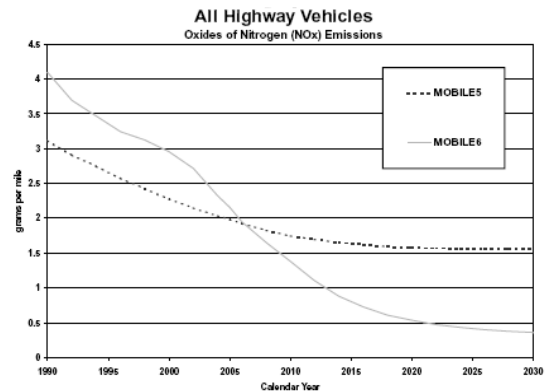


Figure 83 - NOx Mobile 6 vs Mobile 5 comparison

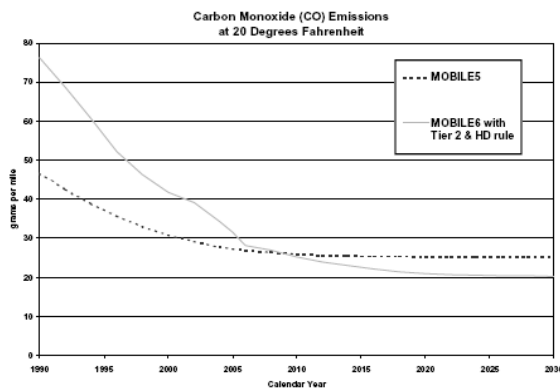


Figure 82 - CO Mobile 6 vs Mobile 5 comparison

MOBILE6 calculates adjustments to the included basic emissions rates to account for the effects of:

- Average speed by roadway type
- Temperature
- Air conditioning
- Humidity
- Gasoline volatility
- Gasoline oxygen content
- Gasoline and diesel fuel sulfur content

- Reformulated gasoline
- Detergent gasoline rule
- Other gasoline fuel properties (used to estimate HAPs only)
- Cold CO rule
- Off-cycle driving and Supplemental Federal Test Procedure (SFTP) rule
- Tampering
- Excess emissions (defeat device)
- Inspection and maintenance programs
- Anti-tampering programs
- Stage II refueling control programs
- Onboard diagnostics

Some adjustments do not affect all emission types or all emissions. Some adjustments, such as inspection and maintenance (I/M) programs, require detailed user-supplied information and complex calculation of the effect.

The program calculates speed sensitive emissions for HC, CO and NO<sub>x</sub> specifically accounting for aggressive driving behavior that was not represented in older driving cycles. An example is shown in Figure A-4.

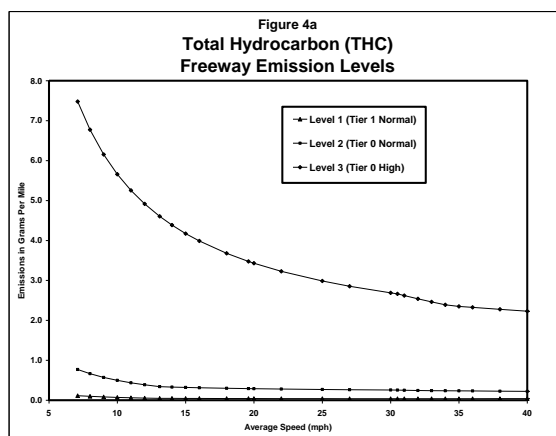


Figure A-4

The calculation of PM, CO<sub>2</sub>, Fuel Consumption and Toxic calculations are not speed sensitive. Road Grade is not taken into account.

## MOVES

The current EPA modeling system is termed the **MO**tor **V**ehicle **E**mission **S**imulator (MOVES). This new system will estimate emissions for on-road and nonroad sources, cover a broad range of pollutants, and allow multiple scale analysis, from fine-scale analysis to national inventory estimation. MOVES2010 is a computer model designed to estimate emissions factors and emissions inventories of VOCs, NO<sub>x</sub>, CO, PM<sub>10</sub>, PM<sub>2.5</sub> and other pollutants and precursors for cars, trucks, buses, and motorcycles. MOVES2010 was designed to replace the previous emissions model, MOBILE6.2.

MOVES2010 improves upon MOBILE6.2 in many respects. For example, MOVES2010 is based on a review of the vast amount of in-use vehicle data collected and analyzed since the release of MOBILE6.2, including millions of emissions measurements from light-duty vehicles. Analysis of this in-use data has enhanced EPA's understanding of how on-road mobile sources contribute to emissions inventories, and has also improved the agency's understanding of the relative effectiveness of various control strategies.

MOVES2010 has a database-centered design that allows users much greater flexibility in organizing input and output data but with the drawback of having a far steeper learning curve. MOVES2010

estimates PM<sub>2.5</sub> and PM<sub>10</sub> to account for speed and temperature variations, and models emissions at high resolution, which allows users to incorporate a much wider array of activity data and to model emissions at the link and project level.

MOVES was first released (in 2004) for Greenhouse Gas (GhG) emissions work. It includes for the first time for EPA speed correction factors for CO<sub>2</sub> emissions (and by reference fuel consumption) as shown in Figure A-5.

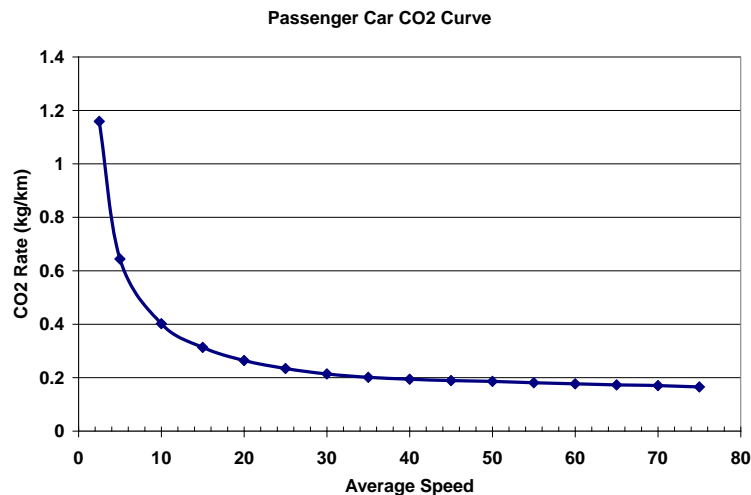


Figure A-5

The changes included in MOVES from the MOBILE framework are:

- MOVES estimates inventories (MOBILE only develops emission factors in grams/mile)
- MOVES is designed for Multi-scale analysis
- MOVES calculates emission rates on a modal basis (MOBILE rates based on aggregate driving cycles)
- The Software framework for MOVES is totally different to MOBILE
  - Relational database structure
  - Graphical User Interface
  - Object-oriented programming approach
- MOVES has Uncertainty estimation

### Modal Approach to Emission Rates

MOVES groups vehicle activity and emissions into “Bins” and any driving pattern can be modeled based on distribution of time spent in each bin. This adds major flexibility compared to MOBILE.

The bins are for Vehicle Specific Power (VSP) and account for speed, acceleration, grade and road load.

This allows common emission rates to be used for:

- Macroscale analysis:- Large-scale inventories - e.g. U.S. at county level - with 1 hour resolution capability
- Mesoscale analysis:- More refined inventories, generally at regional level based on Link-level Travel Demand Model framework. 1 hour resolution capability
- Microscale analysis:- Emission analysis for intersection or group of links based on project-level CAL3QHC framework. 15 minute time resolution

## MOVES Emission “Processes”

MOVES calculates the emissions inventory based on a set of distinct emission processes. An Emission Process in MOVES is an emission pathway with unique activity and emission characteristics. These are defined for:

- Combustion Products (Running exhaust, Start exhaust, Extended idle, Crankcase)
- Hydrocarbon Evaporation (Diurnal, Hot Soak, Running Loss, Resting Loss, Refueling)
- Other (Brake Wear, Tire Wear, Well-To-Pump, Manufacture/Disposal)

Within each process, MOVES characterizes the fleet and vehicle activity as follows:

### Characterizing the Fleet

MOVES characterizes the vehicle fleet based on:

- Source Use Types:- a specific class of vehicles or equipment defined by unique activity patterns. These are mapped to HPMS Vehicle Types for on-road. The Source Use Types are the same as MOBILE6.
- Source Bins:- Subcategories of source use type that differentiate emission levels Examples: weight class, fuel type, engine technology, standard, horsepower range, etc. The source bins open subcategories by:
  - Fuel Type (Gas, Diesel, CNG, LPG, Ethanol (E85/95), Methanol (E85/95), Gas H2, Liquid H2 Electric)
  - Engine Technology (Conventional, Direct Injection, Hybrid, Fuel Cell)
  - Model Year Group (Pre-1981, 1981-85, 86-90, 91+)
  - Loaded Weight (< 2000 lbs, 2000-2500 lbs,...>130,000 lbs)
  - Engine Size (< 2.0 liters, 2.1 – 2.5 liters, ...> 5.0 liters)

### Characterizing Activity

MOVES characterizes the vehicle activity based on:

- Total Activity:- MOVES defines the vehicle population per-source activity for a given time, location, use type, age and proposes a time basis which is more broadly applicable than grams/mile. These include:
  - Running Exhaust, Brake Wear, Tire Wear, Running Loss, Crankcase, Extended Idle
  - Source Hours Operating (SHO)
  - Start Exhaust
  - Number of Starts
  - Diurnal, Hot Soak
  - Source Hours Parked (SHP)
  - Resting Loss, Manufacture/Disposal
  - Source Hours (SH)
  - Refueling, Well-To-Pump
  - Energy (Fuel) Used
- Operating Mode Bins:- MOVES divides each activity into categories that differentiate emissions. These include:
  - Running Exhaust, Brake Wear, Tire Wear,

- Engine Specific Power (ESP)
- Start Exhaust, Hot Soak
- Soak Time
- Diurnal
- Tank Pressure
- Running Loss
- Time since start

### **Characterizing Emissions**

MOVES characterizes the Emissions Rates by:

- Source and operating mode bins
- grams per activity basis e.g. grams/time, grams/start

### ***COPERT***

COPERT 4 is designed to calculate air pollutant emissions inventories from road transport. The development of COPERT was financed by the European Environment Agency (EEA), in the framework of the activities of the European Topic Centre on Air and Climate Change. COPERT was developed primarily to estimate on-road emissions to be included in the official annual national inventories for the European Union Member Nations. The COPERT 4 methodology is also part of the EMEP/CORINAIR Emission Inventory Guidebook.

The Guidebook, developed by the UNECE Task Force on Emissions Inventories and Projections, is intended to support reporting under the UNECE Convention on Long-Range Transboundary Air Pollution and the EU directive on national emission ceilings. The COPERT 4 methodology is fully consistent with the Road Transport chapter of the Guidebook. The use of a software tool to calculate road transport emissions allows for a transparent and standardized, hence consistent and comparable data collecting and emissions reporting procedure, in accordance with the requirements of international conventions and protocols and EU legislation.

### **Methodology Outline**

COPERT 4 estimates emissions of all major air pollutants (CO, NO<sub>x</sub>, VOC, PM, NH<sub>3</sub>, SO<sub>2</sub>, heavy metals) produced by approximately 250 different vehicle sub-categories (passenger cars, light duty vehicles, heavy duty vehicles, mopeds and motorcycles) as well as greenhouse gas emissions (CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub>). The program also provides speciation for NO/NO<sub>2</sub>, elemental carbon and organic matter of PM and non-methane VOCs, including PAHs and POPs. Emissions estimated are distinguished in three sources: Emissions produced during thermally stabilized engine operation (hot emissions); emissions occurring during engine start from ambient temperature (cold-start and warming-up effects); and NMVOC emissions due to fuel evaporation. Non-exhaust PM emissions from tyre and brake wear are also included. The total emissions are calculated as a product of activity data provided by the user and speed-dependent emission factors calculated by the software.

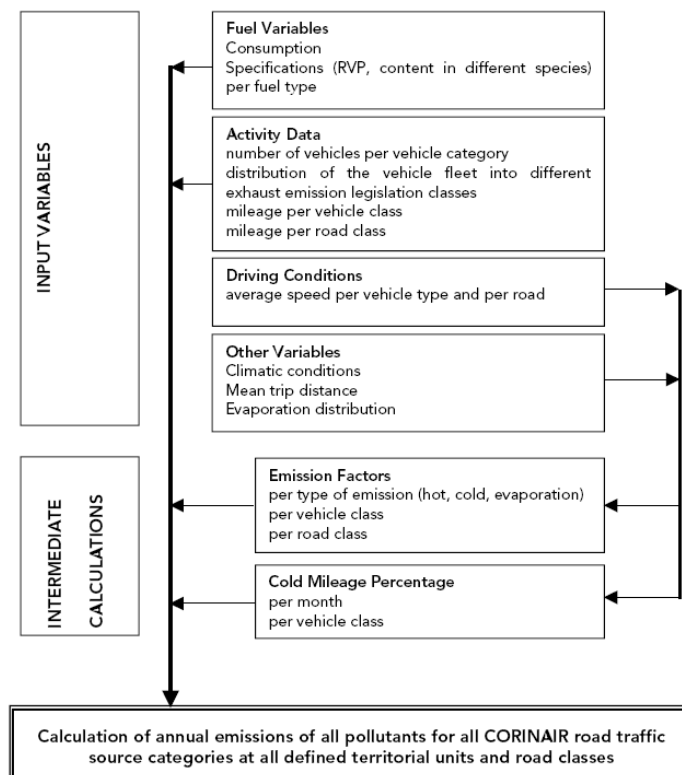


Figure 6

The speed-dependent emission factor formulae are developed empirically from multiple real-world tests on many urban drive cycles at different average speeds (see Figure 84). These drive cycles are not constant-speed but involve stop-go city traffic and suburban driving cycles, and the speed-dependent emission factor curves are derived from the mean results of each distinct cycle.

Whilst the methodology was developed for national inventories, it can be used with a sufficient degree of certainty at a higher resolution too, i.e. for the compilation of urban emission inventories with a spatial resolution of 1x1 km<sup>2</sup> and a temporal resolution of 1 hour. Figure 6 shows the input parameters and intermediate calculations that are used.

COPERT is designed specifically for vehicle fleets that meet European Legislation up to and including EURO VI for gasoline and LPG and EURO 5 for diesel, whilst MOVES is designed for US vehicle technology. COPERT is far simpler to understand and work with than MOBILE or MOVES. It has a very shallow learning curve and it is far easier to use COPERT in for other, non-specified countries or fleets than MOVES. Both have similar spatial and time resolution capability and their Factors, formulae and default data derived from field testing in both cases (with some overlap).

COPERT has speed dependant formulae for CO, VOC, NO<sub>x</sub>, PM and Fuel Consumption/CO<sub>2</sub> whilst MOVES uses speed, acceleration, grade and road load. COPERT includes grade and road load for heavy duty vehicles only. One of the strengths of COPERT is the transparency of application. These speed correction factors are readily available for use outside of the model (see Figure for an example of the CO emission factor formulae)



Vehicle Class	Engine Capacity	Speed Range (km/h)	CO Emission Factor [g/km]	R <sup>2</sup>
PRE ECE	All capacities	10-100	$281V^{0.630}$	0,924
	All capacities	100-130	$0,112V + 4,32$	-
ECE 15-00/01	All capacities	10-50	$313V^{0.760}$	0,898
	All capacities	50-130	$27,22 - 0,406V + 0,0032V^2$	0,158
ECE 15-02	All capacities	10-60	$300V^{0.797}$	0,747
	All capacities	60-130	$26,260 - 0,440V + 0,0026V^2$	0,102
ECE 15-03	All capacities	10-19,3	$161,36 - 45,62\ln(V)$	0,790
	All capacities	19,3-130	$37,92 - 0,680V + 0,00377V^2$	0,247
ECE 15-04	All capacities	10-60	$260,788V^{0.910}$	0,825
	All capacities	60-130	$14,653 - 0,220V + 0,00116386V^2$	0,613
Improved Conventional	CC < 1,4 l	10-130	$14,577 - 0,294V + 0,002478V^2$	0,781
	1,4 l < CC < 2,0 l	10-130	$8,273 - 0,1511V + 0,000957V^2$	0,767
Open Loop	CC < 1,4 l	10-130	$17,882 - 0,377V + 0,002825V^2$	0,656
	1,4 l < CC < 2,0 l	10-130	$9,446 - 0,23012V + 0,002029V^2$	0,719
EURO I	CC < 1,4 l	5-130	$9,846 - 0,2867V + 0,0022V^2$	0,133
	1,4 l < CC < 2,0 l	5-130	$9,617 - 0,245V + 0,0017285V^2$	0,145
	CC > 2,0 l	5-130	$12,826 - 0,2955V + 0,00177V^2$	0,159

Figure A-7

## Model Sensitivities

It can be expected that all the following have large affects on the emission rates predicted by these models. Changing any one of those parameters will have relatively large affects on the emission rates, i.e., an emissions change-to-input change ratio of one or greater and at least a 20% change in emissions.

- Vehicle speed distribution (Drive cycles)
- Vehicle Technology Distribution and VMT distribution by type of road
- Min/Max Temperature
- Gasoline RVP

## COPERT vs MOVES

A sensitivity analysis for Fuel Consumption of Passenger Cars and Light duty Gasoline was performed for each of the 2 methods by varying the percent of traffic flow condition (% free-flow and % congested) and the difference between the project travel time and the baseline travel time for an example route where the baseline travel time is 2.545 min/km. The first table (Figure ) shows the reduction (change) in liters of fuel per day that the 2 methods determined and the second table (Figure ) shows the difference between the results from COPERT and MOVES, where MOVES is taken as the baseline method.

MOBILE6 was excluded from this appraisal because it is the only model that does not include a Speed Correction factor for CO<sub>2</sub> emissions or fuel consumption.

Overall, however, both MOBILE/MOVES and COPERT use essentially the same methodology to estimate historical and projected GHG emissions. Currently MOBILE does not explicitly estimate CH<sub>4</sub> and does not estimate N<sub>2</sub>O emissions. Both models estimate CO<sub>2</sub>, based on fuel consumption factors, but MOBILE's data are preliminary and it does not account for vehicle driving practices (speed). Neither model addresses the fraction of carbon left unoxidized when estimating CO<sub>2</sub> emissions.

		Percent of Traffic flow under congested conditions					Difference between Project Travel Time (min/km) and a Baseline travel time of 2.545 min/km
		80%	70%	60%	50%	40%	
COPERT III		2,724	2,796	2,868	2,940	3,012	
MOVES2004		2,829	2,920	3,011	3,102	3,193	
COPERT III		5,480	5,640	5,800	5,960	6,120	
MOVES2004		5,657	5,839	6,022	6,204	6,386	
COPERT III		8,271	8,536	8,801	9,065	9,330	0.100
MOVES2004		8,486	8,759	9,033	9,306	9,580	
COPERT III		11,099	11,487	11,876	12,265	12,653	0.200
MOVES2004		11,314	11,679	12,044	12,408	12,773	
COPERT III		13,968	14,500	15,033	15,566	16,098	0.300
MOVES2004		14,143	14,599	15,054	15,510	15,966	
COPERT III							0.400
MOVES2004							
COPERT III							0.500
MOVES2004							

Figure A-8

		Percent of Traffic flow under congested conditions					Difference between Project Travel Time (min/km) and a Baseline travel time of 2.545 min/km
		80%	70%	60%	50%	40%	
COPERT III		96%	96%	95%	95%	94%	
MOVES2004		100%	100%	100%	100%	100%	
COPERT III		97%	97%	96%	96%	96%	
MOVES2004		100%	100%	100%	100%	100%	
COPERT III		97%	97%	97%	97%	97%	0.100
MOVES2004		100%	100%	100%	100%	100%	
COPERT III		97%	97%	96%	96%	96%	0.200
MOVES2004		100%	100%	100%	100%	100%	
COPERT III		97%	97%	97%	97%	97%	0.300
MOVES2004		100%	100%	100%	100%	100%	
COPERT III		98%	98%	99%	99%	99%	0.400
MOVES2004		100%	100%	100%	100%	100%	
COPERT III		99%	99%	100%	100%	101%	0.500
MOVES2004		100%	100%	100%	100%	100%	

Figure A-9

It can be seen in the red boxes that under the most probable operating scenario, the difference between the results from each method vary by up to 3%.

However, over a range of 5,640 to 12,408 liters per day (blue box) – which is a range of 220% - the difference between the results from each method varies up to maximum of 4%.

Over an even wider range of 2,724 to 16,098 liters per day (complete table) – which is a range of 590% - the difference between the results from each method and the average of the three methods varies up to maximum of 5%.

The California EMFAC 2000 / '02 model was included in the comparison without increasing the sensitivity uncertainty bounds.

It is important to note that the idle fuel consumption in the MOVES model was calculated at an equivalent speed of 4.0 mph<sup>18</sup>, whilst in COPERT, the minimum speed associated with each Speed Correction Factor was used. For the EMFAC 2000 / '02 model a 2.5 mph speed was used for the idle emissions calculations.

<sup>18</sup> not 2.5 mph as specified by EPA for MOBILE calculations

It can be expected that for the other pollutants this difference will be greater but no direct comparison is easy to perform due to the legislative differences.

### *Measurement and Modeling Uncertainty*

MOVES is the only model that specifically includes a determination of the uncertainty of the model output. MOVES speed-dependant CO<sub>2</sub> formula is a g/hr straight-line relationship to speed

COPERT does include some of the elements, such as the R<sup>2</sup> “curve fit-factor” for the speed sensitive emissions curves (see Figure 84) but does not present a complete determination. Many of the COPERT speed-dependant formulae have low R<sup>2</sup>.

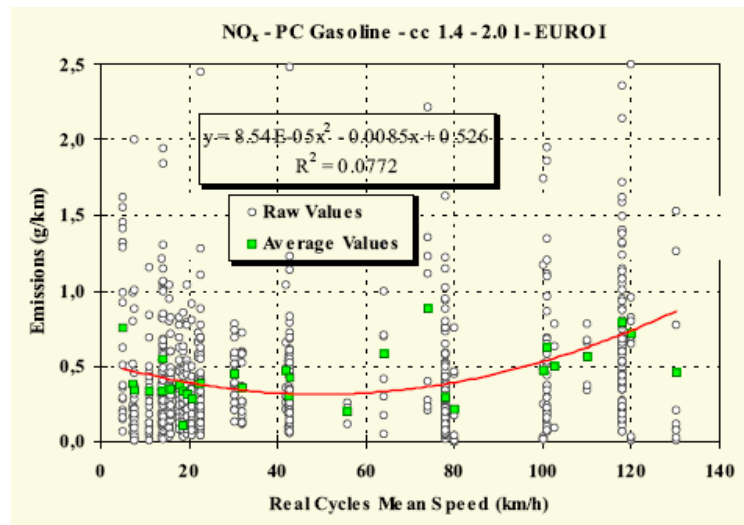


Figure 84 – Typical speed-dependant formula construction

The ISO Guide to the Expression of Uncertainty in Measurement (ISO-GUM) states that every measurement should be accompanied by an indication of the uncertainty associated with it. This should also be true for any modeled results. The user of the model should be able to ascertain the range of uncertainty associated with the end-results. If a model-data combination is capable of generating a forecast within say, only a  $\pm 45\%$  range, the user needs to be aware of this in any policy or other decisions taken based on the model-output.

## Appendix B - Level of disaggregation needed for emissions factor determination

Class	Motorcycles				
Subclass	2T		4T		
Fuel	Petrol		Petrol		
Sub-subclass	up to 50 cc	over 50 cc	up to 250 cc	over 250 and up to 750 cc	over 750 cc
Technology	Conventional	Conventional	Conventional	Conventional	Conventional
	Euro 1	Euro 1	Euro 1	Euro 1	Euro 1
	Euro 2	Euro 2	Euro 2	Euro 2	Euro 2
	Euro 3	Euro 3	Euro 3	Euro 3	Euro 3

Figure 85 - Motorcycle specification detail

Class	Three Wheelers		
Subclass	2T	4T	
Fuel	Petrol	Petrol	LPG / CNG
Sub-subclass	All	All	All
Technology	Carburated, Conventional	Carburated, Conventional	
	Carburated, improved conventional	Carburated, improved conventional	Carburated, improved conventional
	Carburated, high technology	Carburated, high technology	Carburated, high technology
	Fuel injected, Conventional		
		Carburated, catalyst	Carburated, catalyst
		Fuel injected, catalyst	Fuel injected, catalyst

Figure 86 - Three Wheeler specification detail

Class	Passenger Cars									
Subclass	All									
Fuel	Petrol					Diesel		LPG / CNG		
Sub-subclass	up to 1.4 litre	over 1.4 and up to 2.0 litre	over 2.0 litre	2 stroke	hybrid	up to 2.0 litre	over 2.0 litre	up to 1.4 litre	over 1.4 and up to 2.0 litre	over 2.0 litre
Technology	Conventional	Conventional	Conventional	All	All	Conventional	Conventional	Conventional	Conventional	Conventional
	Improved conventional	Improved conventional	Improved conventional							
	Open Loop	Open Loop	Open Loop							
	Euro 1	Euro 1	Euro 1			Euro 1	Euro 1	Euro 1	Euro 1	Euro 1
	Euro 2	Euro 2	Euro 2			Euro 2	Euro 2	Euro 2	Euro 2	Euro 2
	Euro 3	Euro 3	Euro 3			Euro 3	Euro 3	Euro 3	Euro 3	Euro 3
	Euro 4	Euro 4	Euro 4			Euro 4	Euro 4	Euro 4	Euro 4	Euro 4
	Euro 5	Euro 5	Euro 5			Euro 5	Euro 5			
	Euro 6	Euro 6	Euro 6			Euro 6	Euro 6			
	Euro 3 + GDI	Euro 3 + GDI	Euro 3 + GDI			Euro 3 + DPF	Euro 3 + DPF			

Figure 87 - Passenger Car specification detail

Class	Light duty Vehicles				
Subclass	up to 3.5 t GVW		up to 2.5 t GVW		
Fuel	Petrol	Diesel	LPG / CNG		
Sub-subclass	All	All	up to 1.4 litre	over 1.4 and up to 2.0 litre	over 2.0 litre
Technology	Conventional	Conventional	Conventional	Conventional	Conventional
	Euro 1	Euro 1	Euro 1	Euro 1	Euro 1
	Euro 2	Euro 2	Euro 2	Euro 2	Euro 2
	Euro 3	Euro 3	Euro 3	Euro 3	Euro 3
	Euro 4	Euro 4	Euro 4	Euro 4	Euro 4
	Euro 5	Euro 5			
	Euro 6	Euro 6			

Figure 88 - Light Duty Commercial Vehicle specification detail

Class	Heavy duty Vehicles									
Subclass	Long Distance Coach		over 3.5t GVW	Urban bus						
Fuel	Diesel		Petrol	Diesel			LPG / CNG			
Sub-subclass	Standard ≤18t	3-Axles >18t	All	Midi ≤15t	Std >15-18t	Articulated >18t	All			
Technology	Conventional	Conventional	Conventional	Conventional	Conventional	Conventional	Conventional			
	Euro 1	Euro 1	Euro 1	Euro 1	Euro 1	Euro 1	Euro 1			
	Euro 2	Euro 2	Euro 2	Euro 2	Euro 2	Euro 2	Euro 2			
	Euro 3	Euro 3	Euro 3	Euro 3	Euro 3	Euro 3	Euro 3			
	Euro 4	Euro 4	Euro 4	Euro 4	Euro 4	Euro 4				
	Euro 5	Euro 5	Euro 5	Euro 5	Euro 5	Euro 5				
			Euro 6				EEV			
Subclass	Rigid Truck									
Fuel	Diesel									
Sub-subclass	≤7.5t GVW	>7.5-12t GVW	>12-14t GVW	>14-20t GVW	>20-26t GVW	>26-28t GVW	>28-32t GVW	>32t GVW		
Technology	Conventional	Conventional	Conventional	Conventional	Conventional	Conventional	Conventional	Conventional		
	Euro 1	Euro 1	Euro 1	Euro 1	Euro 1	Euro 1	Euro 1	Euro 1		
	Euro 2	Euro 2	Euro 2	Euro 2	Euro 2	Euro 2	Euro 2	Euro 2		
	Euro 3	Euro 3	Euro 3	Euro 3	Euro 3	Euro 3	Euro 3	Euro 3		
	Euro 4	Euro 4	Euro 4	Euro 4	Euro 4	Euro 4	Euro 4	Euro 4		
	Euro 5	Euro 5	Euro 5	Euro 5	Euro 5	Euro 5	Euro 5	Euro 5		
Subclass	Tractor-trailer / Articulated Truck									
Fuel	Diesel									
Sub-subclass			>14-20t GCW	>20-28t GCW	>28-34t GCW	>34-40t GCW	>40-50t GCW	>50-60t GCW		
Technology			Conventional	Conventional	Conventional	Conventional	Conventional	Conventional		
			Euro 1	Euro 1	Euro 1	Euro 1	Euro 1	Euro 1		
			Euro 2	Euro 2	Euro 2	Euro 2	Euro 2	Euro 2		
			Euro 3	Euro 3	Euro 3	Euro 3	Euro 3	Euro 3		
			Euro 4	Euro 4	Euro 4	Euro 4	Euro 4	Euro 4		
			Euro 5	Euro 5	Euro 5	Euro 5	Euro 5	Euro 5		

Figure 89 - Heavy Duty Commercial Vehicle specification detail

## **Appendix C** - *Description of the EFFECT model*

The Energy Forecasting Framework and Emissions Consensus Tool (EFFECT) has been developed by the World Bank through ESMAP/WBI with an integrated eLearning package and is openly available, free of charge, via the World Bank's site. It provides a modeling framework to forecast energy usage and emissions from the principal sectors of the economy over a modeling period of 25 years. The EFFECT model was initially developed as an integral part of the India Low Carbon Growth study. Currently the model contains the on-road transport, the power sector, household electricity use, non-residential electricity and other energy usage, and the six largest energy-consuming industries which together account for over 70 percent of GHG emissions. Other modules (such as household biomass, railways and agriculture) will follow.

### **Objectives**

The objectives of its design as a bottom-up model are:

- to examine alternative scenarios
- to produce a refined and expanded set of assumptions, scenarios and outputs
- to contribute to the assessment of available GHG projections, mitigation potential and associated costs; and
- to be sufficiently flexible to adapt easily to a changing set of assumptions and requirements in each country.

### **Outputs**

The EFFECT model provides the following outputs in a pair-wise comparison of scenarios for multiple scenarios:

- Annual energy consumption by point of consumption in each sector from the initial year to the terminal year
- Annual GHG emissions by energy point of consumption in each sector for each time period
- Local pollutant emissions from transport for each time period
- Process emissions from industry for each time period
- Investment, operating and maintenance costs and fuel costs by energy point of consumption in each sector for each time period
- Fuel consumption and costs by energy point of consumption in each sector for each time period
- Costs of reducing GHG emissions in net present value.
- The model enables the construction of marginal abatement cost curves

### *Modeling framework of the transport model and overall process*

There are two distinct approaches to project on-road transport energy consumption; one makes use of aggregate macro or average data at the country or sub-national/state level.

Another approach uses micro-level data that reflects individual vehicle-type behavior. This approach enables analysis across vehicle sub-groups and uses. The approach used in this model is a variant of this second approach and is sometimes referred to as an end-use, bottom-up, or engineering approach.

While the former aims to accumulate average consumption, the latter examines the ownership, use and life of energy-consuming devices and considers efficiency scenarios from an engineering point of view, as opposed to micro-economic/econometric.

EFFECT constructs a detailed national baseline vehicle population from historic sales data via a mortality function and develops a vehicle usage pattern by vehicle type and age from expert opinion and local data. These, together with a forecast of expected changes in the new vehicle sales mix over the modeling period allow the changes in the vehicle active fleet to be projected using vintaging.

The bottom-up model then calculates locally-calibrated speed-dependant and usage-sensitive emissions factors (from COPERT 4) to determine the fuel usage and emissions (greenhouse gas and local criteria emissions) from each type of vehicle and accumulates this data by vehicle and fuel type for each transport scenario.

The use of highly disaggregated data is particularly valid for studies such as this where departure from historic tendencies needs to be analyzed if improvements in the energy efficiency of access to goods and services are to be achieved.

EFFECT was developed using Visual Basic in Microsoft Excel 2007 to ensure that it is user-friendly and can be run, and modified, without complex equipment or training by diverse institutions and researchers. It has all assumptions and input data clearly visible (with no “black-box” calculations) and is capable of testing a number of divergent scenarios.

There are twelve steps involved in forecasting on-road transport energy consumption and GHG emissions:

**Define the active vehicle population, country-wide over the modeling period**

1. Determine the overall aggregate on-road vehicle population for the economy (country-level) for any base year by type of vehicle.
2. Disaggregate this baseline vehicle population by vehicle type, subtype, engine displacement, technology, GVW, age, and fuel use by using historic vehicle sales through a mortality model.
3. Project the proportional sales mix of new vehicles by vehicle type, subtype, engine displacement, technology, GVW, and fuel use.
4. Use a vehicle mortality calculation to determine the number of vehicles in the active population that must be replaced annually, project annual sales volumes of new vehicles and the annual changes that their incorporation brings to the vehicle population mix.

**Define the average per-vehicle annual usage, country-wide over the modeling period**

5. Project the per-vehicle age-sensitive annual usage (km/year) by vehicle type and subtype based on expert opinion and local data.

**Define local operating conditions**

6. Project average local operating conditions for the vehicle population considering biofuel usage, average vehicle load and average road grade, ambient temperature, and the impact of inspection and maintenance programs on the quality of vehicle maintenance. Determine local prices for automotive fuels.



### **Define new vehicle prices and in-use vehicle operating cost (optional)**

7. Determine new vehicle prices and in-use vehicle operating costs over the modeling period by vehicle type and subtype. This is used in determining the relative impact of improvements in vehicle efficiency versus higher initial cost for distinct types and sub-types of vehicle.

### **Compute fuel consumption and emissions factors by type and sub type of vehicle**

8. Compute the fuel consumption and emissions factors for each specific type and technology of vehicle using the international COPERT4 model. This takes into account the distribution of VKT in each speed bin by type of vehicle from the traffic model, together with other data collected or calculated in these steps.

### **Obtain locally measured calibration data**

9. Calibrate the COPERT4 emissions factors to local conditions using locally measured fuel consumption data for popular in-use vehicles in each category under city and highway driving conditions.

### **Compute fuel consumption and emissions**

10. Compute the fuel consumption and emissions factors for each specific type and technology of vehicle in each scenario.
11. Evaluate improvements in vehicle efficiency using a marginal abatement cost (MAC) curve for distinct types and sub-types of vehicle.
12. Compute the energy consumption and emissions for each type and sub-type of vehicle and for the active city-level vehicle population.

These sub-steps are described below.

## ***Modeling Steps***

### **1. Determine the overall aggregate on-road vehicle population at the country-level.**

The first step is to get a good, solid idea of the total active vehicle mid-year population in the country by type of vehicle for any one base year. The top-level vehicle types are those shown in Table 12.

*Table 12 - Vehicle Types*

<b>Vehicle Types</b>
Two-wheelers (2W)
Three-wheelers (3W)
Passenger Cars (PC)
Light-duty commercial vehicles for passengers (LCV - Passenger)
Light-duty commercial vehicles for freight (LCV - Goods)
Heavy-duty commercial vehicles: Urban buses (HCV - Urban Bus)
Heavy-duty commercial vehicles: long distance coaches (HCV - Coach)
Heavy-duty commercial vehicles: freight (HCV - Truck)

Great care must be taken in using official population figures, since these are usually inflated because most authorities do not have a reliable means to subtract from the active in-use population, those vehicles that no longer circulate.

If the active baseline population of vehicles is not known by type of vehicle, this may be determined as follows:

The average age of a population of vehicles depends on two things; [i] the change in vehicle sales from one year to another (with increasing sales, the population will appear younger than with a stable annual sales figure) and [ii] the average life of each vehicle in the parc. The steps to define the vehicle population (or parc) include:

*Obtain historic sales data*

Vehicle sales data, by type of vehicle, is obtained for as many historic years as possible with the goal of compiling at least 15 consecutive years' worth of data identifying sales and transfers of vehicles into the national market – including imports and excluding any vehicles exported to other countries.

*Conduct a survey of in-use vehicles*

A statistically significant survey of in-use vehicles is conducted in which the model year of each vehicle sampled is recorded by type of vehicle. From this, the arithmetic mean age of the vehicles in service, by type of vehicle can be calculated.

*Use a Mortality model to determine the population.*

For each type of vehicle, a mortality model is built using the historic sales data as described in section IV-2 of this report. The sales of each year are added to the population derived from the sales data using previous years, where the mortality of the previously derived population is calculated using an arbitrary average life "X".

*Adjust "X" in the mortality model to match the survey results.*

Adjust "X" so that the mean age of the calculated population (for each type of vehicle) matches the mean age of the sample of that same type of vehicle. This resultant value of "X" is the average life that should be considered in calculating the size of the population from the mortality analysis.

## **2. Disaggregate the baseline vehicle population by vehicle type, subtype, engine displacement, technology, GVW, age, and fuel use.**

Vehicle fuel consumption varies due to (i) intrinsic vehicle characteristics; and (ii) the conditions of use. Conditions of use include ambient temperature, travel speed, biofuel components, road grade, vehicle load (particularly for heavy duty vehicles), and the presence of an effective vehicle inspection and maintenance program that can lead to improved maintenance. Vehicle characteristics include vehicle type, subtype, engine displacement, technology, GVW, accumulated mileage, and fuel used and thus the baseline population needs to be sub-divided into these categories, and each forecast independently.

The baseline vehicle population is disaggregated by using historic vehicle sales through a mortality model. The sales data is needed specifying vehicle type, subtype, engine displacement, technology, GVW, and fuel used.

To aid forecasting the new vehicle sales mix over the modeling period, it is highly convenient to further disaggregate vehicle types by the sub-types shown in Table 13.

Table 13 - Vehicle Sub-types

Vehicle Type	Sub-types
2W	Mopeds, scooters, and motorcycles
3W	All three-wheelers
PC	Mini, Small, Lower Medium, Medium and Upper Medium, Large and Luxury, SUV and AUV/MUV
LCV - Passenger	All Light Duty commercial vehicles used to transport Passengers
LCV - Goods	Mini van/truck, pick-up, van
HCV - Urban Bus	By GVW group
HCV - Coach	By GVW group
HCV - Truck	Rigid truck by GVW, and tractor-trailer combination by GCW groups

Vehicle mortality is calculated using the Winfrey S3 survival curve as explained in Chapter 10.

Sales data which is reported by manufacturers at the end of each year is first adjusted from mid-year to mid-year since we are interested in modeling the mid-year population to be able to calculate the average fuel consumption and CO<sub>2</sub> emissions over each year.

The total vehicle mortality in each year, which represents the number of vehicles that have to be replaced via new vehicle sales, is the sum of the mortalities for that year calculated from historic sales data. The average vehicle life for each type of vehicle is chosen such that the resultant baseline population matches the exogenous figure. In this way, distinct values of “T” and “s” are defined for each vehicle type and subtype by matching the population, as defined by the mortality model using each year’s historic sales of each vehicle type, with that defined above.

When the mortality model is later used to forecast vehicle sales, these values of “T” and “s” may be modified periodically to take into account changes in vehicle build quality and other factors. Once the values of “T” and “s” are defined for each vehicle type and subtype, these are used to vintage separately each level of detail.

### 3. Project the proportional sales mix of new vehicles by vehicle type, subtype, engine displacement, technology, GVW, and fuel use.

The proportional sales mix of new vehicles is then projected by vehicle type, subtype, engine displacement, technology, GVW and fuel use over the modeling period using expert judgment based on information from manufacturers. This proportional sales mix of new vehicles must take into account expected changes, under a business-as-usual trajectory, of the vehicle sales mix by type of vehicle considering the vehicle sub-types shown in Table 13.

### 4. Determine the number of vehicles in the active population that must be replaced annually, project annual sales volumes of new vehicles and the annual changes that their incorporation brings to the vehicle population mix.

Using the vehicle mortality calculation, the annual new vehicle sales volumes of each type of vehicle are projected taking into account the number of vehicles in the active population that must be replaced annually and the growth of the active population. As described above, the sales figures are adjusted

from mid-fiscal-year to mid-fiscal-year. These annual sales by vehicle type are disaggregated using the proportional mix determined above to project annual sales volumes by vehicle type, subtype, engine displacement, technology, GVW and fuel use. Using the same mortality analysis calculation, the active population is determined for each year by vehicle type, subtype, engine displacement, technology, GVW and fuel use.

#### **5. Define the average per-vehicle annual usage.**

The annual kilometers driven by each vehicle will vary according to the vehicle type and sub-type, its style of usage (private or business), and the age of the vehicle. New vehicles tend to be driven more than older vehicles.

#### **6. Determine average local operating conditions**

The following vehicle operating conditions have a direct impact on fuel consumption, CO<sub>2</sub>, and criteria emissions. They need to be defined for each year of the modeling period to be able to calculate and apply emissions factors to each vehicle in the active population.

##### *Percentage VKT under different urban, rural, and highway road speed conditions*

TAMT or a traffic model can be used to generate the proportion of VKT under different road speed conditions for each vehicle type. This speed mix is assigned to each of the vehicle types in 10km/hr bins (0-10, 10-20 etc). This data will be used to generate the speed-sensitive emissions factors in COPERT4 for each vehicle technology.

##### *Biofuel usage*

The incorporation of biofuels into the gasoline and diesel fuel mix changes the emissions characteristics of each vehicle. Additionally, under UNFCCC rules, the emissions from the combustion of biofuels are counted as agricultural emissions, not transport emissions to avoid double-counting.

##### *Vehicle load*

For heavy-duty vehicles, both passenger and freight, vehicle loading has a first-order impact in fuel consumption and emissions. Normally a 50% load condition is used to determine average fuel consumption to account for deadheading (when the truck runs empty on the return journey or to pick up a load) and to cover the frequent occurrence for lighter weight loads where the volumetric capacity of the truck is reached before its maximum weight limitation. In the Emissions Factors module, these have been calculated for load conditions of 0%, 50% and 100% and the 50% load condition was used to calculate fuel consumption and emissions in all cases.

##### *Road grade*

Road grade also has a first-order impact in fuel consumption and emissions for heavy-duty passenger and freight vehicles. Normally a 0% road grade is used but this may be adjusted to account for the impact of extremely hilly terrain. In the Emissions Factors module, these have been calculated for seven grade conditions ranging from -6% to +6% in 2% increments. The 0% road grade condition was used to calculate fuel consumption and emissions in all cases.

### *Ambient temperature and average trip length*

Ambient temperature impacts the over-emissions due to cold starts and evaporative emissions. In the emission-factor determination it is necessary to include monthly mean high and low temperatures which should be based, not on a national geographical average but on a vehicle-population-weighted average.

The average trip length determines the number of starts per day which impacts cold start over-emissions.

### *Impact of inspection and maintenance programs and accumulated mileage on vehicle maintenance*

Effective vehicle inspection and maintenance (I&M) programs reduce fuel consumption and emissions particularly from older vehicles because of improved maintenance and it is necessary to take into account the average accumulated mileage of the vehicles in the population.

## **7. Determine new vehicle prices and in-use vehicle operating costs**

The benefit-cost analysis methodology used in this model includes the determination on a per-model and per-year basis of the fixed and variable cost components of owning and using a vehicle. This stream of annual net costs can be discounted over the modeling period to derive a present value which can be compared with the accumulated tons of CO<sub>2</sub>e emissions (summed without discounting) to get the cost effectiveness ratio (cost per ton of CO<sub>2</sub>e reduction) for each option.

The costs included in the model structure are:

- New vehicle prices
- Insurance costs
- Maintenance and other variable costs
- Fuel costs

## **8. Compute the fuel consumption and emissions factors.**

COPERT 4 is a windows software program developed as a European tool to calculate emissions from the on-road transport sector. It is used by many countries in the EU to report their annual mobile source emissions. The emissions calculated include CO, NO<sub>x</sub>, VOC, PM, CO<sub>2</sub>, fuel consumption and other pollutants. The program and its extensive methodology documentation (Gkatzoflias, 2007 and Mellios, 2007) is downloadable from the site at <http://lat.eng.auth.gr/copert/>. The speed-sensitive emissions factors calculated by this methodology are derived from empirical data collected in many thousands of tests on real-world vehicles.

To be able to integrate the COPERT 4 emissions factor calculations into the transport module, this methodology was replicated in Excel in a separate module and linked to Transport using Visual Basic for Applications. The Excel-based COPERT4 calculation module generates some 3,500 emission factors, dependant on input parameters mentioned above and the individual vehicle specifications.

Emission estimations are generally distinguished in three sources: Emissions produced during thermally stabilized engine operation (hot emissions), emissions occurring during engine start from ambient temperature (cold-start and warming-up effects) and NMVOC emissions due to fuel evaporation. The

total emissions are calculated as a product of activity data provided by the user and calculated speed-dependent emission factors.

Once the emission factors are calculated it is possible to calculate the Cold and Hot Emissions that the vehicle will make in one year. To reach better refined results, the methodology calculates and uses the Mileage Degradation Factor and the Fuel Effect Factor. The first one takes in account that the age of the vehicle is important (older cars will produce more pollution). The last one is related to the effects that new fuel types can produce in older cars (improved fuels will make the cars produce less pollution even older vehicles).

This COPERT4 based methodology was expanded in two areas:

- Electric vehicles (plug-in) were added to the calculation. A survey of in-use electric vehicles generated an empirical relationship. This average kWh/km for each type of vehicle is used with the power sectors average g CO<sub>2</sub> / kWh for the year in question to determine the emissions from plug-in electric vehicles. Average transmission and distribution losses for the year in question are taken into account. Battery charging has efficiency estimated at 90% and lithium-ion battery efficiency is estimated at 94%.
- Three-wheelers were not sufficiently represented in the COPERT4 based methodology and were added to the calculation. An emissions study (UCR 2004) conducted in Pune, India from March 9, 2003 to March 22, 2003 generated the required data. This study was performed by a partnership between local and regional governments, universities, and non-government officials, the US-EPA and USAEP offices, staff from Global Sustainable Systems research, and the University of California at Riverside (the report and data is available at <http://www.issrc.org/ive/>). The emissions factors for three-wheelers determined by this study, using the international vehicle emissions model (IVEM), were incorporated into the calculation.

## **9. Calibrate the COPERT4 emissions factors to local conditions**

The COPERT 4 methodology generates emissions factors that are representative for average vehicles operating in the EU and these may require adjustment to best represent average vehicles operating in any other specific country.

The adjustment needs to consider the differences in vehicle sub-types and operating conditions. The same COPERT 4 vehicle/engine classification can be used in different sub-types of vehicle. For example, EURO-2 fuel-injected gasoline engines of less than 1.4 L engine displacement are used in both Mini and Small cars and clearly the fuel economy should be different in each of these classifications. Additionally, fuel consumption differences—in addition to the speed sensitive fuel economy change due to road speed conditions—can be expected between, say, Asian cities and the EU.

To compensate for these differences, fuel consumption data needs to be obtained from independent road test results—performed by vehicle owners, companies, magazines and others—on popular vehicles within each category under city and highway driving conditions in each country.

For each vehicle sub-type the VKT weighted fuel economy (of the in-use vehicles) was calculated for liquid fuels using COPERT4 and using this country-specific field data. The percentual difference of the later, with respect to the former, was then applied to all COPERT4 generated figures for CO<sub>2</sub> emissions

and fuel consumption from that vehicle sub-type and country. Since the comparison is under real-life driving conditions, the local road speed and drive share mix from the transport models were used in generating the COPERT4 emissions factor corrections.

#### **10. Compute the fuel consumption and emissions factors for each specific type and technology of vehicle in each scenario.**

The locally calibrated, COPERT4 emissions factors for each type, sub-type and technology of vehicle is then calculated for each scenario taking into account the VKT speed mix of that scenario and the other local and ambient factors. These are then assigned to the forecast population of vehicles and expected per-vehicle VKT in that city under the scenario in question.

#### **11. Project improvements in vehicle efficiency**

Additional scenarios can then be constructed to evaluate the impact of improving the fuel efficiency of new vehicles sold into the active population.

In the “higher technology” option it can be assumed that different measures would be enforced to get manufacturers to comply with tighter CO<sub>2</sub>-emissions standards for passenger cars and N1-class light duty vehicles. In this scenario it is assumed that there are many technological pathways open to manufacturers to improve the fuel economy of their vehicles. These were reviewed in the “Review and analysis of the reduction potential and costs of technological and other measures to reduce CO<sub>2</sub>-emissions from passenger cars” which was carried out by TNO, IEEP and LAT on behalf of the European Commission<sup>19 20</sup>. The report evaluates measures identified by the European Commission. These include the following technical and non-technical measures:

##### *Technical measures*

- technical options to reduce fuel consumption at the vehicle level
- application of fuel efficient air conditioning systems
- options to reduce vehicle and engine resistance factors
- options for application of alternative fuels based on fossil energy
- increased application of biofuels
- possibilities to include N1 vehicles<sup>21</sup> into the Commitments

##### *Non-technical measures*

- fuel efficient driving
- CO<sub>2</sub> based taxation schemes for passenger cars
- options for improved energy or CO<sub>2</sub> labeling
- public procurement proposals

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<sup>19</sup> See TNO, 2006

<sup>20</sup> See CEER 2006 and CEER 21006b

<sup>21</sup> N1: vehicles designed and constructed for the carriage of goods and having a maximum mass not exceeding 3,5 tons

Table 14 - Technical measures

Technology options for gasoline cars	Technology options for diesel cars
<b>Engine</b>	<b>Engine</b>
Reduced engine friction losses DI / homogeneous charge (stoichiometric) DI / Stratified charge (lean burn / complex strategies)  Medium downsizing with turbocharging Strong downsizing with turbocharging Variable Valve Timing Variable valve control Optimized cooling circuit Advanced cooling circuit+ electric water pump	Reduced engine friction losses   Mild downsizing Medium downsizing Strong downsizing  Optimized cooling circuit Advanced cooling circuit+ electric water pump Exhaust heat recovery
<b>Transmission</b>	<b>Transmission</b>
Optimized gearbox ratios Piloted gearbox Dual-Clutch	Piloted gearbox Dual-Clutch
<b>Hybrid</b>	<b>Hybrid</b>
Start-stop function Start-stop + regenerative braking Mild hybrid (motor assist) Full hybrid (electric drive capability)	Start-stop function Start-stop + regenerative braking Mild hybrid (motor assist) Full hybrid (electric drive capability)
<b>Body</b>	<b>Body</b>
Improved aerodynamic efficiency Mild weight reduction (5% BIW = 1.5% veh. weight) Medium weight reduction (12% BIW = 3.6% veh. weight) Strong weight reduction (30% BIW = 9.0% veh. weight)	Improved aerodynamic efficiency Mild weight reduction (5% BIW = 1.5% veh. weight) Medium weight reduction (12% BIW = 3.6% veh. weight) Strong weight reduction (30% BIW = 9.0% veh. weight)
<b>Other</b>	<b>Other</b>
Low rolling resistance tires Electrically assisted steering (EPS, EPHS) Advanced after-treatment  Gear shift indicator	Low rolling resistance tires Electrically assisted steering (EPS, EPHS) DeNOx catalyst Particulate trap / filter Gear shift indicator

Notes:

- Reduced engine friction losses: includes low friction engine and gearbox lubricants
- Mild downsizing with turbocharging:  $\approx 10\%$  cylinder content reduction
- Medium downsizing with turbocharging:  $\approx 20\%$  cylinder content reduction
- Strong downsizing with turbocharging:  $\approx 30\%$  cylinder content reduction
- Mild weight reduction:  $\approx 5\%$  reduction of weight on Body-In-White
- Medium weight reduction:  $\approx 15\%$  reduction of weight on Body-In-White
- Strong weight reduction:  $\approx 30\%$  reduction of weight on Body-In-White



- Advanced aftertreatment: e.g. NOx-storage catalyst for DI gasoline engines

## **12. Compute the energy consumption and emissions**

The Transport model uses all of the previous steps to compute and disaggregate:

- Active Vehicle Population
- New Vehicle Sales
- Vehicle-kms traveled (VKT)
- Passenger-kms traveled (PKT)
- Purchase cost of New Vehicles (optional)
- Annual operating cost - no fuel (optional)
- Fuel cost
- Total Fuel Consumed
- Fossil Fuel Consumed
- Ultimate CO<sub>2</sub> emissions (with and without the Biofuel portion)
- CO emissions
- VOC emissions
- NOx emissions
- PM emissions

and all their derivatives for each vehicle type, sub-type and every year and scenario in the modeling period.

Whilst all the data and formulae are in Excel, Visual Basic is used to automate this process.

## Appendix D - Guidelines for Evaluating and Expressing the Uncertainty of Measurement Results

This is a brief summary of the method of evaluating and expressing uncertainty in measurement. It is adapted from the “Measurement Good Practice Guide No. 11 (Issue 2) - A Beginner’s Guide to Uncertainty of Measurement” by Stephanie Bell of the UK National Physical Laboratory<sup>22</sup>. Another more technical source would be the information presented by NIST on-line at <http://physics.nist.gov/cuu/Uncertainty/basic.html> which is adapted from NIST Technical Note 1297 (TN 1297<sup>23</sup>), prepared by B.N. Taylor and C.E. Kuyatt and entitled *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*. This Technical Note is based on the comprehensive International Organization for Standardization (ISO) *Guide to the Expression of Uncertainty in Measurement*<sup>24</sup> (GUM).

### *Why is important to express the uncertainty of measurement?*

In measuring transport activity, we have seen that it is impossible to measure every trip made by every vehicle that is operating within the study region. Sampling is needed to get data for the traffic counts, and GPS samples are used to get traffic speeds and drive cycles. Additionally any emissions factors used, from COPERT, MOVES, or locally measured emissions, are also based on a sample of vehicles.

The driving patterns of no two vehicles will be identical and thus their emissions will also differ. If the samples are small, then the risk of their results being different from the total population of vehicle-trips also may increase. Using larger samples may diminish this risk, but at the same time increase cost and so getting the “right” size for the samples is a delicate matter.

Take the case in which traffic activity is measured on a street, then traffic light synchronization is changed, and the traffic activity is measured again to see what difference this made. If the uncertainty in each of the measurements is large it may be impossible to detect the change caused by the traffic light synchronization. If the samples are increased to reduce this level of uncertainty, measurement costs also go up.

Assume that we measure the speed change in every vehicle and this is shown in Figure 90. As there is variation in vehicle speed it is best to take many readings and take an average. An average gives you an estimate of the ‘true’ value. An **average** or **arithmetic mean** is usually shown by a symbol with a bar above it, e.g.  $\bar{x}$  (‘x-bar’) is the mean value of  $x$ .

The formula for calculating the **average** or **arithmetic mean** of a series of “n” measurements is:

$$\bar{x} = \frac{\sum_{i=0}^n x_i}{n} \quad (1)$$

<sup>22</sup> Available at [http://www.wmo.int/pages/prog/gcos/documents/gruanmanuals/UK\\_NPL/mgpg11.pdf](http://www.wmo.int/pages/prog/gcos/documents/gruanmanuals/UK_NPL/mgpg11.pdf)

<sup>23</sup> Available at <http://physics.nist.gov/Pubs/guidelines/TN1297/tn1297s.pdf>

<sup>24</sup> see <http://physics.nist.gov/cuu/Uncertainty/isoorder.html>

Figure 90 shows that there was a net higher mean traffic speed after the traffic light synchronization. However, if we had taken smaller samples we could have got totally different results. These could vary between Figure 91 which shows a far larger mean traffic speed increase, and Figure 92 which shows a decrease in traffic speed—all due to the reduced sample size causing the measurement uncertainties to be larger than the difference that we had hoped to measure.

When repeated measurements give different results, we need to know how widely spread the readings are. The spread of values tells us something about the uncertainty of a measurement and by knowing how large this spread is, we can begin to judge the quality of the measurement or the set of measurements. However a large spread could arise because a single reading is very different from the others. Because of this it is usually not sufficient to know the range between the highest and lowest values and the usual way to quantify spread is **standard deviation**. The standard deviation of a set of numbers tells us about how different the individual readings typically are from the average of the set.

As a rule of thumb, roughly two thirds of all readings can be expected to lie between plus and minus ( $\pm$ ) one standard deviation of the average. Roughly 95% of all readings will fall within two standard deviations. This rule applies widely although it is by no means universal. The 'true' value for the standard deviation can only be found from a very large (infinite) set of readings. From a moderate number of values, only an estimate of the standard deviation can be found. The symbol "s" is usually used for the estimated standard deviation.

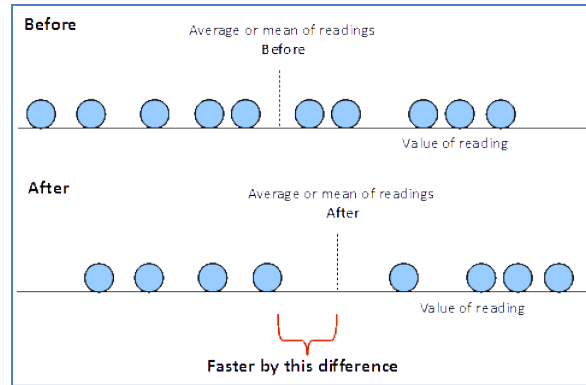


Figure 90 - Change in the mean traffic speed

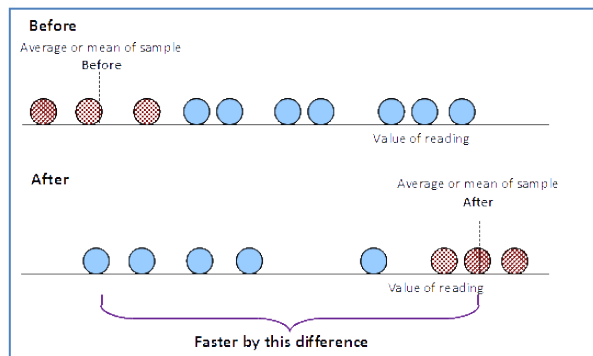


Figure 91 - Apparent large change in speed due to small sample size

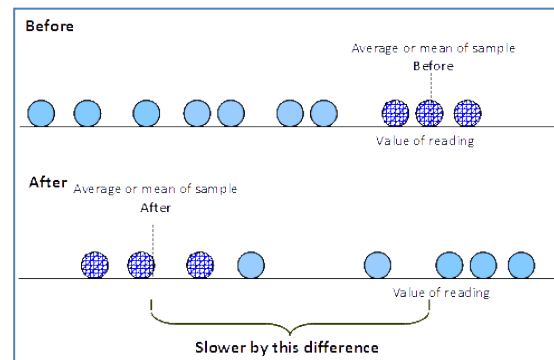


Figure 92 - Apparent negative change in speed due to small sample size

The process of calculating the **estimated standard deviation “s”** for a series of “n” measurements is given by:

$$s = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{(n-1)}} \quad (2)$$

where  $x_i$  is the result of the  $i$ th measurement and  $\bar{x}$  is the arithmetic mean of the  $n$  results considered.

## Basic definitions

### What is a measurement?

A measurement tells us about a property of something. It might tell us how heavy an object is, or how hot, or how long it is. A measurement gives a number to that property. In measuring traffic flow, a sample is a measurement.

### What is uncertainty of measurement?

It is important not to confuse the terms “error” and “uncertainty”. **Error** is the difference between the measured value and the *true value* of the thing being measured. Usually in transport activity measurement we do not know the “true” value and thus we cannot express the error in a sample.

*Uncertainty of measurement* is the doubt that exists about the result of any measurement. You might think that well-made rulers, clocks and thermometers should be trustworthy, and give the right answers. But for every measurement - even the most careful - there is always a margin of doubt. In samples there is always doubt as to how well the sample represents the “total”.

### **Expressing uncertainty of measurement**

Since there is always a margin of doubt about any measurement, we need to ascertain how big the margin is, and how great is the doubt. Thus, two numbers are really needed in order to quantify an uncertainty. One is the width of the margin, or *interval*. The other is a *confidence level*, and states how sure we are that the “true value” is within that margin.

Broadly speaking, the more measurements you use, the better the estimate you will have of the “true” value. The ideal would be to find the mean from an infinite set of values. The more results you use, the closer you get to that ideal estimate of the mean. But performing more readings takes extra effort, and yields diminishing returns.

### **How to express results**

What is important is to express the uncertainty of each sample or measurement that is taken in a way that gives the reader this information. The main things to mention are:

1. The measurement result, together with the uncertainty figure, e.g. ‘The length of the stick was 20 cm  $\pm$  1 cm.’
2. The statement of the coverage factor and the level of confidence. A recommended wording is: ‘The reported uncertainty is based on a standard uncertainty multiplied by a coverage factor  $k = 2$ , providing a level of confidence of approximately 95%.’; and
3. How the uncertainty was estimated (you could refer to a publication where the method is described, e.g. GUM).

### *How to evaluate overall uncertainty*

There are eight main steps to follow:

1. Decide what you need to find out from your measurements. Decide what actual measurements and calculations are needed to produce the final result.
2. Carry out the measurements needed.
3. Estimate the uncertainty of each input quantity that feeds into the final result. Express all uncertainties in similar terms.
4. Decide whether the errors of the input quantities are independent of each other. If you think not, then some extra calculations or information are needed.
5. Calculate the result of your measurement (including any known corrections for things such as calibration).
6. Find the combined standard uncertainty from all the individual aspects.
7. Express the uncertainty in terms of a coverage factor together with a size of the uncertainty interval, and state a level of confidence.
8. Write down the measurement result and the uncertainty, and state how you got both of these.

### *How to calculate the uncertainty*

For example, the amount of fuel (L) consumed by buses operating in a study region in one year could be calculated from the following equation:

$$L = f(N, K, D, E) = N * K * D * E \quad (3)$$

Where:

- N = the number of buses,
- K = The kilometres travelled per day per bus,
- D = The number of days of operation per year,
- E = The fuel economy of the bus in km/L.

The uncertainty of the estimated value of the fuel consumed “L” arises from the uncertainties of the estimated values of the number of buses, “N”; the kilometres travelled per day per bus, “K”; the number of days of operation per year, “D”; and the fuel economy of the bus in km/L, “E”. In general, components of uncertainty may be categorized according to the **method** used to evaluate them.

Thus the uncertainty of the estimated value of the fuel consumed “L” is calculated by combining the uncertainties of “N”, “K”, “D”, and “E”.

There are two types of uncertainty evaluation:

**Type A evaluation:** method of evaluation of uncertainty by the statistical analysis of series of observations,

**Type B evaluation:** method of evaluation of uncertainty by means other than the statistical analysis of series of observations.

#### Calculating standard uncertainty for a Type A evaluation

When a set of several repeated readings has been taken (for a Type A estimate of uncertainty), the mean,  $\bar{x}$ , and estimated standard deviation,  $s$ , can be calculated for the set. From these, the estimated standard uncertainty,  $u$ , of the mean is calculated from:

$$u = \frac{s}{\sqrt{n}} \quad (4)$$

where “n” was the number of measurements in the set. (The standard uncertainty of the mean has historically also been called the standard deviation of the mean, or the **standard error of the mean**).

#### Calculating standard uncertainty for a Type B evaluation

A Type B evaluation of standard uncertainty is usually based on scientific judgment using all of the relevant information available, which may include:

- a) previous measurement data,
- b) experience with, or general knowledge of, the behavior and property of relevant materials and instruments,
- c) manufacturer's specifications,
- d) data provided in calibration and other reports, and
- e) uncertainties assigned to reference data taken from handbooks.

Below are some examples of Type B evaluations in different situations, depending on the available information and the assumptions used. Broadly speaking, the uncertainty is either obtained from an outside source, or obtained from an assumed distribution.

#### *Uncertainty obtained from an outside source*

##### **Multiple of a standard deviation**

Convert an uncertainty quoted in a handbook, manufacturer's specification, calibration certificate, etc., that is a stated multiple of an estimated standard deviation to a standard uncertainty by dividing the quoted uncertainty "Q", by the multiplier "m".

$$u = \frac{Q}{m} \quad (5)$$

##### **Confidence interval**

Convert an uncertainty quoted in a handbook, manufacturer's specification, calibration certificate, etc., that defines a "confidence interval" having a stated level of confidence, such as 95 % or 99 %, to a standard uncertainty by treating the quoted uncertainty as if a normal probability distribution had been used to calculate it (unless otherwise indicated) and dividing the confidence interval "C" by the appropriate factor for such a distribution. These factors are 1.960 and 2.576 for the two levels of confidence given.

$$u = \frac{C_{95}}{1.960} \quad \text{or} \quad u = \frac{C_{99}}{2.576} \quad (6)$$

#### *Uncertainty obtained from an assumed distribution*

##### **Uniform (rectangular) distribution**

Estimate lower and upper limits "l" and "h" for the value of the input quantity in question such that the probability that the value lies in the interval "l" and "h" is, for all practical purposes, 100 %. Provided that there is no contradictory information, treat the quantity as if it is equally probable for its value to lie anywhere within the interval "l" to "h"; that is, model it by a uniform (i.e., rectangular) probability distribution.

$$u = \frac{\left(\frac{l+h}{2}\right)}{\sqrt{3}} \quad (7)$$

##### **Triangular distribution**

The rectangular distribution is a reasonable default model in the absence of any other information. But if it is known that values of the quantity in question near the center of the limits are more likely than values close to the limits, a normal distribution or, for simplicity, a triangular distribution, may be a better model.

Estimate lower and upper limits "l" and "h" for the value of the input quantity in question such that the probability that the value lies in the interval "l" and "h" is, for all practical purposes, 100 %. Provided that there is no contradictory information, model the quantity by a triangular probability distribution. The best estimate of the value of the quantity is then  $(l + h)/2$  with  $u_j = a$  divided by the square root of 6, where  $a = (l + h)/2$  is the half-width of the interval.

$$u = \frac{\left(\frac{l+h}{2}\right)}{\sqrt{6}} \quad (8)$$

**Normal distribution: "1 out of 2"**

Model the input quantity in question by a normal probability distribution and estimate lower and upper limits "l" and "h" such that the best estimated value of the input quantity is  $(l + h)/2$  (i.e., the center of the limits) and there is 1 chance out of 2 (i.e., a 50 % probability) that the value of the quantity lies in the interval "l" to "h".

$$u = 1.48 * \frac{(l+h)}{2} \quad (9)$$

**Normal distribution: "2 out of 3"**

Model the input quantity in question by a normal probability distribution and estimate lower and upper limits "l" and "h" such that the best estimated value of the input quantity is  $(l + h)/2$  (i.e., the center of the limits) and there are 2 chances out of 3 (i.e., a 67 % probability) that the value of the quantity lies in the interval "l" to "h".

$$u = \frac{(l+h)}{2} \quad (10)$$

**Normal distribution: "99.73 %"**

If the quantity in question is modeled by a normal probability distribution, there are no finite limits that will contain 100 % of its possible values. However, plus and minus 3 standard deviations about the mean of a normal distribution corresponds to 99.73 % limits. Thus, if the limits "l" and "h" of a normally distributed quantity with mean  $(l + h)/2$  are considered to contain "almost all" of the possible values of the quantity, that is, approximately 99.73 % of them.

$$u = \frac{\left(\frac{l+h}{2}\right)}{3} \quad (11)$$

***Schematic illustration of probability distributions***

Figure 93 schematically illustrates the three distributions described above: normal, rectangular, and triangular. In the figures,  $\mu$  is the expectation or mean of the distribution, and the shaded areas represent  $\pm$  one standard uncertainty  $u$  about the mean. For a normal distribution,  $\pm u$  encompasses about 68 % of the distribution; for a uniform distribution,  $\pm u$  encompasses about 58 % of the distribution; and for a triangular distribution,  $\pm u$  encompasses about 65 % of the distribution.



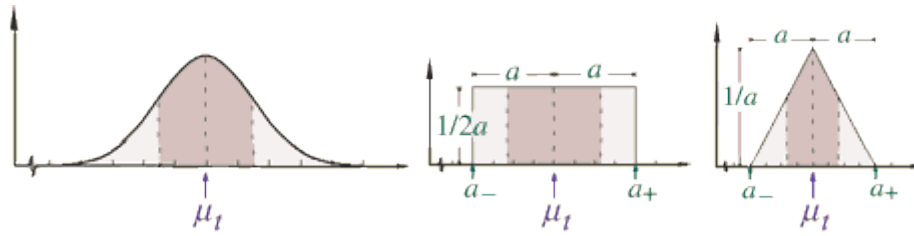


Figure 93 - Normal, rectangular, and triangular distributions

## Combining uncertainty components

### Converting uncertainties from one unit of measurement to another

Uncertainty contributions must be in the same units before they are combined.

For example, in making a measurement of length, the measurement uncertainty will also eventually be stated in terms of length. One source of uncertainty might be the variation in room temperature.

Although the *source* of this uncertainty is temperature, the *effect* is in terms of length, and it must be accounted for in units of length. You might know that the material being measured expands in length by 0.1 percent for every degree rise in temperature. In that case, a temperature uncertainty of  $\pm 2$  °C would give a length uncertainty of  $\pm 0.2$  cm in a piece of the material 100 cm long.

### Calculation of combined standard uncertainty

Individual standard uncertainties calculated by Type A or Type B evaluations can be combined validly by the 'root sum of the squares'. The result of this is called the *combined standard uncertainty*, shown by  $u_c$  or  $u_c(y)$ .

Combining is simplest where the result of a measurement is reached by addition or subtraction. The more complicated cases are also covered below for the multiplication and division of measurements, as well as for other functions.

#### Adding or subtracting uncertainties

The simplest case is where the result is the sum of a series of measured values (either added together or subtracted). For example, you might need to find the total length of a fence made up of different width fence panels. If the standard uncertainty (in metres) in the length of each fence panel was given by  $a$ ,  $b$ ,  $c$ , etc., then the combined standard uncertainty " $u_c$ " (in metres) for the whole fence would be found by squaring the uncertainties, adding them all together, and then taking the square root of the total.

$$u_c = \sqrt{(a^2 + b^2 + c^2)} \quad (12)$$

#### Multiplying or dividing uncertainties

For these cases, it is necessary to work in terms of relative or fractional uncertainties which are equal to the uncertainty divided by the measurement.

For example, you might need to find the area " $A$ ", of a rectangular carpet, by multiplying the

Length “ $L$ ”, by the width “ $W$ ” (i.e.  $A=L*W$ ). The relative or fractional uncertainty in the area of the carpet can be found from the fractional uncertainties in the length and width. Of course, neither “ $L$ ” or “ $W$ ” may be zero.

For length “ $L$ ” with uncertainty  $u_L$ , the relative uncertainty is  $u_L/L$ .  
For width “ $W$ ”, the relative uncertainty is  $u_W/W$ .

Then the relative uncertainty  $u_A/A$  in the area is given by:

$$\frac{u_A}{A} = \sqrt{\left(\frac{u_L}{L}\right)^2 + \left(\frac{u_W}{W}\right)^2} \quad (13)$$

For a case where a result is found by multiplying three or more factors together, equation (13) would have three or more such terms. This equation can also be used (in exactly the same form) for a case where the result is a quotient of two values (i.e. one number divided by another, for example, length divided by width). In other words, this form of the equation covers all cases where the operations are multiplication or division.

#### *More complicated functions*

Where a value is squared (e.g.  $Z^2$ ) in the calculation of the final measurement result, then the relative uncertainty due to the squared component is in the form:

$$\frac{2u_Z}{Z} \quad (14)$$

Where a square root (e.g.  $\sqrt{Z}$ ) is part of the calculation of a result, then the relative uncertainty due to that component is in the form:

$$\frac{u_Z}{2Z} \quad (15)$$

Generally speaking, for multi-step calculations, the process of combination of standard uncertainties can also be done in multiple steps, using the relevant form for addition, multiplication, etc. at each step.

#### *Correlation*

The equations given above to calculate the combined standard uncertainty are only correct if the input standard uncertainties are not inter-related or *correlated*. This means we usually need to question whether all the uncertainty contributions are independent. Could a large error in one input cause a large error in another? Could some outside influence, such as temperature, have a similar effect on several aspects of uncertainty at once - visibly or invisibly? Often individual errors are independent. But if they are not, extra calculations are needed. These are not detailed here.

## *Expanded uncertainty and coverage factor*

### **Expanded uncertainty**

The combined standard uncertainty  $u_c$  is used to express the uncertainty of a combination of measurement results. This combined standard uncertainty may be thought of as equivalent to “one standard deviation”, but we may wish to have an overall uncertainty stated at another level of confidence, e.g. 95 percent. This re-scaling can be done using a *coverage factor*, “ $k$ ” to give a measure of uncertainty that is termed **expanded uncertainty**, “ $U$ ”.

“ $U$ ” is obtained by multiplying  $u_c(y)$  by a **coverage factor**, “ $k$ ”.

### **Coverage factor $k$**

In general, the value of the coverage factor “ $k$ ” is chosen on the basis of the desired level of confidence to be associated with the interval defined by  $U = ku_c$ .

A particular value of coverage factor gives a particular confidence level for the expanded uncertainty. Most commonly, we scale the overall uncertainty by using the coverage factor  $k = 2$ , to give a level of confidence of approximately 95 percent. ( $k = 2$  is correct if the combined standard uncertainty is normally distributed).

Some other coverage factors (for a normal distribution) are:

$k = 1$  for a confidence level of approximately 68 percent

$k = 2.58$  for a confidence level of 99 percent

$k = 3$  for a confidence level of 99.7 percent

Conversely, wherever an expanded uncertainty is quoted with a given coverage factor, you can find the standard uncertainty by the reverse process, i.e. by dividing by the appropriate coverage factor.

### **Relative expanded uncertainty**

In analogy with relative standard uncertainty  $u_r$  and relative combined standard uncertainty  $u_{c,r}$  defined above the **relative expanded uncertainty** of a measurement result  $y$  is  $U_r = U/y$ , where  $y$  may not be equal to zero.

## *Example:- Calculating the uncertainty in the length of a piece of string*

*Step 1. Decide what you need to find out from your measurements. Decide what actual measurements and calculations are needed to produce the final result.*

You need to make a measurement of the length, using a tape measure. Apart from the actual length reading on the tape measure, you may need to consider:

- Possible errors of the tape measure
  - Does it need any correction, or has calibration shown it to read correctly – and what is the uncertainty in the calibration?
  - Is the tape prone to stretching?
  - Could bending have shortened it? How much could it have changed since it was calibrated?

- What is the resolution, i.e. how small are the divisions on the tape (e.g. millimetres)?
- Possible errors due to the item being measured
  - Does the string lie straight? Is it under- or over-stretched?
  - Does the prevailing temperature or humidity (or anything else) affect its actual length?
  - Are the ends of the string well-defined, or are they frayed?
- Possible errors due to the measuring process, and the person making the measurement
  - How well can you line up the beginning of the string with the beginning of the tape measure?
  - Can the tape be laid properly parallel with the string?
  - How repeatable is the measurement?

*Step 2. Carry out the measurements needed.*

You make and record your measurements of length. To be extra thorough, you repeat the measurement a total of 10 times, aligning the tape measure freshly each time. Let us suppose you calculate the mean to be 5.017 metres (m), and the estimated standard deviation to be 0.0021 m (i.e. 2.1 millimetres).

For a careful measurement you might also record:

- when you did it
- how you did it, e.g. along the ground or vertically, reversing the tape measure or not, and other details of how you aligned the tape with the string
- which tape measure you used
- environmental conditions (if you think these could affect your results)
- anything else that could be relevant.

*Step 3. Estimate the uncertainty of each input quantity that feeds into the final result. Express all uncertainties in similar terms (standard uncertainty,  $u$ ).*

You would look at all the possible sources of uncertainty and estimate the magnitude of each. Let us say that in this case:

- The tape measure has been calibrated. It needs no correction, but the calibration uncertainty is 0.1 percent of reading, at a coverage factor  $k = 2$  (for a normal distribution). In this case, 0.1 percent of 5.017 m is close to 5 mm. Dividing by 2 gives the standard uncertainty (for  $k = 1$ ) to be  $u = 2.5$  mm.
- The divisions on the tape are millimetres. Reading to the nearest division gives an error of no more than  $\pm 0.5$  mm. We can take this to be a uniformly distributed uncertainty (the true readings could lie variously anywhere in the 1 mm interval - i.e.  $\pm 0.5$  mm). To find the standard uncertainty,  $u$ , we divide the half-width (0.5 mm) by  $\sqrt{3}$ , giving  $u = 0.3$  mm, approximately.
- The tape lies straight, but let us suppose the string unavoidably has a few slight bends in it. Therefore the measurement is likely to underestimate the actual length of the string. Let us guess that the underestimate is about 0.2 percent, and that the uncertainty in this is also 0.2 percent at most. That means we should correct the result by adding 0.2 percent (i.e. 10 mm). The uncertainty is assumed to be uniformly distributed, in the absence of better information. Dividing the half-width of the uncertainty (10 mm) by  $\sqrt{3}$  gives the standard uncertainty  $u = 5.8$  mm (to the nearest 0.1 mm).

The above are all Type B estimates. Below is a Type A estimate.

- The standard deviation tells us about how repeatable the placement of the tape measure is, and how much this contributes to the uncertainty of the mean value. The estimated standard deviation of the mean of the 10 readings is found using the formula:

$$\frac{s}{\sqrt{n}} = \frac{2.1}{\sqrt{10}} = 0.7 \text{ mm (to one decimal place)}$$

Let us suppose that no other uncertainties need to be counted in this example. (In reality, other things would probably need to be included.)

*Step 4. Decide whether the errors of the input quantities are independent of each other. (If you think not, then some extra calculations or information are needed.)*

In this case, let us say that they are all independent.

*Step 5. Calculate the result of your measurement (including any known corrections for things such as calibration).*

The result comes from the mean reading, together with the correction needed for the string lying slightly crookedly, i.e. 5.017 m + 0.010 m = 5.027 m.

*Step 6. Find the combined standard uncertainty from all the individual aspects.*

The only calculation used in finding the result was the addition of a correction, so summation can be used in its simplest form. The standard uncertainties are combined as:

$$\begin{aligned} \text{Combined standard uncertainty} &= \sqrt{2.5^2 + 0.3^2 + 5.8^2 + 0.7^2} \\ \text{Combined standard uncertainty} &= 6.4 \text{ mm (to one decimal place)} \end{aligned}$$

*Step 7. Express the uncertainty in terms of a coverage factor (see Section 7.4 above), together with a size of the uncertainty interval, and state a level of confidence.*

For a coverage factor  $k = 2$ , multiply the combined standard uncertainty by 2, to give an expanded uncertainty of 12.8 mm (i.e. 0.0128 m). This gives a level of confidence of about 95 percent.

*Step 8. Write down the measurement result and the uncertainty, and state how you got both of these.*

You might record:

The length of the string was 5.027 m ±0.013 m. The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor  $k = 2$ , providing a level of confidence of approximately 95%.

The reported length is the mean of 10 repeated measurements of the string laid horizontally. The result is corrected for the estimated effect of the string not lying completely straight when measured. The uncertainty was estimated according to the method in “Measurement Good Practice Guide No. 11 (Issue 2) - A Beginner’s Guide to Uncertainty of Measurement” by Stephanie Bell of the UK National Physical Laboratory.”

### **Analysis of uncertainty - spreadsheet model**

To help in the process of calculation, it can be useful to summarize the uncertainty analysis or ‘uncertainty budget’ in a spreadsheet as shown in Table 15.

Table 15 - Analysis of uncertainty - spreadsheet model

Source of uncertainty	Value $\pm$	Probability distribution	Divisor	Standard uncertainty
Calibration uncertainty	5.0 mm	Normal	2	2.5 mm
Resolution (size of divisions)	0.5 mm*	Rectangular	$\sqrt{3}$	0.3 mm
String not lying perfectly straight	10.0 mm*	Rectangular	$\sqrt{3}$	5.8 mm
Standard uncertainty of mean of 10 repeated readings	0.7 mm	Normal	1	0.7 mm
Combined standard uncertainty		Assumed normal		6.4 mm
<b>Expanded uncertainty</b>		<b>Assumed normal (k=2)</b>		<b>12.8 mm</b>

\*Here the ( $\pm$ ) half-width divided by  $\sqrt{3}$  is used