

## **Work Package 2 – Review of Environmental and Transportation Modelling Methods and Development of Transport Emissions Model**

Deliverable D2.1 – Technical report detailing the research conducted in WP2. Literature review of transportation models. Deadline Month 12

### **Authors**

Páraic Carroll - Trinity College Dublin

Shreya Dey - Trinity College Dublin

Brian Caulfield - Trinity College Dublin

Francesco Pilla - Trinity College Dublin

Bidisha Ghosh - Trinity College Dublin

Aoife Ahern – University College Dublin

Edgar Morgenroth – ESRI

**May 2016**



## Table of Contents

<b>Section 1: Examining the most appropriate Transportation Models and Data</b>	<b>1</b>
1.1 Introduction	1
1.2 Transportation Models for Ireland	2
1.2.1 NTA Model	2
1.2.2 TII Model	6
1.2.3 ESRI HERMES	9
1.2.4 ESRI ISus	12
1.2.5 UCD MOLAND	15
1.3 DTTaS Common Appraisal Framework for Transport Projects and Programmes	18
1.4 International Best Practice	20
<b>Section 2: Examining the most appropriate Environmental Models and Data</b>	<b>25</b>
2.1 Introduction	25
2.1.1 Classification of emission model	25
2.2 The Existing Emission Modelling Tools	26
2.2.1 ARTEMIS	26
2.2.2 COPERT	27
2.2.3 HBEFA	28
2.2.4 MOBILE	31
2.2.5 MOVES	31
2.2.6 NAEI	32
2.2.7 PHEM	32
2.2.8 TREMOD	32
2.2.9 VEPM	33
2.2.10 VFEM	33
2.2.11 VERSIT+	33
2.3 Transportation Emission Model for Ireland	34
2.3.1 Executive Review of COPERT 4	34
2.3.2 COPERT 4 in Ireland	35
2.4 COPERT 4: Elements and Properties	35
2.4.1 COPERT 4: Software development and Use	35
2.4.2 Properties of COPERT4	37
2.4.3 Major individual application	37
2.4.4 Input parameters	37
2.4.5 Expected Results	44
2.4.6 Additions in COPERT 5	45
2.5 Validation of COPERT	45

3.1 Discussion and Conclusion	46
3.2 The Transport Emissions Model	47
References	51

## List of Tables

Table 1: NTA Model	2
Table 2: TII Model	6
Table 3: ISus Model	12
Table 4: MOLAND Model	15
Table 5: DTTaS Transport Parameter Values	19
Table 6: Key Elements from the Models	23
Table 7: Emission models	26
Table 8: Various relevant emissions models	29
Table 9: Sources of COPERT 4 input data	43
Table 10: Technology class of different vehicles	43
Table 11: Importance and availability of statistics of different parameters	44

## List of Figures

Figure 1: GDA Model Structure	4
Figure 2: TII Model Structure	7
Figure 3: Choice Structure of the Variable Demand Model	8
Figure 4: Key mechanisms within the HERMES model	10
Figure 5: Flowchart of ISus	13
Figure 6: MOLAND Model Structure	16
Figure 7: UK NTM Model Structure	20
Figure 8: Sweden SAMPERS Model Structure	22
Figure 9: The European Topic Centre on Air Pollution and Climate Change Mitigation (ETC/ACM)	35
Figure 10: Distribution of different model usage for transportation-emission calculation	36
Figure 11: Continent wise distribution of COPERT application	36
Figure 12: COPERT application in different areas	36
Figure 13: Screenshot of COPERT 4: Meteorological information	38
Figure 14: Screenshot of COPERT 4: Fleet configuration	38
Figure 15: Screenshot of COPERT 4: Activity Data	39
Figure 16: Screenshot of COPERT 4: Circulation Data	40
Figure 17: Screenshot of COPERT 4: Evaporation Data	40
Figure 18: Screenshot of COPERT 4: Output forms for Hot emission	41
Figure 19: Screenshot of COPERT 4: Output forms for cold start emission	42
Figure 20: Flowchart of Transport Emissions Model	42
Figure 21. Instrumental set up	46
Figure 22: Current Scenario	48
Figure 23: Projected Scenario	48

## **Section 1: Examining the most appropriate Transportation Models and Data**

### **1.1 Introduction**

This deliverable provides an extensive overview of a selection of relevant economic, environmental, land-use and transportation models currently available in the Republic of Ireland and internationally that have been designated as being appropriate for use in research in the Greening Transport Project. The models were deemed suitable by the project team due to the methods that they employ, the nature of the inputs that are included in the models and most importantly based upon the utility of the outputs generated. It is the key goal of the Greening Transport Project to develop a Transport Emissions Model capable of combining transportation modelling practices with the outputs generated from an emission model (Task 2.2) to accurately analyse the effect of behavioural and policy changes on greenhouse gas emissions from transport in Ireland. In this way, the outputs from the selected models will be fed into the newly developed model to effectively inform policymaking decisions on a regional and national level and to provide the basis for further research conducted as part of the project.

The transport-related models that have been reviewed are:

- (1) The National Transport Authority (NTA) Greater Dublin Area (GDA) Model;
- (2) Transport Infrastructure Ireland (TII) National Transport Model (NTpM);
- (3) The Economic and Social Research Institute's (ESRI) HERMES (Harmonized Economic Research Models on Energy Systems);
- (4) ISus (Irish Sustainable Development Model) models and finally;
- (5) University College Dublin's (UCD) MOLAND (Monitoring Urban Land Cover Dynamics) model.

In addition to this, transport parameters from the Department of Transport, Tourism and Sport (DTTaS) will be consulted and modelling frameworks will be examined from the UK, the Netherlands and Sweden in the form of a comparative analysis of international best practice in this area of transport and emissions model unification.

## 1.2 Transportation Models for Ireland

### 1.2.1 The NTA Greater Dublin Area Model

The first iteration of the NTA model was developed in 1991 as part of the Dublin Transportation Initiative (DTI) study and in 1996 the Dublin Transportation Office (DTO) (subsumed into the NTA in December, 2009) took ownership of the model which has since undergone a number of updates with input from external consultants. One such consultant was Steer Davies Gleave who in 2008 were commissioned to aid in the update and re-calibration of the model, results of which have been detailed in a number of model calibration reports (DTO and Steer Davies Gleave, 2009). National Transport Authority (NTA) is the main government funded entity responsible for a range of transportation functions in Ireland including: transport planning and investment in the GDA, national public transport delivery and bus and taxi regulation, the NTA accordingly has the most comprehensive bank of transportation data in Ireland. As a result of this, the NTA's foremost transportation model: the Greater Dublin Area Model which has been central to the Draft Transport Strategy 2011-2030 in addition to the proposed GDA Transport Strategy 2015-2035 and Dublin City Development Plan; has been identified as being the most suitable for the nature of the research conducted in Greening Transport Project. An overview of the inputs and outputs of the NTA GDA Model are presented in Table 1 below.

**Table 1: NTA Model**

Inputs	Outputs
Place of Work and School Census of Anonymised Records (POWSCAR)	Trip Generation – estimation and prediction of the number of trips generated by and attracted to a zone (travel demand) by purpose (commuting, education, business, etc.)
GDA Travel to Education Survey	Trip Distribution - Patterns of trips between sets of trip generators and trip attractions (trip ends)
GDA Household Survey	Car Ownership Model – car ownership trends over time, determination of the probability of car availability for a particular trip (i.e. car available/ not available)
CSO Small Area Population Statistics (SAPS) datasets	Mode Choice – trips matrices split into different modes of travel (car, public transport and active modes i.e. walking and cycling)  Hour of Travel Choice (AM Peak only) – trips further split down to the hour of travel (7-8:00, 8-9:00, 9-10:00)
Macroeconomic forecasts and Regional Planning Guidelines (RPG) to determine travel demand into the future (i.e. target year 2030)	Trip assignment to their respective (road or public transport networks)

The GDA Model is a multi-modal, network based transport model, and it is a valuable policy and planning tool that is capable of forecasting travel demand in a variety of possible future scenarios based on changes in population, employment, travel patterns and mode share. The base year that is modelled is 2006 and the forecast year is until 2030 as part of the strategy.

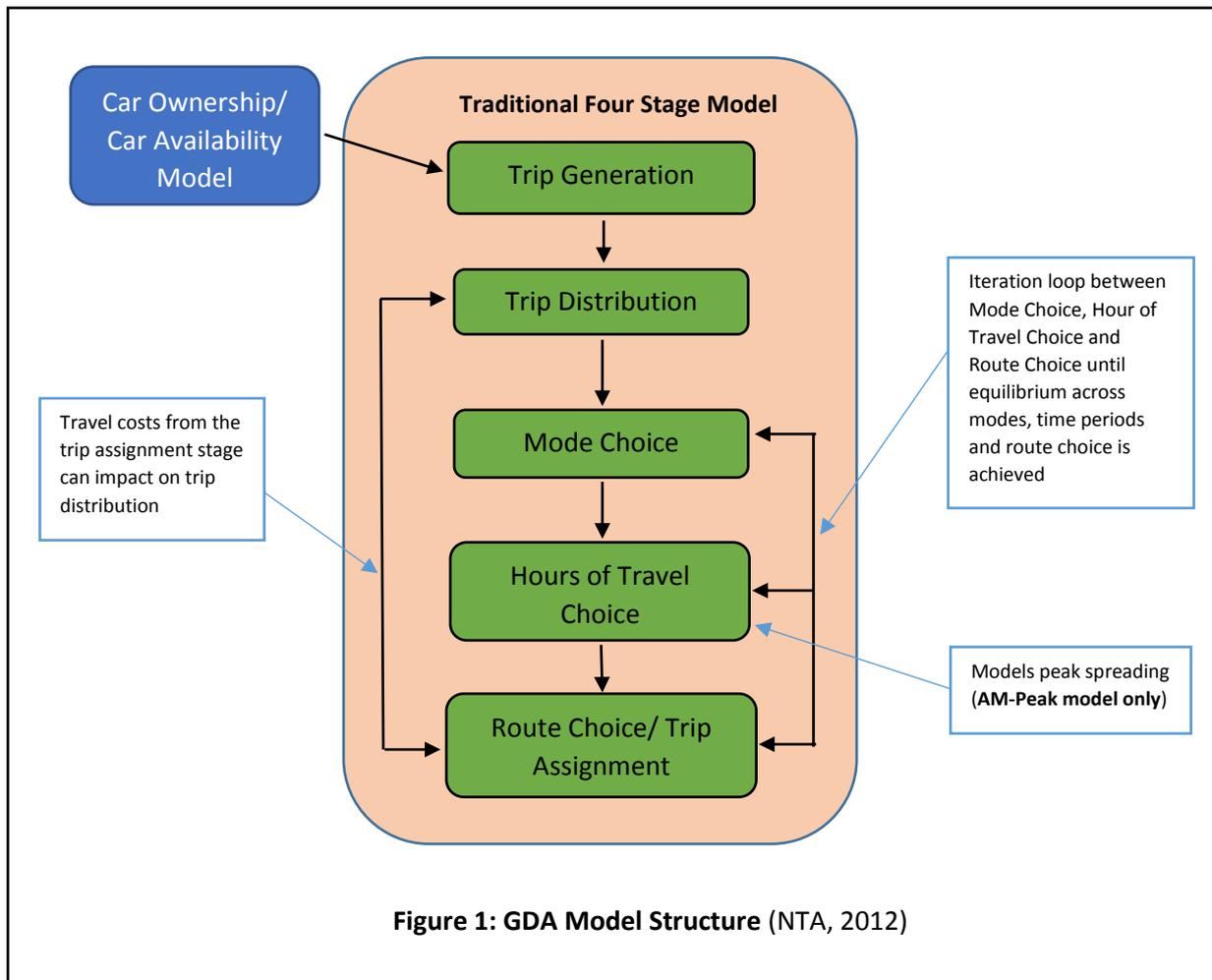
Macroeconomic forecasts and Regional Planning Guidelines (RPG) are the main determinants of travel demand in the 2030 target year, the ESRI (HERMES and ISus) and the UCD MOLAND models are crucial in this respect. It is comprised of 666 zones (657 internal fine zones covering the modelled area and 9 external zones representing travel between the modelled area and the rest of Ireland) (NTA, 2012).

**Model Structure:** The current GDA Model was created following the 2008 Dublin Transport Authority (DTA) Act's (Section 12) plan to develop a Draft Transport Strategy for the NTA Eastern Regional Model (ERM)/ Greater Dublin Area consisting of the counties of Dublin, Meath, Kildare and Wicklow. It covers the morning (AM Peak) period between 07:00 and 10:00 and the afternoon Off/ Inter-Peak period between 14:00 and 15:00. The ERM is one of five other regional models operated by the NTA (South East Regional Model, South West Regional Model, Mid-West Regional Model and the Western Regional Model). The model contains coded networks for all networks for all mechanised modes of travel – including car, HGV, heavy rail and Luas (NTA, 2012).

The AM Peak and Off Peak period differ slightly in their structure as the AM Peak includes an extra component: 'Hours of Travel Choice'. This is only relevant to the AM Peak as it is used to "model the impacts of peak spreading where people decide to depart at an earlier (or later) time to avoid congestion or crowding during the morning peak" (NTA, 2012). The GDA AM Peak Model continuously iterates between the mode choice, time of travel choice and trip assignment stages of model until an equilibrium of travel costs across travel modes, time periods and travel routes is achieved. Travel costs derived from the trip assignment stage can also impact on trip distribution. The Off Peak Model follows the Traditional Four Stage Model (FSM) as it simply relates to a one hour period that isn't usually affected by peak spreading. The model is displayed in Figure 1 below.

The GDA Model organises travel demand in the form of six journey purposes: Work (commuting), Education, Employer's Business, Shopping, Other and Non-Home Based and for each of these journey purposes travel demand is segmented into a Car Available and Car Not Available groups, this represents the purpose of the Car Ownership/ Car Availability Model. This model feeds into the Trip Generation stage and it tracks and predict growth in car ownership over time and determines the probability of people in a particular zone owning a car.

There are three stages to car ownership represented in an *S-curve*: 1) a very slow rise at the start; 2) followed by rapid growth with increasing wealth and prosperity being experienced; 3) then finally resulting in a levelling off period with the number of cars reaching saturation levels. Car saturation is defined by a *saturation point* at which car ownership rates stop increasing (i.e. level off). "Beyond the saturation point, changes in the total car stock are directly proportional to the changes in the population or its demographic components. [The Economic and Social Research Institute] assume that saturation is reached at 0.8 cars per adult (where adults are defined as residents between the ages of 15 and 64 years), the level in Germany". Germany being a country has had relatively stable economic performance in recent years (Devitt et al., 2010). Furthermore, Car Availability is heavily reliant on car ownership levels which are taken from CSO Census data (Household survey). The Car Ownership Model (COM) derives a car ownership versus car availability relationship for all day trips made for each journey purpose. This enables the COM to output % car availability rates for each journey purpose for different times of the day (NTA, 2012).



## Critical Analysis of the NTA GDA Model

### Pros:

- A wide range of stakeholders, partners and other parties can make use of the model ensuring maximum possible dissemination of model outputs and increasing the productivity associated with it.
- The model includes trips by all the main modes of travel – including trips by walking and cycling. These active modes are of particular interest in the context of the project as they represent a viable, sustainable and smart alternatives to private car travel, especially in urban areas.
- Travel behaviour is based on comprehensive and detailed travel surveys and travel datasets not generally available in strategic models elsewhere. By studying behavioural changes and restraints in this respect our research will be capable of examining the steps needed to induce emissions reductions as result of such behavioural shifts.
- The model covers the GDA, and takes full account of travel within, into and out of the modelled area. The GDA is of substantial national importance in terms of sustaining the economic competitiveness of Ireland and attracting international investment which plays a vital part in driving economic prosperity in the country.

- To enhance its functionality, the GDA transport model includes an additional stage ('hour of travel choice') in the modelling process. As stated before, this additional stage is used to represent the phenomenon of peak spreading as a response to congestion and is not captured in many strategic models of this kind. By studying peak spreading it provides a further level of scope to the analysis of trip decision making which in this way, highlights areas of low accessibility to public transport services or fleet management issues such as poor fleet capacity during peak hours.
- Peak Spreading highlights the advantages of taking active modes of transport to avoid this problem – for this reason active modes are not included in the Hour of Travel Choice stage of the model

#### Cons:

- The model doesn't include car sharing, carpooling, taxi/ on demand services (Uber/ Hailo) that are examples of sustainable and efficient use of resources which have an effect on reducing road congestion and encourage higher occupancy of cars. Taxis are only treated as cars and are not separated as an individual mode in itself. Thus, given the growth and popularity of on-demand services like Hailo/ Uber, it is necessary to include these services in updated versions of the model.
- Though walking and cycling trips are included in the model, they are not assigned to equivalent walking and cycling networks. Hence, whereas the cost of travel by mechanised modes is based on travel demand and network characteristics, the cost of travel for non-mechanised modes is calculated as a simple combination of travel time and distance. The model is thus limited in its ability to test policies that seek to increase trips by walking and cycling. In particular, the model cannot automatically capture the time savings and other user benefits accruing to pedestrians and cyclists as a result of priority and other network improvements that confer advantages on these modes (NTA, 2012).
- Walkability maps or audits and walk and cycling networks must be created and integrated into the model in order to fully take account of the assignment of active travel modes in the GDA which are growing thanks to schemes like the *Dublin Bikes*. This may help to highlight the cost benefit analysis of investing more financial resources into our walking and cycling infrastructure to further encourage these sustainable modes, particularly in suburban and rural areas where transport by means of the privately owned car is the safest and sometimes the only form of transport.
- There is no reference to carbon trajectories which could be linked to travel demand patterns on road and public transport networks in order to bring about closer integration between transport and emissions estimates. Examples of this can be taken from Great Britain in the period of 1999-2001 (UK NTM) where emissions targets and carbon trajectories have been combined with transport modelling processes to generate greater coordination on this issue (WSP, 2011).
- A larger focus on urban environmental impacts and accessibility to public transport should be built into our transport modelling practices. An example of which can be taken from Sweden in the Early 1980s (WSP, 2011). This is ultimately the aim of the Greening Transport Project

For more background reading, please consult: NRA (2014) *'The National Transport Model Brochure'*. Dublin: National Roads Authority, Transport Infrastructure Ireland.

### 1.2.2 TII National Transport Model (NTpM)

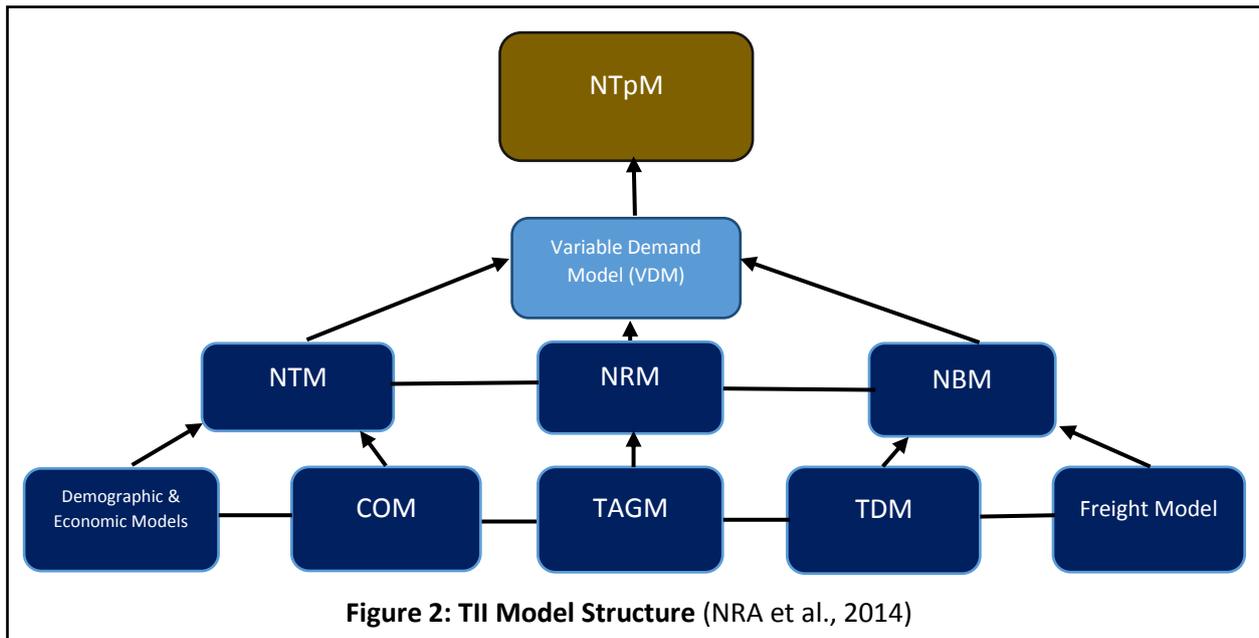
Transport Infrastructure Ireland (TII) has the responsibility for securing a safe and efficient network of national roads in the Republic of Ireland. It commissioned the development of the *National Traffic Model (NTM)* completed in 2008, which was subsequently enhanced in 2010 and 2011 to include the *National Rail Model*, *National Bus Model* and a *Variable Demand Model*. An overview of the inputs and outputs of the TII NTpM Model are outlined in Table 2 below that include the sub-models stated.

**Table 2: TII Model**

Inputs	Outputs
NAVTEQ GIS data (now part of <i>HERE</i> technology owned by Nokia) for all existing roads in Ireland	TAGM – outputs from the Demographic & Economic Models (i.e. population and jobs) and the Car Ownership Model (COM) converted into Origin and Destination (O-D) Trip End totals (vehicle or passenger trips) for each mode
TII Traffic Monitoring Units (TMU) network data	TDM – O-D Trip End total distributed between the zones in the model
CSO Census data – Small Area Population Statistics (SAPS)	NTM, NRM, NBM – assign demand for travel (trip matrices) to the network  Travel costs generated (e.g. time, distance, tolls and fares) for each mode
POWSCAR – Place of Work, School or College Census of Anonymised Records  Public transport timetables and scheduling	Variable Demand Model – impact of a change in the transport network or a change in travel costs (fuel price fluctuations, fares) on travel demand is assessed  Highway, Public Transport demand by trip purpose  AM & Inter Peak O-D vehicle demand

The full model that contains all of these modules is what constitutes the National Transport Model (NTpM), the structure of which is illustrated in Figure 2 below (NRA et al., 2014)

The NTpM is the first all-Ireland strategic multi-modal transport model that can be used to assess and evaluate the impact of transport infrastructure, policy, demand management initiatives and strategic development plans. 1,077 transport zones are modelled, 927 of which are aggregated from the 3,440 Electoral Divisions (EDs) in the Republic of Ireland and 150 zones aggregated from the 582 Electoral Wards in Northern Ireland (NRA, 2014).

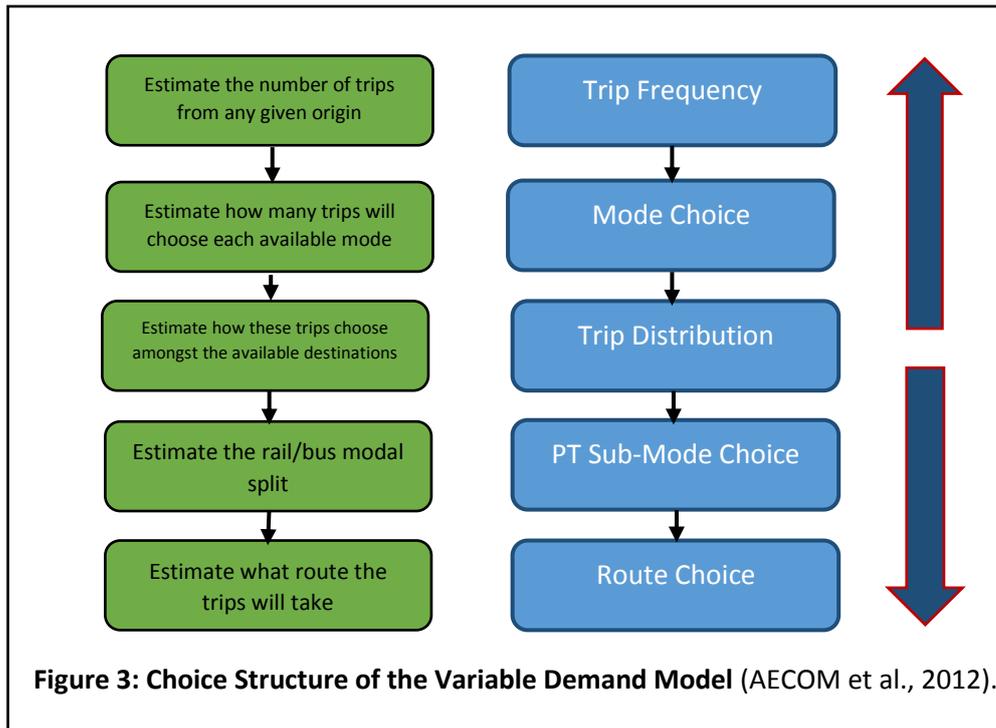


The NTpM is linked to the NTA GDA Model by means of using many of the models that the GDA Model employs, such as the COM, Trip Attraction and Generation Model (TAGM) and the Trip Distribution Model however it uses these models on a national scale as opposed to a regional scale. The fundamental function of the NTpM is to “support and complement the existing and planned urban area transport models that are in use, or will be used by authorities in Dublin, Cork, Limerick, Waterford and Galway” (NRA et al., 2014). The NTpM models inter-city/inter-urban public transport and road networks which are not included in urban area transport models.

The Variable Demand Model (VDM) is the central tool of the model suite which interfaces with the highway and public transport elements of the NTpM developed using Python programming and VISUM modelling software (AECOM et al., 2012). It simulates a ‘Do Minimum’ scenario whereby the least possible action taken is compared with a ‘Do Something’ where the maximum amount of action is executed. Multiple regression analysis is the method used to produce forecast trip ends.

The costs changes of both scenarios are the subject of the comparison which occurs when model calculations for variable demand are executed. Similarly to the NTA model, the NTpM performs the calculations based on the AM and Inter Peak periods for the Road, Rail and Bus Assignment Models, the same trip purposes (work, education, shopping, leisure etc.) and the car availability groups are also employed as a reference demand in the trip matrices.

In addition to the COM, TAGM, and TDM, the VDM is supplemented by a range of economic and modelling parameters, namely: fuel efficiency and consumption, vehicle occupancy, trip frequency and proportions of travel from home which are required for each trip purpose. This data is then fed into the traffic, road/ highway and public transport assignment models before being passed onto the VDM for the travel demand to be calculated and processed. The VDM process can be seen in Figure 3 below.



### Critical Analysis of the TII Model

#### Pros:

- The NTpM provides a high level of functionality, allowing for the following responses to be assessed:
  - Changes in traffic assignment due to network changes, traffic management or public transport priority; change in mode share due to increases/ decreases in travel time by car,
  - Changes in mode share due to increases/decreases in travel time by car, public transport fares, fuel prices, tolling/road pricing or changes in public transport service levels;
  - Demand responses to changes in the cost of travel, including fuel price, public transport fares, congestion, tolling/road pricing and other demand management policies;
  - Calculation of costs and benefits based on outputs of travel time, congestion, vehicle kilometres and accident predictions on individual links and across the network as a whole (using project appraisal software); and
  - The impact of network costs on future land use (NRA et al., 2014).
- Analysis of these responses will be beneficial in Work Package 5 specifically, which will measure the impacts of fiscal changes on promoting sustainable car usage.
- It is the first Irish model to provide an All-Ireland/ Island perspective to transportation modelling which is invaluable in aiding understanding of travel between city areas in Ireland. This is instrumental in assessing current travel demand and forecasting trends in car ownership and network performance in future scenarios.
- The Variable Demand Model is effective in forecasting behavioural decisions in various scenarios based from a Do Minimum Scenario. Data from Northern Ireland included in model enhancements estimates inter urban and cross border rail and bus demand.

The method of performing base case, Do Minimum and Do Strategy has been applied to the GDA Draft Transport Strategy will be an area of concentration in the project.

- “This approach enables some of the complex behavioural decisions which inform the base demand to be carried through to alternative scenarios. Such an approach is also referred to as ‘Incremental’ modelling and is a common form of demand modelling in large complex models” (AECOM et al., 2012).

#### Cons:

- As previously noted, the NTpM does not model urban/ city transport networks and services as these are left to urban/ city transportation models. As the project is aimed at researching behavioural changes, and how these changes can impact on emission levels; the project will thus direct attention to specific mechanisms that can be implemented in a suburban or city context where there is high population density and multi-use development.
- As a result of this, these urban areas are centres of highly concentrated greenhouse gas emissions. For example, examining the benefits of walking and cycling, exploring the growth of renewable and sustainable fuels and alternative tax scenarios will be distinctly studied with the perspective of city- suburban areas. Therefore, the outputs from NTpM, although very beneficial nationally, will only be utilised to a minor extent in the research conducted as part of the Greening Transport Project

### **1.2.3 ESRI HERMES and ISus Models**

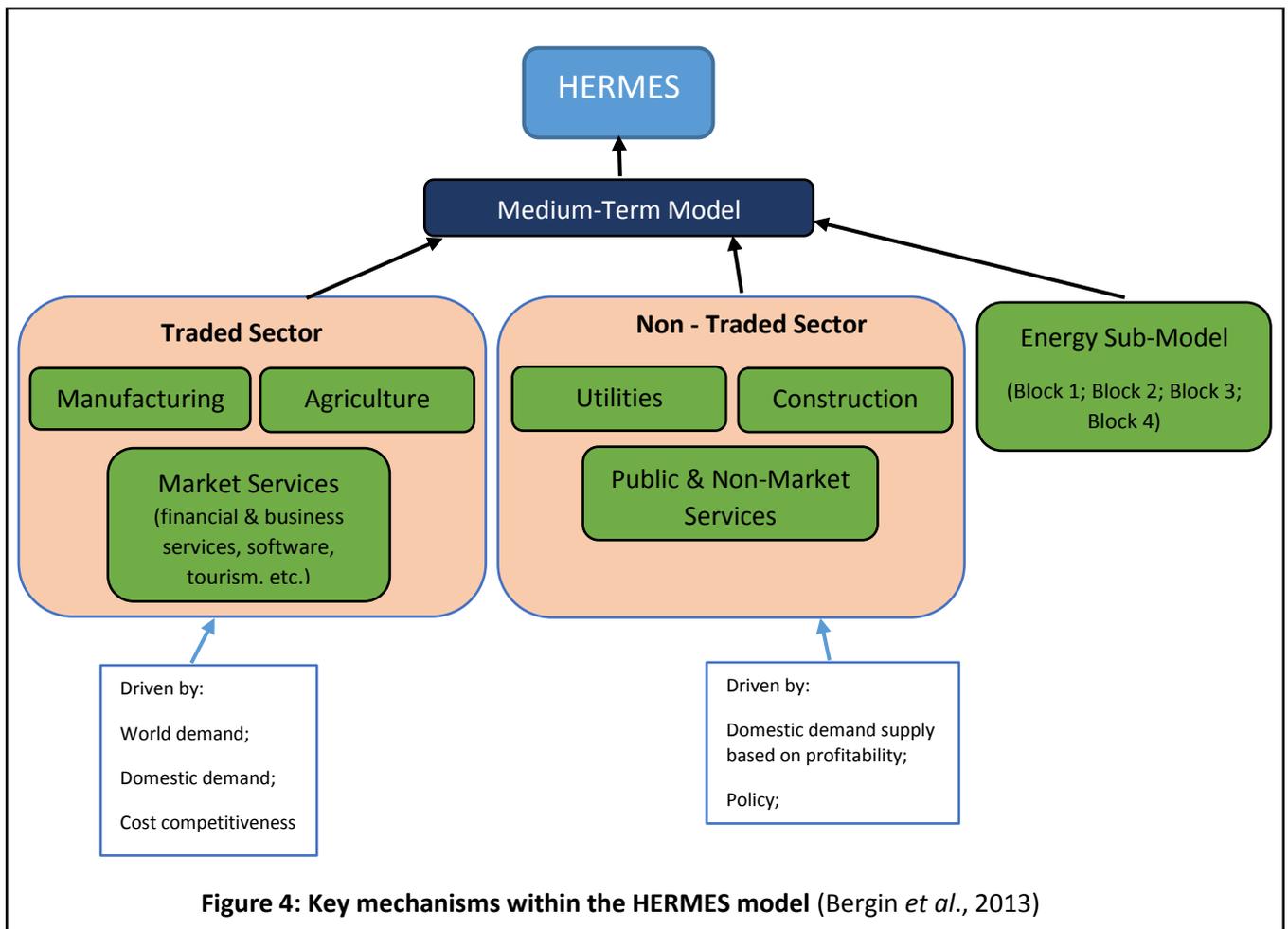
The models produced by the Economic and Social Research Institute (ESRI) differ significantly from the first two models detailed, in that they examine economic and environmental processes based on policy and fiscal measures aimed at highlighting the performance of the Irish economy and its effect on the environment and emission levels. HERMES is primarily concerned with modelling key economic variables but it also includes an energy sub-model. ISUS provides a more detailed decomposition of energy and environment effects, driven by economic activity as projected or simulated by HERMES. These models emphasize the need to focus on constructing robust, real and clear policy measures that correspond to likely economic scenarios rather than setting overambitious targets for tackling environmental problems that are not consistent with economic developments, and this view corresponds to the nature of the research on the Greening Transport project. The Greening Transport Project’s Transport Emissions model will be an effective tool to inform policymaking decisions that support a reduction in emissions from transportation in Ireland.

#### HERMES

The HERMES (Harmonized Economic Research Models on Energy Systems) macroeconomic model was first developed in 1980s and has been extensively used for over 25 years to perform medium-term forecasting and scenario analysis of the Irish economy (Bergin *et al.*, 2013). It has been particularly valuable in recent years in analysing the cause and effects of the economic recession which was disastrously experienced in Ireland. The model has benefitted from continuous developments and updating and includes modelling capabilities for energy demand and supply and the resulting impact on carbon emissions (Bergin, et al., 2004, Hennessy and FitzGerald, 2011). While HERMES has a higher level of disaggregation than most other macro-economic models, the level of disaggregation is insufficient for many energy/ environment applications, which are better handled by a model specially developed for this purpose in the ESRI under an EPA project. This latter model can be linked to HERMES through feedbacks from the environment to the macro-economy (Bergin et al., 2013).

The HERMES model distinguishes between the sectors of the economy that are exposed to the competitive world trading environment (the international traded sector) and those sectors that are sheltered from direct exposure to international competition (the non-traded sector). The traded sector consists of manufacturing, agriculture, and an element of market services (e.g. financial and business services, software, tourism, etc.).

The non-traded sectors comprise the rest of the economy (i.e. utilities, building, most of market services and all public or non-market services). The model gathers input performance data from these sectors to produce forecasting and scenario analysis estimates which in turn are used to inform the government, so that calculated decisions can be employed. The structure of HERMES is illustrated in Figure 4 below.



HERMES is relevant to the project as it implements behavioural equations (180 in total), together with aggregations, transformations and other identities. The simulation model includes a total of 824 equations and the role of the transport sector feeds into the Energy Sub-model. This recognises the fact that transport is a derived demand; demonstrating that as an economy grows or more specifically as increasing numbers of people become employed, this consequently generates a direct demand for transport and applies pressure on the transport network in addition to energy demand. The Energy Model of HERMES reflects carbon dioxide emissions associated with levels of energy consumption, which are modelled as inputs into the production process and consumption and facilitates simulations of the effects of alternative policies on reducing greenhouse gas emissions. This model consists of four interrelated blocks: Block 1) electricity demand is modelled for all sectors

in the economy, which is then aggregated to give total electricity demand; Block 2) concerns the electricity generation sector, based on a series of exogenous engineering relationships that are passed on as an input to the wider energy model; Block 3) aggregate carbon dioxide emissions are obtained by multiplying an estimate of energy consumption for each fuel by an appropriate emission factor; Block 4) develops a series of relationships that provide a direct link between the energy model and the medium-term model (Bergin et al., 2013).

Price determination for different fuels is also included in Block 4 which takes account of the impact of carbon taxes (an issue that will be further explored in Work Package 5 in measuring the impacts of fiscal change on promoting sustainable car use). The Energy Model is hence a vital part of HERMES, as it analyses the impacts economic activity on greenhouse gas emissions in Ireland in a consistent way.

For example the current transport network capacity constraints in the GDA are arising as an outcome of unprecedented/ rapid economic growth and the road network is showing clear signs of strain. Such tell-tale signs of the capacity constraints are already apparent in the GDA, longer commuting times due to congestion issues leading to major centres of employment in Dublin which is exacerbated by the increasing numbers of first-time house buyers opting to live further away from Dublin city centre and suburbs owing to lack of housing and rising house prices. The majority of these commuters of course (by no fault to themselves) use privately owned transport as their primary means of mobility. Thus, demand within the transport sector is increasing the fastest as well as having the largest energy demand.

Finally, the HERMES model has a functionality within it to estimate the demand for private cars (SCARS) which in turn determines the demand for petrol. "The demand for cars is estimated using a logistical function with a saturation rate on car ownership. This variable is driven by the ratio of real personal disposable income (YRPERD) to the number of people in the age group 15-64 (a behavioural variable in the HERMES model – previously noted in the NTA model section of the report) (Hennessy and FitzGerald, 2011).

### **Critical Analysis of the HERMES Model**

#### Pros:

- The model has the ability to explore how the Irish economy would react to exogenous variables (e.g. policy variable changes such as taxes and public expenditure and world growth)
- Outputs of the model are vital in the development of policy measures and in providing essential information to government officials
- The services sector, in which transport is major element, represents a large part of the output that is generated in the economy and thus this is a central component that the model examines. The service sector overall is a key channel in which world economic growth is transmitted to the Irish economy (Bergin et al., 2013)

#### Cons:

- The mapping of specific policy interventions within the structure of the model may not always be obvious, requiring the use of microeconomic evidence and theory, but also a degree of judgement. In other words, the model may not always offer a direct 'lever' to simulate the effect of proposed reform and, in such circumstances, it may be necessary to use a proxy to mimic the anticipated effect of the measure. This process involves assessing how the reform is assumed to impact upon exogenous variables (and possibly parameter values) in the model and determining

a quantitative indicator of the impact, preferably through microeconomic or historical evidence. This at times involves applying a degree of judgement (Dept. of Finance, 2014)

- HERMES does not explicitly handle how households’ expectations are formed and how they affect consumption and household investment. This means that the model may not fully capture the short-term response of households to fiscal policy. For example, if households expect the government to tighten fiscal policy in the future they may react by increasing savings in the expectation of future tax increases (Bergin et al., 2013). This is an important element in our research as it looks at decision making triggers and behaviour analysis.
- HERMES does not have a well-developed banking sector. Since the global financial crisis, research on macro-financial linkages has increased significantly although much of the work remains at an early stage. Research is ongoing to develop the treatment of the banking sector so that the transmission of financial sector shocks to the economy can be better understood (Bergin et al., 2013). This invariably is a distinct limitation of the model which has effected expenditure in transport provision in recent years during the economic crisis.
- HERMES is being replaced with a more compact macro-economic model called COSMO, which has only three sectors, but will feature an energy sub-model.

#### 1.2.4 ISus

The Irish Sustainable Development Model (ISus) as previously specified, is a specially developed model capable of modelling the impact of economic activity on the environment that can be linked to HERMES through feedbacks from the environment to the macro-economy. Its function therefore is to provide a tool “to assess the implications of different growth paths for national objectives on sustainable development and is used to project emissions and resources” (O’Doherty, et al., 2007). An overview of the inputs and outputs of the ISus Model are presented here in Table 3:

**Table 3: ISus Model**

Inputs	Outputs
CSO data (Small Area Population Statistics (SAPS))	Projections of greenhouse gas emissions from economic processes to 2025
<u>Car Stock Model</u> CSO Household Budget Survey – income elasticity of demand for each engine category CSO data on the average distance travelled by type of car SEAI fuel efficiency data	Levels of Car Ownership Stock, distance travelled, emission levels based on population income and automotive drivers
Estimates and forecasts fed from HERMES and returned to inform economic policy making decisions concerning the environment	Assessments of implications of different growth paths for national objectives on sustainable transport
	Fuel efficiency estimate of each car by its engine size, age and fuel type

The model as illustrated in Figure 5 below consists of two distinct sources of inputs to be modelled: 1) production which includes a private car stock model, energy, agriculture, and waste inputs; and 2)

consumption. This data is then fed into an input-output model that is used to attribute emissions from these sources.

The Car Stock Sub-Model projects future car ownership, it utilizes distance travelled and emissions data based on population, income, other automotive drivers, together with elasticity assumptions (provided by CSO datasets) (Curtis, 2012).

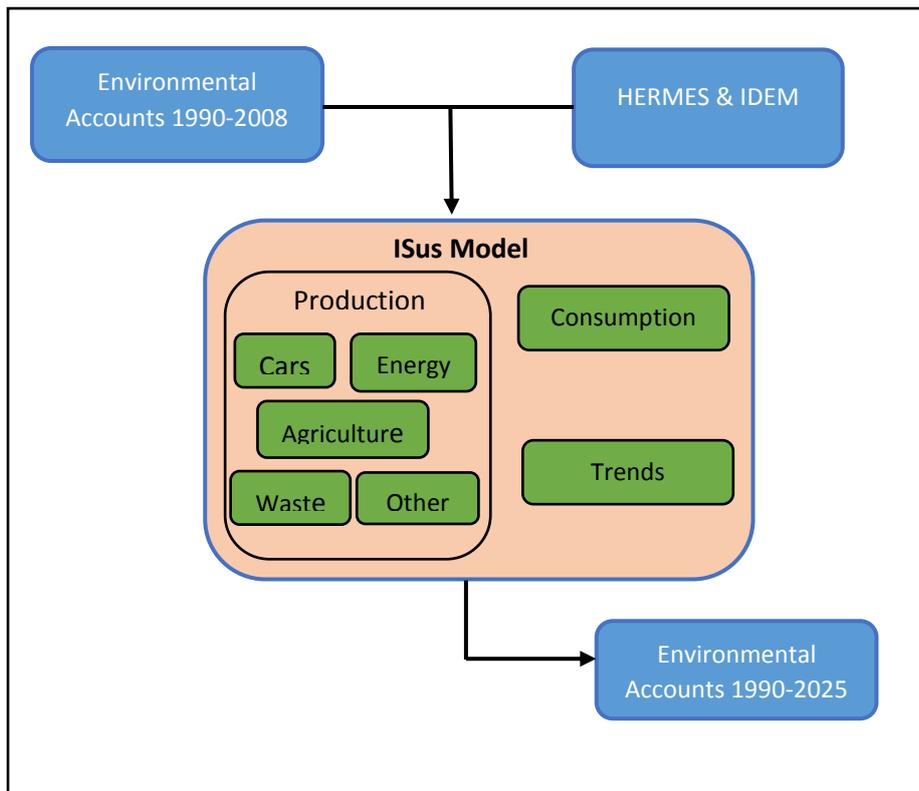
This model is the most substantial and reliable that is readily available, (yet there are plans to estimate a new car ownership model as part of an energy satellite model for COSMO) therefore it has been identified as being the model of interest in relation to the conversion of car usage into carbon emissions in Ireland. The equation to determine the stock of private cars to 2025 utilises three key variables: the level of disposable income in the economy (Y), the number of cars (C) and the population between 15 and 64 (P) (as similarly outlined in the COM of the NTA model).

The A15 equation is as follows:

$$(A15) \quad \Delta \ln \frac{0.8 C_t}{P_t - 1} = \alpha + \beta \frac{Y_t}{P_t}$$

(Devitt et al., 2010)

Once this is calculated the next steps may progress which include the estimation of car stock by engine size and the demographics associated with the stock (car demographic model which identifies 9 engines and 25 age classes), in addition to the distance model that analyses the average distance travelled by a specific type of car (CSO data) and finally the distance travelled is converted into carbon dioxide emissions expelled to finally generate a fuel efficiency estimate (estimated by SEAI) for each car by its engine size, age and fuel type (Devitt et al., 2010). The Car Stock Model provides the most systematic and decisive analysis of the effects of private car transport on the environment in Ireland and so it is of distinct importance to the research carried out in this project.



**Figure 5: Flowchart of ISus** (Devitt et al., 2010)

Lastly, the ESRI Environmental Accounts, which provide trends in emissions and hence highlight areas of concern, are a significant source of information on environmental policy in Ireland that adhere to strict international standards. However the environmental accounts are most useful in projecting the ramifications of policies into the future to test their possible success or failure based on an environmental perspective (Lyons and Tol, 2006).

### **Critical Analysis of the ISus Model**

#### Pros:

- Projections of greenhouse gas emissions from economic processes to 2025 are significant in the context of the GDA Draft Transport Strategy for 2030 and as a result, these forecasts will provide substantial support and guidance to the development of our transport emissions model.
- The Car Stock Model will be applied in our research in examining the effect of sustainable car usage and reduced car ownership rates. More up to date data will be fed into this model to provide new compelling results.
- The synchronisation between HERMES and ISus will prove to be highly significant in the context of Work Package 5 as our analysis of fiscal changes and other economic policies will be tested to study their potential promotion of sustainable car use.

#### Cons:

- A closer examination of other modes of transport and their carbon emission projections to 2025 is stark limitation of ISUs, as public transport, although sustainable in the long term, must be studied in order to increase fuel efficiency and to reduce high emitting vehicles in the fleet (this will be examined in Work Package 4).

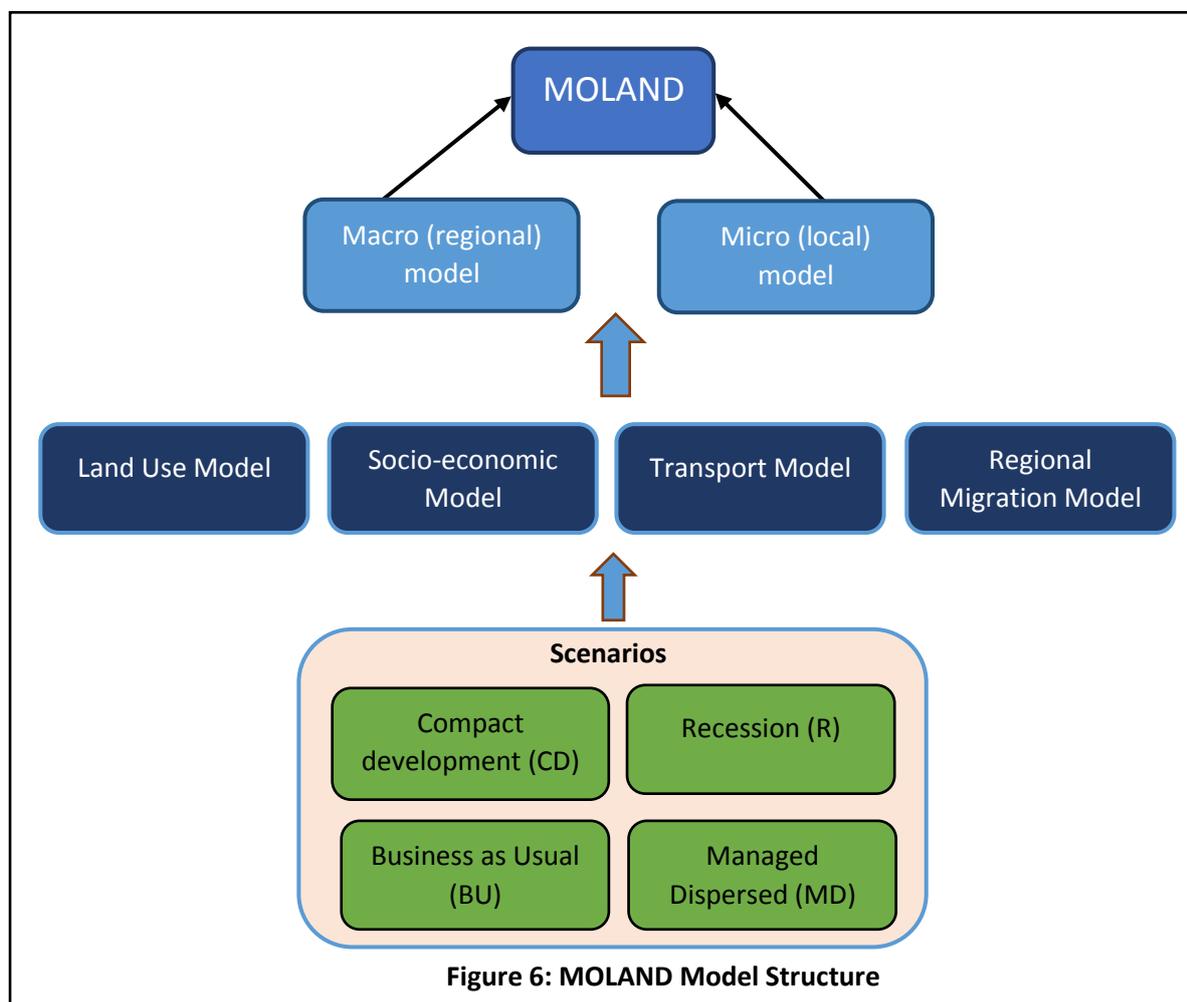
### 1.2.5 UCD MOLAND Model

The MOLAND (Monitoring Urban Land Cover Dynamics) model was developed as part of a European Commission’s Joint Research Centre for assessing and analysing urban and regional development trends across Europe. It was originally developed by *RIKS b.v.*2 (formerly the University of Maastricht, the Netherlands) and was piloted-tested in 2009 in the GDA using 1990, 2000 and 2006 data (Williams and Convery, 2012). ‘It is the main tool for Land Use Modelling Platform project that supports policy needs of different services of the Commission, for *ex-ante* assessments and more specific impact assessments’ (Petrov, et al., 2011). Presented in Table 4 are the main inputs and outputs associated with the MOLAND Model:

**Table 4: MOLAND Model**

Inputs	Outputs
Land use maps produced by ERA-Maptec Ltd. County boundary and Electoral Division (ED) maps from Ordnance Survey Ireland (OSI)	Maps of predicted land uses and their locations (analyses quantitatively and spatially)
Transport network – roads and rail datasets from DTO/ NTA and NRA	Illustration of land use change over time which identifies irresponsible planning and zoning of land
Zoning maps developed with protection, conservation and national heritage areas included	Provides a tool to aid understanding of outcomes to specific policies spatially and the effect that this has on transport accessibility
Suitability – highly suitable towns map in the Dublin-Belfast transport corridor used for MD scenario,  -restricted 2km buffer zone along coastline for CD scenario and  - BU and R scenarios a default suitability map used (Petrov et al., 2011).	Planning scenario analysis up to 2026 (Business as Usual (BU); Compact development (CD); Managed Dispersed (MD) and Recession (R))
Socio-Economic data – CSO and ESRI datasets used and extrapolation technique used to generate forecasts	Illustration of socio-economic trends using GIS software  Recognises that mixed-use higher density land-use the best strategy for urban planning in order to reduce or limit emissions from transport

MOLAND was implemented in Step 3 of the Strategic Environmental Assessment (SEA) section of the Regional Planning Guidelines (RPGs) of Ireland for which University College Dublin (UCD) assembled an academic research team and UCD have been heavily involved in its development as a tool by applying it to Irish scenarios. The model comprises of 4 interrelated models: (i) a dynamic land use model; (ii) a socio-economic model; (iii) a transport model; (iv) a regional migration model. Accordingly, it has many uses of which the most important is its ability to perform a range socio-economic scenario simulations such as population growth or an increase in un-employment and the assessment of alternative policy options like restrictive zoning plans or per-km car levies (Convery and Williams, 2013). These models are fed into 2 sub-models: the Macro Model (accounts for international trends in population and economic growth and it applies international trends to areas such as the GDA to represent processes like regional migration and urban sprawl) and Micro Model (provides the most detailed account of economic activities in the form of a land use model).



The four interrelated model listed above are the instruments used to carry out a range of scenarios based on changing patterns up to year 2026 (similarly in line with NTA, HERMES and ISus model forecast targets) which are influenced by socio-economic trends taken from CSO and ESRI estimates with regards to population, employment and residential configurations. These scenarios as illustrated in Figure 6 above are: Business as Usual (BU); Compact development (CD); Managed Dispersed (MD) and Recession (R) and each of them examine an alternate form of development in the GDA.

“BU scenario explores the further development of urban patterns emerging before the economic crisis whereas the R scenario focuses on future urban development due to recession, including a recovery by 2016. The CD scenario is important in demonstrating less pressure on natural land uses, exploring urban growth and urban/regional development in the frame of a strong environmental protection policy. In the MD scenario we investigated in more details the growth and sprawl of rural town and villages in open countryside particularly along the Dublin-Belfast motorway” (Petrov et al., 2011).

The main differences that are witnessed between the scenarios are related to population processes such as inward and outward migration in the GDA, both nationally (regional and local scale) and internationally (global scale), as well as the employment figures associated with each of the scenarios. Aspects of employment are particularly significant in the context of transport modelling as employment trends dictate much of what occurs in terms of residential/ urban settlement patterns and centres of employment. Questions such as: Are these locations adequately accessible with strong and reliable links to the transport network? Are commuting patterns in a particular area sustainable? Issues regarding commuting times, public transport priority, infrastructure for active travel modes (walking and cycling) are all highly complex matters which is why new development projects tend to have a large number of stakeholders/ policymakers involved in the process. In response to the outcomes of the proposed scenarios, Petrov *et al.* (2012) have stated that the highest increase in urban areas in the 2006-2026 period is in MD (269%) and BU (268%) scenarios in County Meath, followed by Wicklow, Kildare and Louth. In 2026 the GDA is estimated to have 9.2% residential, 0.4 commercial, 1.1% industrial and 0.5% service increase in the MD scenario.

Urban development in the GDA has historically been sporadic, poorly controlled and even reckless at times with residential patterns stretching further and further away from large urban zones as a result of an unstable housing market which has resulted in longer commuting times for many people that has a clear and direct knock-on effect on rising car ownership and emissions levels, especially at rush hours. Thus, a model such as MOLAND has been instrumental in assessing hypothetical but highly realistic environmental and land use management situations such as urban form characteristics (density, mixed-use development, proximity to public transport and distance to urban centres) which are vital in the promotion of sustainable development practices. As transport network data is provided by the NTA and NRA much of the information can be examined in greater detail from those sources, the MOLAND model functions as tool to simulate scenarios based on a range of socio-economic being fed into it, and produced GIS based maps to illustrate its outcomes. However, results such as the percentage of urban areas within 1km of transport nodes and the minimum distance of residential areas urban centres are considerably useful to the research aims of the project.

### **Critical Analysis of the MOLAND Model**

#### Pros:

- Provides a tool to aid understanding of outcomes to specific policies spatially and the effect that this has on transport accessibility.
- A variety of spatial planning scenarios can be analysed and the effects to specific sectors of the economy can be measured as well environmental impacts as a result.

- MOLAND offers an extensive framework for the comparison of conflicting socio-economic trends up to 2026 (in line with NTA, NRA and ESRI forecasts) and visualises these patterns using GIS software.
- The 'business as usual' scenario acts essentially as a 'do minimum' scenario in relation to current trends which similarly links up well with the NTA and NRA models.
- Increasing land density with more mixed-use development is proven to reduce transport-related emissions and by reducing travel to employment and services this could allow for an increased modal shift to public transport or active modes (Williams and Convery, 2012). The MOLAND model supports this agenda which could influence policymakers and stakeholders in coming years.

Cons:

- The updated version of MOLAND with the extended transport model was not made available within the time frame of this research undertaken by UCD, the work of populating the transport model with relevant data and associated calibration was preliminary (Williams and Convery, 2012).
- Significant data gaps exist that have been highlighted by the MOLAND project team including a lack of harmonised data (both scalar, temporal and contextual) relating to zoning status of lands in the GDA region.

### **1.3 The Department of Transport, Tourism and Sport (DTTaS) (2016) Common Appraisal Framework for Transport Projects and Programmes**

Supplementary to the transportation models detailed above, it is necessary to consider important transport parameters included in the DTTaS Common Appraisal Framework for Transport Projects and Programmes (DTTaS, 2016). This document was released in March 2016 as a replacement to the Guidance document from 2009, it develops a framework for the evaluation of investments in transport that is also consistent with the Public Spending Code (PSC) to aid in the preparation of business cases of transport investment prior to Government submission (DTTaS, 2016). The document consists of 7 sections each representing a themed issue, the fifth of which will be of specific interest to the Greening Transport Project as it deals with significant transport parameters for use in economic appraisal in examining a project's broader economic, social and environmental impacts' (DTTaS, 2016).

Cost-Benefit Analysis (CBA) represents a significant part of the Common Appraisal Framework, particularly in relation to the assessment of whether social and economic benefits of an investment project outweigh associated cost in transport appraisal. The Swedish model detailed below highlights the advantages of incorporating CBA in transport modelling frameworks. In the case of transport modelling, CBA is useful in determining the benefits of reduced emissions and travel time savings for example.

The range of transport parameter values are displayed in Table 5 below.

**Table 5: DTTaS Transport Parameter Values**

Parameter	Values
Value of Time	<ul style="list-style-type: none"> <li>- <u>Work</u> (hourly labour costs = dividing aggregate labour costs by annual hours worked)</li> <li>- <u>Commuting</u> (10% above the leisure value of time)</li> <li>- <u>Leisure</u> (40% of average hourly earnings of travellers)</li> </ul>
Vehicle Operating Costs	<ul style="list-style-type: none"> <li>- <u>Fuel Costs</u> (weighted average of Irish road vehicle fleet and applying standard fuel consumption factors by vehicle and road type)</li> <li>- <u>Non-fuel Costs</u> (oil, tyres, maintenance and depreciation and main vehicle types)</li> </ul> <p>Estimated using function <math>C = a_1 + b_1/V</math>,            where: C is cost in cents per kilometre, V is average link speed in km/h, a1 and b1 are parameters for each vehicle category</p>
Emission Values	<ul style="list-style-type: none"> <li>- <u>Noise</u> (€30 per DB(A) per person per year proposed, not definite)</li> <li>- <u>CO<sub>2</sub>, NO<sub>x</sub> and PM</u> (apply rate of emissions per vehicle km, derive total emissions, apply monetary value to each amount of emission from motorways, urban and rural)</li> </ul>
Active Travel Values	<ul style="list-style-type: none"> <li>- <u>Health Benefits</u> (calculated reductions in risk of death and no. of walkers and cyclists used to calculate a figure for the potential no. of lives saved based on average mortality rate. No. of potentially prevented deaths multiplied by value of prevented fatality used in accident analysis to give a monetary benefit)</li> <li>- <u>Absenteeism Benefits</u> (monetary value is the product of the total hours per year saved and value of work time per hour)</li> </ul>

Value of time refers to the benefit of travel time savings and this varies according to journey purpose (e.g. work (commuting), education, employer’s Business, shopping, other leisure and non-home based travel as stated in the NTA model). Aggregation of these time savings are calculated to determine the value of such benefits, from 2011 data. The parameters of interest are: Value of Time, Vehicle Operating Costs, Emission Values and Active Travel Values which are explained in Table 5 above.

Future carbon emissions values are set by the Department of Public Expenditure and Reform to 2050. Vehicle emission factors are estimated from the default values contained with the COPERT 4 road transport emissions model and weighted to the Irish vehicle fleet (DTTaS, 2016). A comprehensive analysis of COPERT 4 will be presented in Section 2.2 of this deliverable. From 2015 to 2020 the price of CO<sub>2</sub> on the EU ETS system of the European Climate Exchange is used as the cost of CO<sub>2</sub> as well as linear extrapolation for carbon price between 2017 and 2020. In the period of 2020 onwards the Impact Assessment from the EU 2030 Framework for Climate and Energy Policy provides a price projection for the ETS. For other gases such as NO<sub>x</sub> and PM, they are determined by a willingness-to-pay (WTP) valuation method and future values reflect future earnings related to increases in GNP per person employed (DTTaS, 2016).

Active travel benefits and/ or costs are considered by combining benefits from a reduction of health risk and absenteeism as result of increased numbers of people walking and cycling.

Specific values for each of the parameters and an in-depth analysis is provided in Annex 1 of the Appraisal Framework document

## 1.4 International Best Practice - UK, the Netherlands and Sweden

Evidence supporting international best practice in transportation modelling in the context of measuring emission levels will be examined in this section taking case studies of countries in Europe: the United Kingdom, the Netherlands and Sweden, in a comparative analysis. These studies have been suggested based on the range of policy applications that these National Transportation Models present that have been advised by the WSP (2011) report which states that “their use has been central to the development of closer integration with physical and environmental planning of new approaches to transport pricing policy”.

### UK National Transport Model (NTM)

Akin to the NTA and NRA models the UK model is an integrated, multi-modal model which is based on the framework of a 10 Year Plan. The model examines car drivers, car passengers, rail, bus, walk and cycle and is comprised of a series of sub-models which are applied in iteration to produce the main model outputs. These models are: the Demand Model, the Road Capacity and Costs Model and the National Rail Model, the functions of which are to produce forecasts of modal share and to examine effect of a change in mode costs due to congestion, road pricing etc. (DtF, 2003). An overview of the model structure is displayed below in Figure 7.

The model utilizes data from a wide range of trustworthy sources such as: the National Travel Survey, Family Expenditure Survey, the Traffic Census, ticket sales data as well as the Department of Transport’s National Trip End model data amongst others.

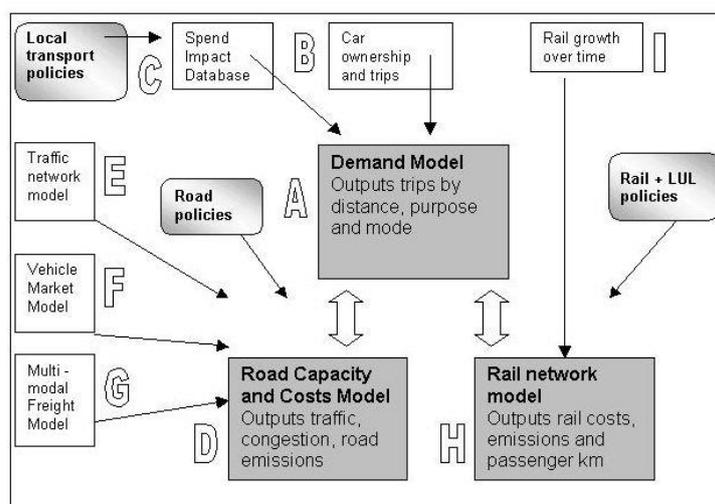


Figure 7: UK NTM Model Structure (DtF, 2003)

The Road Capacity and Costs Model (FORGE) is the most apparent difference between the Irish NTA and NRA models and the UK model, as the other Demand and Rail models are in fact very parallel to the Irish equivalent. FORGE however is used to show the impact of road schemes and other road-based policies. The outputs of the model are of specific interest to the aims of the project: it models traffic by journey purpose and vehicle type; calculates congestion (by road type, area type); total tailpipe emissions of three key pollutants – CO<sub>2</sub>, NO<sub>x</sub> and PM<sub>10</sub> – which are measured using emission equations as a function of speed at a detailed level (by time period), and finally car speeds by road type, area type etc., that are then fed back into the Demand Model (DtF, 2003). The ESRI ISus Car Stock model is alike in that it calculates emissions from private cars however, the FORGE model takes into consideration not only CO<sub>2</sub> but other equally harmful gases like mono-nitrogen oxides, nitric oxide and nitrogen dioxide (NO<sub>x</sub>) and particulate matter (PM<sub>10</sub>), and as just stated it

links directly back to the demand model. The outputs are produced thanks to the volume of data provided from the UK's Traffic Network Model (highway distribution and assignment) and the Vehicle Market Model (fuel efficiency and vehicle fleet characteristics). Therefore, emissions and transport modelling are interlinked in the FORGE model which is necessary to engender direct coordination.

On the contrary, the ISus Car Stock Model is completely detached from transportation models in Ireland, it is connected to HERMES, and this highlights the fundamental issue that there needs to be greater synchronisation between environmental planning and transport modelling and policy to ensure that environmental policies are adequately enforced to achieve the environmental results. The Greening Transport project proposes to considerably reduce this separation by creating a Transport Emissions model that influences aggregation between these models.

#### The Netherlands National Model System (NMS)

The Dutch National Model System is a prime example of a highly disaggregate model for predicting travel demand which has been in operation since 1986 and updated on numerous occasions since then. It was originally designed to be a tool for strategic appraisal of new road and rail links but its scope of application has gradually widened to also include environmental and IT issues (Lundqvist and Mattsson, 2001).

The model structure is based upon age-cohort licence holding and car ownership models that are fed into trip frequency, mode and destination choice models. The resultant Origin-Destination rail and car driver trip matrices are then assigned to the rail and road networks. These models are usually based on individual utility maximisation represented in the form of multinomial nested logit models. When applied to forecasting, enumeration of prototypical samples are used together with the 'pivot-point' approach for driver and train passenger flows i.e. the model system is only used to calculate changes that are applied to the 'observed' based year O/D matrices (Lundqvist and Mattsson, 2001).

What sets the NMS apart is the clarity given to the behavioural mechanisms that it implements which in turn means that the model can be deciphered a lot easier. It devotes particular emphasis to Stated Preference (SP) choice modelling to inform the multinomial nested logit models by means of the national travel survey. This technique is unique in that it is designed to infer the maximum amount of information from the survey respondent which is important in the context of demand forecasting using hypothetical situations. For instance in cases where new alternate modes of transport are introduced to the network, a new travel demand will subsequently need to be created to account for this new development. SP presents a useful means of modelling demand for scenarios such as this, which in this way highlights its importance in a transport model and why it should be given more attention (Lundqvist and Mattsson, 2001).

The examination of smarter travel options and opportunities for sustainable car use in Ireland in Work Package 3 and 5, will require an acute analysis of SP modelling to further study and discover opportunities for a shift in behavioural change in the project.

#### Sweden SAMPERS Model

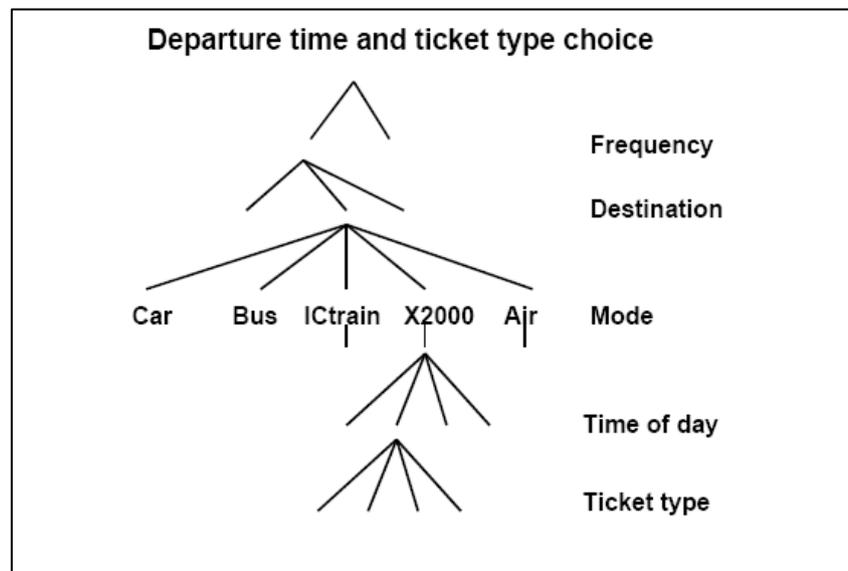
"The first generation of the Swedish national model, SAMPERS, was developed in the beginning of the 1980s, a second generation during the first half of 1990s. The Swedish system aims to provide not only demand forecast for the national planning process, but also environmental impact and cost-benefit (CBA) calculations for investment planning in transport" (Sillaparcharn, 2007). The model has been in use in many planning situations such as in: medium and long-term transport strategies/plans with CBA being a major element; regional development planning in large cities like Stockholm

and Gothenburg that focused on transport accessibility, land use and carbon emissions; congestion charges and potential consequences of their introduction as well as in modal demand shifts and route choice decision making processes (Jonsson et al., 2011).

There are five regional models that generate O-D trips in SAMPERS of which nested logit models are used to carry out the estimation of six trip purposes (work, business, school, visits, leisure and other trips) from five modes of transport (car, car passenger, public transport, bicycle and walking). The model inputs time and cost parameters from census data and socio-economic parameters that provide data on car ownership, income and other attraction variables for destinations. The demand model is reliant on matrices from the time and cost parameters that are computed and assigned to traffic/ road and public transport networks in EMME/2 module software (Jonsson et al., 2011).

Special software modules such as this have been developed for the design of scenarios, with an automatic control of input data, and for the analysis, aggregation and visualisation of the results (Lundqvist and Mattsson, 2001).

SAMPERS like all resource intensive modelling such as transport, it is not free of limitations or errors, and many of such errors become apparent whilst the model is functioning. In a sub-model of SAMPERS entitled SAMKALK that carries out the function of costs and benefits, errors are inadvertently exposed during the functioning of the model. As this sub-model computes CBA the inadequacies in the sensitivity analyses completed elsewhere in SAMPERS as well as quality control features of EMME/2 become apparent. The reason for this is due to the fact that “the sensitivity analyses were not done on model assumptions, only on the CBA assumptions” (Lundqvist and Mattsson, 2001). These errors have been acknowledged by industry partner and other stakeholders, however the model has continued to be used irrespective of this as the model is still very valuable and compares well with state-of-practice. The SAMPERS model structure as depicted by SIKa is display here in Figure 8.



**Figure 8: Sweden SAMPERS Model Structure (SIKA, 2002)**

### **Conclusion**

The different European national models mentioned above have much in common. They often use disaggregate nested (tree) logit structures and require similar kind of data (Sillaparcharn, 2007). However, of the three international examples of transportation models, the UK NTM proves the most beneficial to the project aims and it is most in keeping with the existing Irish model such as the

NTA, NRA and ISus models and provides district recognition of the emissions modelling. Notwithstanding this, elements from the Dutch and Swedish models will also be considered in the development of the transport emissions model and lessons from them will also be taken into careful consideration.

- Learning from the EU examples

The bulk of learning potential in terms of the European examples listed can be taken from the UK NTM as it applies specific emphasis to the collaboration of emission modelling with more generalised transport modelling techniques. The gap between these modelling areas must be significantly bridged in Ireland through greater coordination and unification to calculate more accurate GHG emissions from different modes of transport into the future. Lessons can be taken from SAMPERS use of the CBA assumptions mechanism in the Swedish model, especially in planning investment into sustainable modes and taking a longer term perspective. Finally the Dutch model is particularly useful with respect to the incorporation of utility maximisation in multinomial nested logit modelling techniques that may similarly be applied to our transport emissions model in examining travel behaviour. An overview of the key elements from the transportation models discussed is presented in Table 6.

**Table 6: Key Elements from the Models**

Models	Elements						Stated Preference Modelling of scenarios
	AM and PM Peak	Carbon Emissions & Environmental Concerns	Land Use	Private Car Ownership	TAGM	Demand Forecasting	
NTA GDA Model	✓	✓	✓	✓	✓	✓	
UCD MOLAND			✓	✓		✓	
ESRI HERMES		✓		✓		✓	
ESRI ISus		✓		✓		✓	
NRA NTpM	✓			✓	✓	✓	✓
UK NTM Model	✓	✓		✓	✓	✓	✓
The Netherlands NMS	✓		✓	✓	✓	✓	✓
Sweden SAMPERS	✓		✓	✓	✓	✓	✓

The following section of this deliverable will offer an executive review and critical analysis of the various international emissions models that are currently available and adaptable to the Irish setting. This represents a significant proportion of the work being conducted in the Greening Transport project as the selected emissions model will be utilised in the generation of valuable emissions projections based on transport data taken from the NTA model and ISus Car Stock Model. The transport data will be secured in collaboration with the NTA and ESRI during subsequent work packages of the project. Various scenarios will be simulated in the NTA and ISus models which will account for modal shifts and car ownership levels as a result of specific measures being applied, for example changes in the private car and public transport fleet, renewable fuel growth scenarios, alternative vehicle tax scenarios as well as changes in modal share due to increased use of active modes such as walking and cycling and increased public transport usage.

## **Section 2: Examining the most appropriate Environmental Models and Data**

### **2.1 Introduction**

Road traffic is one of the greatest contributors to the greenhouse gas (GHG) and reducing it has become one of the main target for sustainable transport policies. Analysis of the main factors influencing GHG emissions is essential for designing environmentally efficient strategies for the road transport. Section 2 describes the review of transportation emission models carried out as a part of Task 2.2.

#### **2.1.1 Classification of emission model**

There are various models to calculate emission from road transport which can broadly be classified into Static models (also known as Top-down or Macro-scale emission models) and Dynamic models (also known as Bottom-up or Micro-scale models) (Elkafoury et al., 2014). The Static models can further be classified to Average speed models and Aggregated emission factor models whereas Dynamic models can be sub-classified to Traffic situation model and Instantaneous model. These models have been discussed in the following section.

##### **Average speed model:**

These are the most commonly used models which assume that the average emission rate throughout a trip depends on the average speed of the vehicle during that trip. One important drawback of average emission models is that these models don't allow to calculate emission on spatial resolution but this limitation isn't much relevant for vehicular emission calculation for vehicle fleet or at national level (Elkafoury et al., 2014). Few examples of average speed models are Computer programme to calculate emissions from road transport (COPERT), Vehicle emissions prediction model (VEPM) etc.

##### **Aggregated emission factor model:**

Models of this type operate at the simplest level, with a single emission factor being used for a broad category of vehicles and a general driving condition such as, urban roads, rural roads etc. (Wang and McGlinchy, 2009). These models calculate vehicular emission on the basis of amount of fuel consumed and vehicle kilometre travelled (VKT) (Elkafoury et al., 2014). A few examples of this type of model are the Mobile Source Emission Factor Model (MOBILE), National Atmospheric Emission Inventory (NAEI) etc.

##### **Traffic situation model:**

In this type of modelling approach, driving dynamics is also taken into account along with average speed. Traffic situations are defined by traffic conditions (e.g. congested, free flow, stop and go etc.) on a specific type of road such as, urban, along with the speed limit value on that particular road (Wang and McGlinchy, 2009). One issue with this type of model is that it requires detailed statistics about vehicle speed and traffic situation associated with the trips (Elkafoury et al., 2014). Examples of traffic situation models are Handbook emission factors for road transport (HBEFA), Assessment of road transport emission model (ARTEMIS) and Vehicle fleet emission model (VFEM) etc.

##### **Instantaneous model:**

These are the models which operates at highest level of complexity. Models of this type assign some emission rates to each combination instantaneous speed and acceleration rate (Wang and McGlinchy, 2009). The disadvantage about this model is that it demands detailed data about vehicle, engine characteristics, the geometry of road and ambient temperature (Elkafoury et al., 2014). Example of Instantaneous or modal model is Passenger car and heavy duty vehicle emission model (PHEM).

Table 7 shows the input data required to define the vehicle operation, characteristics and area of application of the above mentioned transportation emission models.

**Table 7: Emission models** (Ref. NZ Transport Agency, 2013)

Type	Input data required to define vehicle operation	Characteristics	Application
Aggregated emission factor model	Area or road type	Simplest level, no speed or vehicle specific dependency	National inventories
Average speed model	Average trip speed	Speed and vehicle type/ technology specific	National and regional inventories
Traffic situation Model	Type of road, speed limits, congestion level	Driving pattern (speed, acceleration etc.) and vehicle type/technology specific	Environmental impact assessment, area-wide urban traffic management (UTM) assessment
Instantaneous Model	Driving pattern, vehicle specific data- power, speed etc.	Micro-scale modelling, individual vehicle specific	UTM assessment

## 2.2 The existing emission modelling tools

This section gives brief summary of various models developed to calculate emission from road transport. Apart from models which has been developed by European countries, models developed in USA and New Zealand has also been included. Table 8 presents advantages and disadvantages of all the important transportation emission models.

### 2.2.1 Assessment of Road Transport Emission Model (ARTEMIS)

ARTEMIS is a Traffic Situation model (André et al., 2004). This is one of the most comprehensive transportation emission models and it can operate at both macro and micro level (Wang and McGlinchy, 2009).

It contains five sub-models, one Traffic situation model, one Average speed model, two Instantaneous model and one Kinematic regression model. The instantaneous models and kinematic regression models are for calculating emission from light vehicle but the models are very complex. The average speed model is same as COPERT and traffic situation model is better than HBEFA as it contains more than 200 traffic situations (Wang and McGlinchy, 2009). In terms of required input data, ARTEMIS requires very elaborated and reliable data regarding, vehicle activity, fleet composition, driving condition etc. Also a detailed classification of the vehicles (e.g. size, technology etc.) are required in order to have accuracy in emission calculation. The vehicles are to be classified as, cars, light-duty vehicles, motorcycles, heavy duty vehicles (HDV), buses, and coaches. The sub-categories like, rigid, articulated etc. can also be provided. The model can estimate most of the pollutants, regulated pollutants such as, Carbon Monoxide (CO), Hydrocarbon (HC), Oxides of Nitrogen (NOx), Particulate Matter (PM), Lead (Pb), Sulphur Dioxide (SO<sub>2</sub>) and non-regulated pollutants such as, Carbon Dioxide (CO<sub>2</sub>), benzene, toluene, xylene, polycyclic aromatic hydrocarbons, methane, ammonia etc. (André et al., 2004).

ARTEMIS can calculate emission for road, rail, air and ship transport and provides consistent emission estimates at both national and regional level. The ARTEMIS tools were designed for three main applications, emission inventories, scenario calculation for assessing the impacts of alternative measures and inputs for air quality models in order to assess spatial and temporal impacts on the environment (UNECE Transport Division report, 2012). The model has many similarities with COPERT and HBEFA models (these models have been discussed on the following two sections), especially in terms of input vehicle classes and categories of GHG and air pollutants to be obtained as output. For emissions from light vehicles, ARTEMIS have improved emission factors than COPERT and HBEFA (Wang and McGlinchy, 2009).

As per UNECE Transport Division report (2012), ARTEMIS has only been fully implemented for compiling national air emission inventories in four countries, i.e. Germany, Austria, Switzerland and Sweden. Application of the model to other countries is not possible without the involvement of the ARTEMIS modelling team.

### **2.2.2 Computer Programme to Calculate Emissions from Road Transport (COPERT)**

COPERT is an Average Speed model. COPERT has been developed for official road transport emission inventory preparation for European Environment Agency (EEA) member countries (Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech republic, Denmark, Estonia, Finland, France, Macedonia, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherland, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United kingdom) (EMISIA, 2014). COPERT 4 is the most modified and latest available version of COPERT which took elements from few other popular emission models like, MEET, ARTEMIS, COST and PARTICULATES. Its initial version was COPERT 85 (1989), followed by COPERT 90 (1993), COPERT II (1997) and COPERT III (1999). COPERT 4 (2006). COPERT II was the first one with a GUI (Graphical Use Interface), built on MS Access 2. COPERT II provided emission factors up to Euro 1. COPERT III was based on menus and compared to COPERT II, it has new features like, hot emission factors for Euro 1 passenger cars, reduction factors over Euro 1 according to AutoOil, Impact on emissions from 2000, 2005 fuel qualities, Cold-start methodology for post Euro 1 Passenger cars (PC), Emission degradation due to mileage, Alternative evaporation methodology, Detailed NMVOC (Non-methane Volatile Organic Compounds speciation (Polycyclic Aromatic Hydrocarbon (PAH)), Persistent Organic pollutants (POP), Dioxins and Furans), Updated hot emission factors for non regulated pollutants.

COPERT 4 can calculate emission from a wide range and variety of vehicles e.g. Hybrid passenger cars, Compressed Natural Gas (CNG) buses, Liquefied Petroleum Gas (LPG) passenger cars, conventional heavy duty vehicles in addition to the conventional diesel vehicles. Three types of roadway situations can be considered in COPERT i.e. Urban, Rural and Motorways. The shortcoming about heavy vehicle (>13T) emission in NAEI is improved in COPERT and it gives more reliable results for emissions from heavy vehicle as it is tested on more no. of vehicles. COPERT 4 includes many important emission factors such as, cold over hot ratio, ambient temperature, vehicle use, mileage, fuel characteristics etc. For heavy vehicles, loading and gradients are also taken into account. The latest version of COPERT i.e. COPERT 5 will be launched in September, 2016 (EMISIA, 2015). Street level COPERT is also available which calculates only hot emissions with at street level and can be combined with meso and macro emission models (Dilara, 2015).

The uncertainty in estimating non-exhaust PM emission is also associated with COPERT 4 like the other emission models. However, it is applicable to all relevant research, scientific and academic applications. The input data are consistent with the Eurostat classification. As a result, the model is well suited for EU Member States reporting detailed statistical information (UNECE Transport Division, 2012). [Please refer to section 2.3 and 2.4 for further details on COPERT]

### 2.2.3 Handbook Emission Factors for Road Transport (HBEFA)

HBEFA is a traffic situation model. The first version of HBEFA was published in 1995 and the most recent version of HBEFA (3.2) was produced in 2014. It is developed on behalf of several European countries (e.g. Germany, France, Sweden, Switzerland, Austria) (HBEFA, 2014).

It takes into account all important vehicle classes, including passenger cars, light commercial vehicles, heavy duty trucks, buses, motorcycles, mopeds etc. differentiated by fuel, engine capacity and weight classes for a variety of traffic situations. Emission values are obtained in grams and calculated as below,

$$\text{Emission} = \text{Traffic activity (vkm)} * \text{Emission factors (g/vkm)} \quad (1)$$

The input factors required to calculate emission are (Schmied, 2014):

- Vehicle category (Passenger Car, Motorcycle, Light duty vehicle (LCV), Urban bus, Single truck, Coaches, Truck trailer)
- Vehicle size (PC: <1.4 L, 1.4-2.0 L, >2.0 L; Truck: <= 7.5 t, 7.5-12 t, 12-14 t)
- Fuel type (Diesel, Gasoline, LPG, CNG, FFV (Flexible Fuel Vehicle))
- Technology class i.e. Emission standards (Pre Euro 1, Euro 1, Euro 2, Euro 3, Euro 4, Euro 5, Euro 6)
- Load factor (for trucks)
- Reduction Technologies (Particle filter, Silicon Controlled Rectifier (SCR), Exhaust Gas Recirculation (EGR))
- Road gradient
- Traffic situation/driving cycles

HBEFA calculates emissions of GHG and most air pollutants from road transport. HBEFA provides emission factors (hot exhaust emission, cold start emission, evaporative emission) for all regulated and important non-regulated air pollutants. [Hot exhaust emission: “Exhaust emissions that occur under ‘hot stabilized’ conditions, which means that the engine and the emission control system (e.g. catalytic converter) have reached their typical operating temperatures. Cold start emission: “Exhaust emissions that occur in addition to hot running emissions because engines and catalysts are not (fully) warmed up and operate in a non-optimal manner” (Smit et al., (2013).

HBEFA can be applicable to city/local levels or regional levels. However, HBEFA contains a database with all country-specific vehicle fleet data necessary for running the model. It is not possible for the user to apply the model for different country than those already included in the database (Wang and McGlinchy, 2009; Schmied, 2014; NZ Transport Agency, 2013). Thus HBEFA cannot be applied for calculating emission from road transportation in Irish scenario.

**Table 8: Various relevant emissions models**

Name	Places used	Type of model	Advantages	Drawbacks
ARTEMIS (Assessment of road transport emission model) [2.2.1]*	Europe	Traffic situation model	Use the largest emission database till date. Improved a lot upon COPERT and HBEFA.	Few sub-models are very complex.
COPERT 4 (Computer Programme to Calculate Emissions from Road Transport) [2.2.2]	Europe	Average Speed Model	Suitable for emission calculation for both light and heavy vehicle. It has different set of emission models for urban, rural and highways.	It doesn't calculate emission for new technology vehicles such as electric vehicles, plugin hybrid vehicles etc. It does not calculate non-exhaust PM emission.
HBEFA (Handbook Emission Factor for Road Transport) [2.2.3]	Europe (Germany, Switzerland and Austria)	Traffic situation model	Uses traffic situation approach	Applicable in limited places.
MOBILE (Mobile Source Emission Factor Model) [2.2.4]	US	Aggregated Emission factor model	Model freeway ramps separately. Calculates the effects from gross emitters.	No engine size breakdown for light vehicles. BERs based on FTP rather than "real world" driving cycles.
MOVES (Motor Vehicle Emission simulator)	USA		It is applicable to motor cycles, cars and buses and non-road emissions are also planned to be included in future. MOVES can estimate future year emissions or	Emission estimation based on fuel sales may lead to over- or underestimation of the GHGs.

[2.2.5]			energy consumption more precisely because MOVES accounts for future changes in the vehicle fleet and its activity.	
NAEI (National Atmospheric Emission Inventory) [2.2.6]	Europe	Aggregated Emission factor model	Suitable for light vehicle Calculates pollution for variety of pollutants	Emission factors for heavy vehicle are not good.
PHEM (Passenger car and Heavy Vehicle Emission Model) [2.2.7]	European	Instantaneous Model	It gives consistent results for most of the vehicle categories. Calculates emission factors for different road gradients, different vehicle loadings and different gear shift behaviours of drivers in a consistent way. The model PHEM can set up engine emission maps from all sources of measurements as long as high quality instantaneous test results are available.	
VEPM (Vehicle Emissions Prediction Model) [2.2.9]	New Zealand	Average Speed Model	Recently developed and well documented. European database (COPERT III for heavy vehicle and NAEI for light vehicles) has been used as the primary source of model development. For non-European like Japanese and NZ, JCAP1 and NZ2 has been used respectively.	Based mostly on European data which sometimes cause issue for emission calculation for New Zealand. After development of VEPM3, revised and new models were developed like, COPERT 4, ARTEMIS, JCAP2.
VFEM (Vehicle Fleet Emission Model) [2.2.10]	New Zealand	Traffic situation model	A traffic situation model. The vehicle fleet and traffic sub-models has been revised many times.	Only 12 traffic situation have been defined whereas for ARTEMIS, it's more than 200. Emission factors has not been revised.
VERSIT+ [2.2.11]	Europe	Traffic situation model	It takes into account the complex emission behaviour for the modern light duty vehicles.	Suitable for light duty vehicles only. Good for local use.

\*Refers to section numbers for the detailed description of the models.

#### **2.2.4 Mobile Source Emission Factor Model (MOBILE)**

MOBILE is also an aggregated emission factor model. MOBILE is an USEPA (United States Environmental protection Agency) model which calculates emissions from almost all types of vehicle (28 types of vehicles were tested). It was first developed as MOBILE1 in 1978, and has been upgraded periodically since then. MOBILE6 is the latest approved USEPA motor vehicle emission factor model (USEPA, 2016).

The basic parameters considered for aggregation are, vehicle model year, vehicle type and engine technology. Emission rates depend on many factors which can be broadly classified into six categories i.e. travel-related, weather-related, vehicle-related, roadway related, traffic-related, and driver related (Ahn et al., 2002). The input parameters for MOBILE6 are Calendar year, Month, Weekend/weekday, Hourly Temperature, Altitude, Fuel characteristics (Reid vapour pressure, sulphur content, oxygenate content etc.), Humidity and solar load, Registration (age) distribution by vehicle class, Annual mileage accumulation by vehicle class, Diesel sales fractions by vehicle class and model year, Average speed distribution by hour and roadway, Trip end distribution by hour, Distribution of vehicle miles travelled by roadway type, Engine starts per day by vehicle class and distribution by hour, Engine start soak time distribution by hour, Average trip length distribution, Distribution of vehicle miles travelled by vehicle class, Natural gas vehicle fractions, HC species output, Particle size cut off, Emission factors for PM and Hazardous Air Pollutants (HAP), Output format specifications and selections etc. (USEPA, 2003). One notable feature about this model is that it calculates emission from motorway and motorway ramps separately. It was found that vehicles emit significantly more pollutants on motorway ramps than on motorways. This observation indicates that the models which are not considering ramps separately are underestimating the emission (Wang and McGlinchy, 2009).

One drawback of this model is that it considers all passenger cars in the same category irrespective of the engine size. Given the differences between the Ireland and US vehicle fleets, as well as between driving conditions in these two countries, it is not recommended to use this model for emission calculation in Ireland.

#### **2.2.5 Motor Vehicle Emission Simulator (MOVES)**

Motor Vehicle Emission Simulator (MOVES) is also an USEPA model. In 2010, EPA approved the MOVES model and the latest version of MOVES is MOVES2014a (USEPA, 2016).

It can estimate emissions from all onroad vehicles including cars, trucks, motorcycles, and buses. MOVES is capable of estimating emissions for mobile sources at the national or for criteria air pollutants (i.e. particulate matter, photochemical oxidants and ground-level ozone, carbon monoxide, sulphur oxides, nitrogen oxides, and lead), greenhouse gases, and air toxics. It derives its emission estimates from second-by-second vehicle performance characteristics for various driving modes (e.g. cruise, acceleration etc.). It incorporates large amounts of in-use data from a wide variety of sources, such as data from vehicle inspection and maintenance programs, remote sensing device testing, certification testing, portable emission measurement systems (US EPA, 2012c). MOVES can also calculate emissions due to combustion, evaporation, and other processes (brake wear, tyre wear, well-to-pump, vehicle manufacture and disposal).

It can also estimate future year emissions or energy consumption more precisely because MOVES accounts for future changes in the vehicle fleet and its activity. Future year estimates of GHG emissions based on fuel sales may be based on anticipated population and demographic changes over time. However, fuel based estimates may not be able to account for changes in vehicle activity. At the national level, fuel sales can provide an accurate estimate of GHG emissions, but such estimates may not be as accurate for a specific state, metropolitan area, or county. Because for small area people may sometimes purchase fuel outside the geographic boundary of that particular area and this may lead to underestimation or overestimation of GHGs. While CO<sub>2</sub> emissions can be estimated using fuel sales, this method does not work as well for other GHGs that users may want to

include in their analyses. These other GHGs are more dependent on fuel and vehicle standards than fuel consumption, and thus cannot be accurately estimated based on fuel sales. As mentioned earlier MOVES was conceived for the United States, for which it includes a default database of meteorology, vehicle fleet, vehicle activity, fuel, and emission control program data (USEPA, 2012; NZ Transport Agency, 2013). Thus MOVES is clearly not suitable for this study.

### **2.2.6 National Atmospheric Emission Inventory (NAEI)**

NAEI is an aggregated emission factor model. This model is mainly developed for UK in 1970 (NAEI, 2014). It provides historic and projected emission estimates of a range of air quality pollutants and GHGs across a wide range of sectors including transport, waste, energy, industry etc. NAEI calculates emission from, hot exhaust, cold start, brake and tyre wear. The database of NAEI comprises of emission data from about 2800 vehicles and over 25000 tests but very small number of heavy vehicles were tested. Though NAEI is referred as aggregated emission factor model but the aggregated emission factors have been derived from average speeds of vehicle fleet composition and traffic volume observed in UK (Wang and McGlinchy, 2009). Thus has to be checked and calibrated if to be used for other countries.

### **2.2.7 Passenger Car and Heavy Vehicle Emission Models (PHEM)**

PHEM is an Instantaneous model. PHEM is a vehicle simulation tool capable of simulating vehicle hot and cold emissions for different driving cycles, gear shift strategies, vehicle loadings, road gradients, vehicle characteristics (mass, size, air resistance, etc.) (ERMES, 2016).

PHEM has been validated by emission measurements both from light and heavy duty vehicles in the laboratories and on the road (with Portable emissions measurement system) and under different test conditions. If fed with a detailed list of vehicle specifications, PHEM is capable of modelling emission levels on a large variety of conditions not covered by the available measurements. Average emission factor for each vehicle category and then produced taking into consideration the fleet population and technology offer on the market (TUG, 2009).

Advantages with PEMS are the model is already validated, capable of simulating influences of different driving cycles, different road gradients, different gear shift strategies, different vehicle characteristics (mass, size, air resistance etc.), different vehicle loadings in a consistent way based on engine emission maps. It has high accuracy for estimating fuel consumption and CO<sub>2</sub>, NO<sub>x</sub>, PM and Particle Number (PN). PEMS is also capable of simulating emission factors for scenarios on future technologies.

The disadvantages with this model are, it needs instantaneous emission data of vehicle speed, detailed vehicle data as input from each measured vehicle and it has uncertainties in accuracy of estimated CO and HC emissions from modern cars.

### **2.2.8 Transport Emission Model (TREMOD)**

TREMOT (TRansport Emission MODel) was developed in 1993 in the framework of the research and development project carried out on behalf of the German Federal Environmental Agency (TREMOT, 2015). The scope of the project was the analysis of motorized transport (its mileage, energy use and emissions) in Germany. In the road transport sector, TREMOD is harmonized with the HBEFA. TREMOD analyses all means of passenger transportation (cars, two-wheelers, buses, trains, aircrafts) and all means of freight transportation (lorries, light duty commercial vehicles and trailers, trains, navigation vessels, aircraft) for Germany. Since the model uses the HBEFA for calculating road transport emissions, all necessary input data on the vehicle fleet in operation are included in the database of the model. This includes the number of vehicles, travelling speeds for urban, rural and highway conditions, annual mileage values and their shares, vehicle divisions as per fuel and technology level (UNECE Transport Division, 2012). The application of this model to other countries is limited by its country specific, in this case German, traffic database.

### **2.2.9 Vehicle Emissions Prediction Model (VEPM)**

VEPM is an average speed model. It has been developed by the Transport Agency and Auckland Council to predict emissions from vehicles in the New Zealand fleet (NZ Transport Agency, 2013).

VEPM is generally appropriate for assessments of air quality effects where average emissions are required over 1 hour or 24 hour assessment periods for the 'average fleet'. VEPM cannot accurately represent, extreme driver behaviour, emissions from a particular vehicle, micro events, e.g. emissions over a short time period at a particular location. The model takes three engine capacity categories for passenger cars, <1.4L, 1.4-2.0L and >2.0L. Whereas it was reported (Ministry of Transport statistics) that vehicles with engine capacities above 3.0L account for around 20% of passenger car. This means that VEPM may underestimate fuel consumption and CO<sub>2</sub> emissions (NZ Transport Agency, 2013). The key parameters included in this model are cold start emissions, rate of removal of catalytic converter, fuel properties and emission performance degradation due to vehicles cumulative distance travelled (Wang and McGlinchy, 2009). This model had specifically been developed for NZ transportation emission calculation and cannot be used for Irish transportation emission calculation.

### **2.2.10 Vehicle Fleet emission model (VFEM)**

VFEM is a traffic situation model and it is based on the New Zealand (NZ) fleet data. Four types of road situations has been incorporated in this model e.g. Urban, Sub-urban, Rural and Motorways. Three level of services has been included like, free flow, congested flow and interrupted flow. VFEM has three submodels, a fleet model, a traffic activity model and an emission factor model. Initially vehicles were divided into three categories depending on engine size but now they are divided into five categories to fit more with NZ fleet. Engine size is a very important factor as CO<sub>2</sub> emission rate is closely related to engine size. The main drawback of this model is its poor documentation of emission and fuel consumption factors. Moreover many emission data used for model development are based on assumption rather than the actual observation (Wang and McGlinchy, 2009).

### **2.2.11 VERSIT+**

VERSIT+ is a traffic situation model. It is developed by TNO (Toegepast Natuurwetenschappelijk Onderzoek), in Norway (ERMES, 2016).

VERSIT+ has two different modules for Light duty (LD) and Heavy duty (HD) vehicles. The aim of VERSIT+ LD is to predict traffic stream emissions for light-duty vehicles in any particular traffic situation. It is based on a database of 12,000 emission tests, mimicking all aspects of real-time driving behaviour. Whereas VERSIT+ HD is largely based on PHEM software (Lange, 2008). Emission factors are differentiated for various vehicle types and traffic situations, and take into account real-world driving conditions. The pollutants VERSIT+ can calculate are, regulated, CO<sub>2</sub>, Nitrogen Dioxide (NO<sub>2</sub>), PM<sub>2.5</sub>, EC, PAH, PM wear (Tyre, Brake etc.) (ERMES, 2013).

VERSIT+ takes account of the complex emission behaviour of modern light-duty vehicles with advanced exhaust systems that makes it suitable for supporting local air quality improvement and traffic management policies. VERSIT+ can be used for local air quality improvement, investigating national greenhouse gas reduction strategies in a consistent manner by projecting emissions for road traffic (trucks, buses, passenger cars and motorcycles) into the future (Smit et al., 2007). This model has been developed typically for Dutch situation, thus this might not be give reliable results for emissions calculated in Irish traffic behaviour.

**Conclusion:**

It can be seen from the above literature review that the vehicle emission models vary in their modelling approaches, and in the levels of detail required in their input data. They are suitable for different applications and situations regarding spatial and temporal scales, and depending on whether the models are being used to test relative changes from different scenarios or to predict absolute levels of emissions at a given time or place. However, COPERT 4 is a widely used emission model in Europe for its ease of use, broad scope and reliable results.

**2.3 Transportation Emission Model for Ireland**

From the available literature it can be stated that COPERT and MOVES (or its previous version MOBILE) are the most extensively used modelling methods to calculate emission from mobile source. As mentioned earlier, MOVES is an US-EPA model and developed on the basis of vehicle fleet and traffic behaviour observed in USA. In order to use them for Irish conditions (or any other European country) the models have to be calibrated and validated with the country specific data. The other emission models (Table 8) are also limited by their country specific application. COPERT is the only software which can be used in a European country such as Ireland.

**2.3.1 Executive Review of COPERT 4**

COPERT is an EPA approved software tool that has been designed to develop National or state level motor vehicle emission inventories (MVEIs), and Emission factors as a function of vehicle speed for road-based emission calculations. COPERT 4 is a recommended model by European Environmental Agency (EEA) to calculate emission and 33 European countries use COPERT 4 (EMISIA, 2014).

There are other emission models which were developed for specific European countries. HBEFA is one of such models, which have been derived based on the driving characteristics in Germany and Switzerland (Wang and McGlinchy, 2009). In order to check its applicability and accuracy for any other European country, Borge et al. (2012) has studied NO<sub>x</sub> emissions from road transportation, mainly NO<sub>2</sub> emission in Madrid (Spain) and compared the two models, HBEFA which is a traffic situation model and COPERT which is an average speed model. It was found that the emission value obtained from HBEFA is more than that of COPERT. As an explanation of such variable result, it was concluded that COPERT underestimated the pollution probably because it considers the average speed whereas in HBEFA different driving dynamics can be taken and different speeds can be fed. After validating both the models it was observed that the actual emission value was below the model estimated values which indicates that COPERT predicts more realistic emission values. HBEFA is a traffic situation model (combination of road type, speed limit and service level) and takes into account many traffic situation but it has been developed on traffic data and driving scenarios seen in other countries (Germany, Switzerland, Austria, Norway and Sweden), thus in order to use or compare the emission from road transport it is essential to examine traffic situation and traffic behaviour of the country under study.

There are many factors (e.g. fleet data, mileage information, fuel information, engine size etc.) to be provided as input in COPERT and it's very important to use them as accurately as possible. Fameli & Assimakopoulos (2012) has used COPERT to examine road traffic emission trend in Greece and did sensitivity analysis of input parameters on emission calculation. He studied different scenarios like, replacing a percentage of gasoline passenger cars by diesel ones, varying minimum and maximum monthly average temperature, HDV fleet, driving condition share, velocity, mean trip length and euro standards and reported effect of accuracy of emission factors on pollutants.

Other authors like, Ong et al. (2011), Pouliot et al. (2012) used COPERT in their study and reported the reason of its usefulness and feasibility in transportation emission calculation. Ong et al. (2011) used COPERT to calculate road transport emission because COPERT has been developed on the basis of a large database which includes information on vehicle fleet, speed related emission factors, fuel related information, annual mileage and average speed for each vehicle category and has capability

of calculating a wide range of pollutants. Besides the basic emission factors, correction factors can also be provided to account for cold start emission and degradation of the emission reduction equipment due to age/mileage of vehicles. Pouliot et al. (2012) also reported that the use of the COPERT software tool to calculate road transport emissions allows for a comparable, and consistent data collecting and emissions reporting procedure, complying with the requirements of international conventions and protocols and EU legislation.

### 2.3.2 COPERT in Ireland

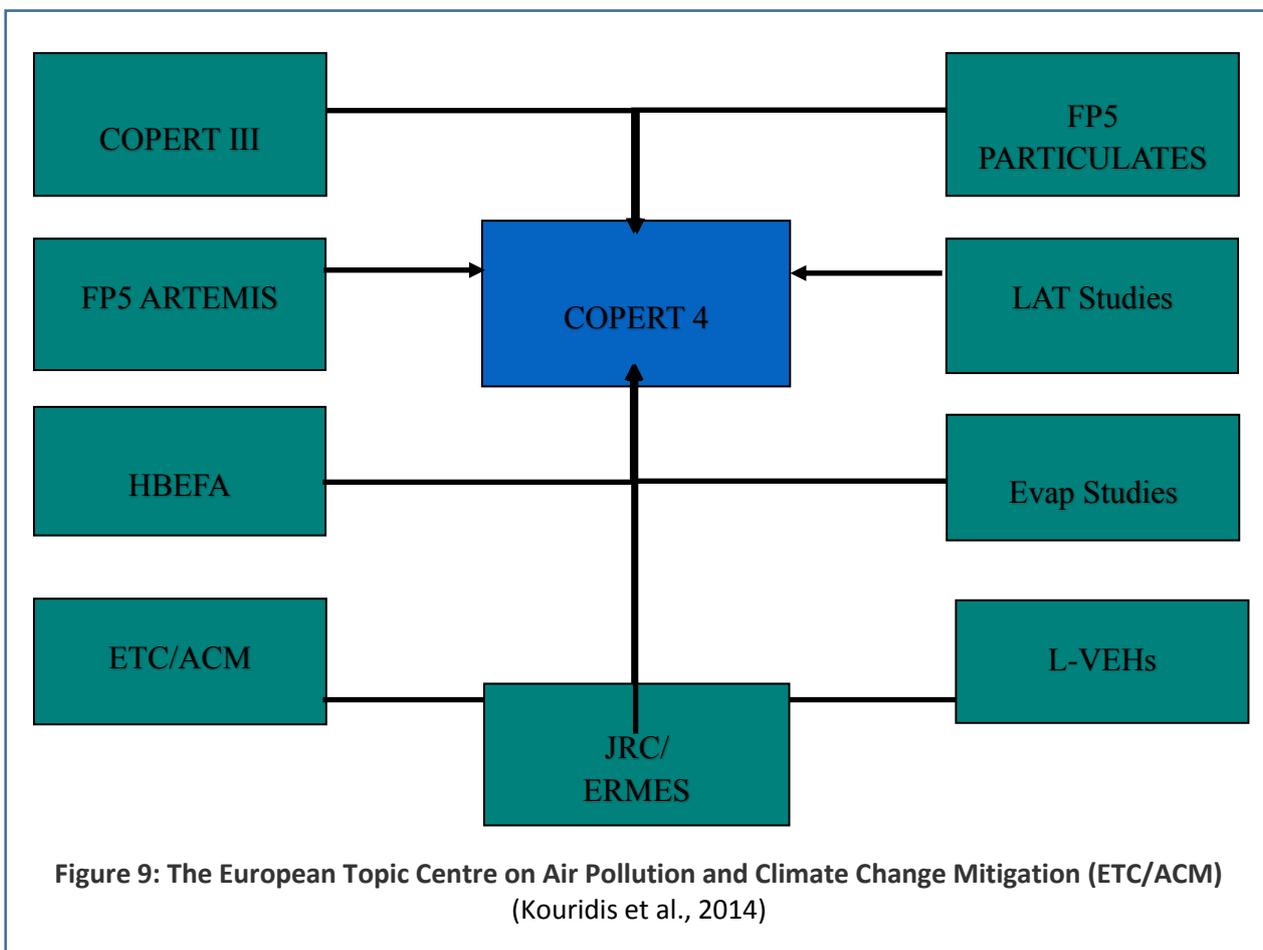
Researchers in Ireland have been using COPERT 4 for significant number of years. Farrell et al. (2010), Caulfield (2009) and Brady and O'Mahony (2011) have used COPERT 4 for their research in calculating emission for the home to work trips. Doorley et al. (2015) have used COPERT 4 to calculate emission reduction as a result of vehicle kilometre saved due to active travel in Dublin, Ireland. Alam et al. (2015) have also used COPERT 4 to estimate transportation emission for Ireland over the period from 1987 to 2013.

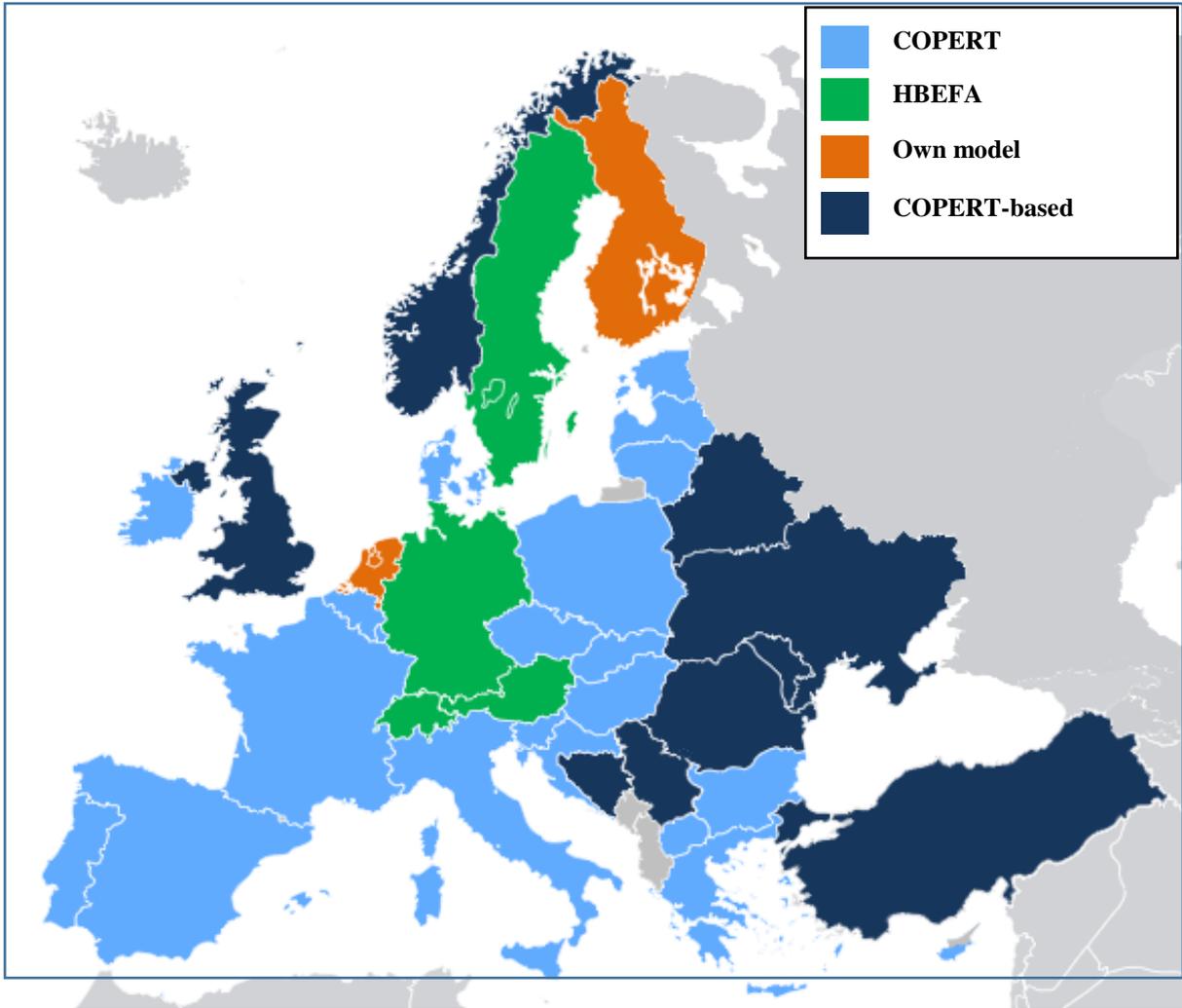
## 2.4 COPERT 4: Elements and Properties

This section consists of detailed information about COPERT 4 in terms of its development, properties, applicability, input, output etc.

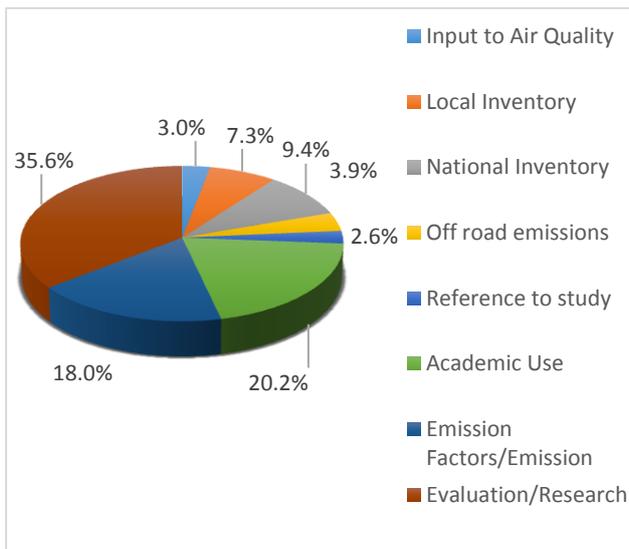
### 2.4.1 COPERT 4: Software development and Use

COPERT 4 is developed taking elements from other models and research results as described in Figure 9. Whereas Figure 10 presents the countries which use COPERT for transportation emission calculation. Figure 11 and Figure 12 show continent-wise use and different applications of COPERT 4 respectively.

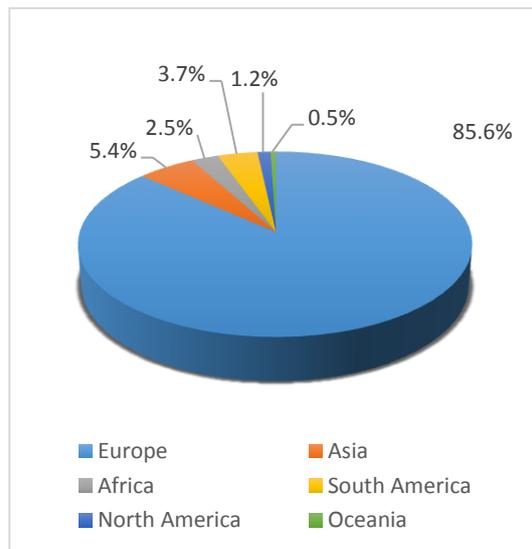




**Figure 10: Distribution of different model usage for transportation-emission calculation (ERMES, 2016)**



**Figure 11: Continent wise distribution of COPERT application (Kouridis et al., 2014)**



**Figure 12: COPERT application in different areas (Kouridis et al., 2014)**

#### 2.4.2 Properties of COPERT 4:

- An average speed model.
- Suitable for emission calculation for both light and heavy vehicle.
- It has different set of emission models for urban, rural and highways.
- It doesn't calculate emission for new technology vehicles.
- It does not calculate non-exhaust PM emission.

#### 2.4.3 Major individual application (Kouridis et al., 2014):

- Air quality and impact assessments
- Projections (energy, CO<sub>2</sub>, pollutants)
- Urban/regional inventories
- New road (road section) construction
- Optimization of loading capacity of HDV
- Airports (ground traffic)

#### 2.4.4 Input parameters (Gkatzoflias et al., 2012):

- Country info- Name, year under study, monthly average minimum and maximum temperature, monthly relative humidity
- Fuel info- Leaded and Unleaded Gasoline, Diesel, Light Petroleum, Gas (LPG), Compressed Natural Gas (CNG), Biodiesel and Bioethanol.
- Fleet configuration- Engine size, Legislation standard
- Activity Data- Fleet data (Population, annual mileage, mean fleet mileage), Circulation data (average speed) and Evaporation data (Fuel tank size, canister size, percentage of vehicles with fuel injection)

The input parameters have been discussed in details in the following section.

Besides the country name and year under study, average overall trip length and average overall trip duration (averaged over year) are also to be provided.

**Meteorological information-** Monthly average minimum & maximum temperature and relative humidity (%) are to be provided (Gkatzoflias et al., 2012). These data are required as ambient temperature affects cold start emissions. Ambient temperature and relative humidity affect air conditioning use and therefore emission levels. Figure 13 shows the screenshot from COPERT 4 where the meteorological information are to be provided.

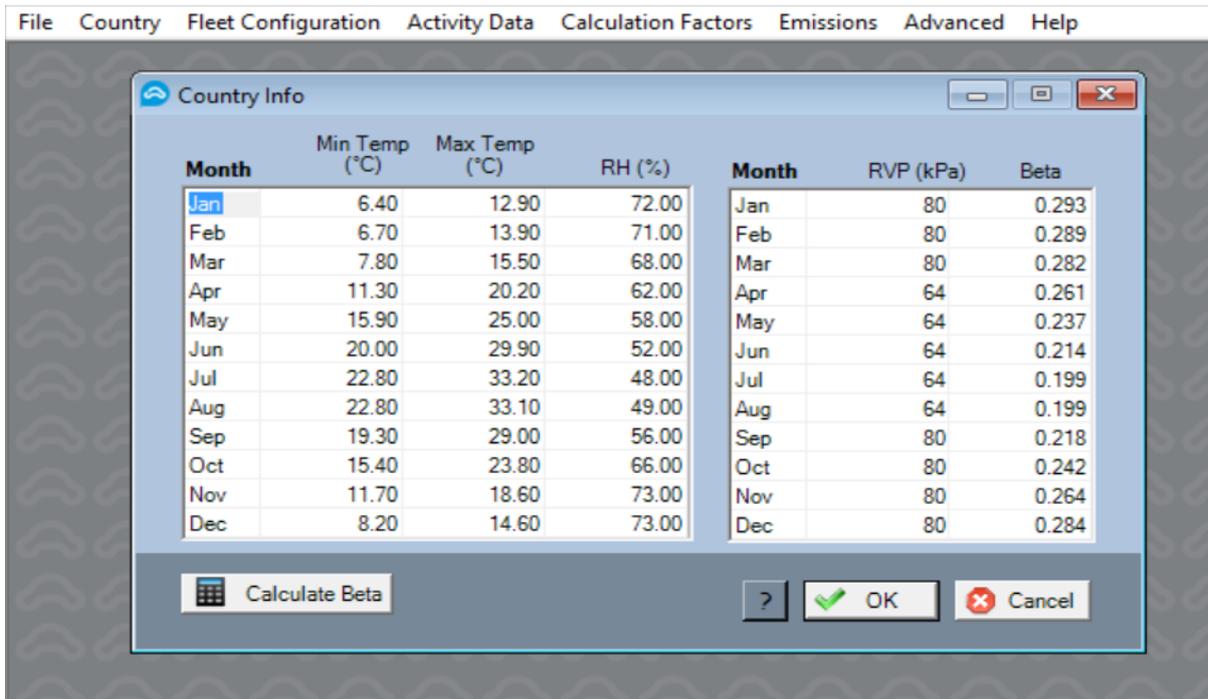


Figure 13: Screenshot of COPERT 4: Meteorological information (Data source: EMISIA, 2014)

Fleet configuration- Six default classes of vehicles can be selected (see Figure 14), passenger car, light

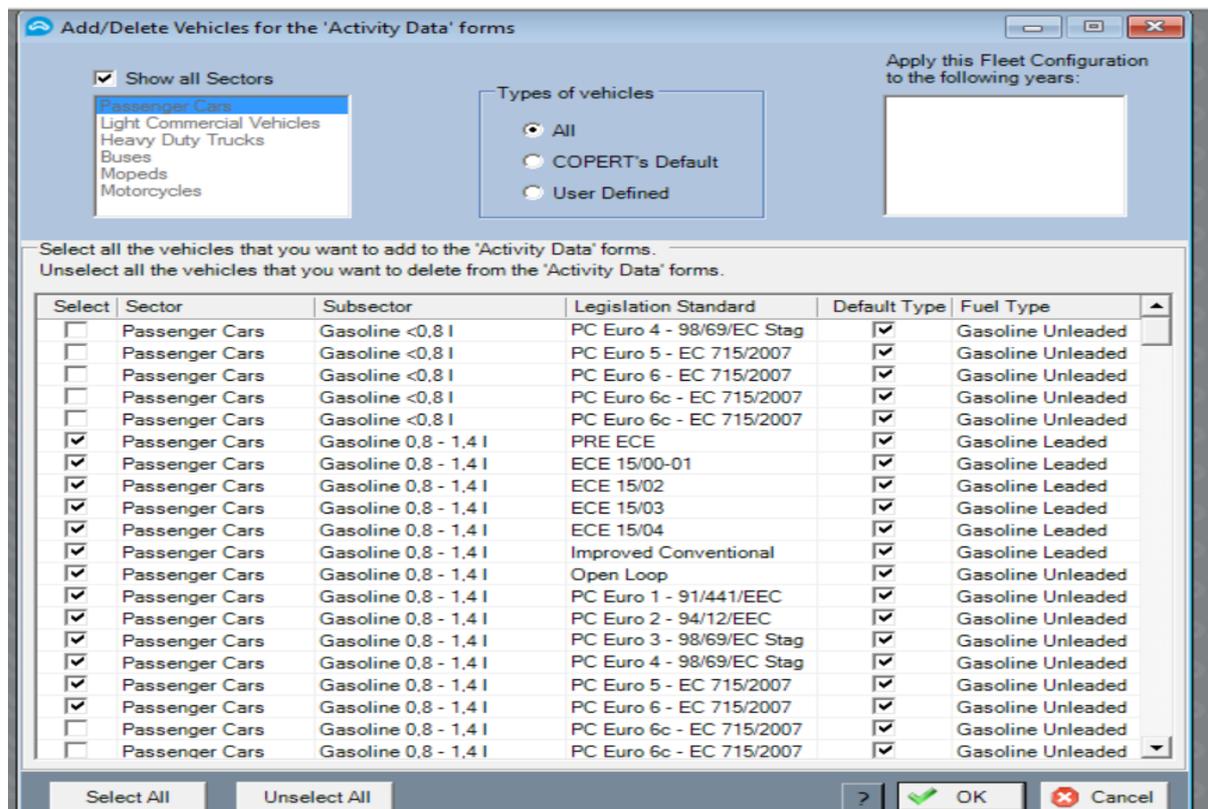


Figure 14: Screenshot of COPERT 4: Fleet configuration (Data source: EMISIA, 2014)

commercial vehicle (LCV), Heavy duty trucks, Buses, Mopeds and motorcycles. Every class (sector) of vehicles have sub-sectors on the basis of engine size, legislation standard and fuel type. A new vehicle sector can be added if all the sub-sector information are known. The default combinations can be deleted by deselecting those (Gkatzoflias et al., 2012). Hence our own dataset will be created depending on the data availability. Figure 14 on the previous page shows the screenshot from COPERT 4 where vehicle categories along with the fuel types, sub-sector information and legislation standards are to be given.

### Activity Data-

Fleet data: Mean fleet mileage (km) is needed, it is the average cumulative distance travelled by each type of vehicles since their introduction in the market (Gkatzoflias et al., 2012). This value helps to calculate an emission degradation factor depending on age. Figure 15 presents the screenshot from COPERT 4 where vehicle mileage information are to be provided.

Subsector	Legislation Standard	Population	Mileage (km/year)	Mean fleet mileage (km)
Gasoline 0.8 - 1.4 l	PRE ECE	100000	10000	N/A
Gasoline 0.8 - 1.4 l	ECE 15/00-01	100000	10000	N/A
Gasoline 0.8 - 1.4 l	ECE 15/02	100000	10000	N/A
Gasoline 0.8 - 1.4 l	ECE 15/03	100000	10000	N/A
Gasoline 0.8 - 1.4 l	ECE 15/04	100000	10000	N/A
Gasoline 0.8 - 1.4 l	Improved Conventional	100000	10000	N/A
Gasoline 0.8 - 1.4 l	Open Loop	100000	10000	250000
Gasoline 0.8 - 1.4 l	PC Euro 1 - 91/441/EEC	100000	10000	180000
Gasoline 0.8 - 1.4 l	PC Euro 2 - 94/12/EEC	100000	10000	120000
Gasoline 0.8 - 1.4 l	PC Euro 3 - 98/69/EC Stage20	100000	10000	80000
Gasoline 0.8 - 1.4 l	PC Euro 4 - 98/69/EC Stage20	100000	10000	25000
Gasoline 0.8 - 1.4 l	PC Euro 5 - EC 715/2007	100000	10000	10000
Gasoline 0.8 - 1.4 l	PC Euro 6 - EC 715/2007	100000	10000	10000
Gasoline 1.4 - 2.0 l	PRE ECE	100000	10000	N/A
Gasoline 1.4 - 2.0 l	ECE 15/00-01	100000	10000	N/A
Gasoline 1.4 - 2.0 l	ECE 15/02	100000	10000	N/A
Gasoline 1.4 - 2.0 l	ECE 15/03	100000	10000	N/A

**Figure 15: Screenshot of COPERT 4: Activity Data** (Data source: EMISIA, 2014)

Circulation Data: Average speed (kmph) which can be assumed in absence of specific information for each driving mode i.e. Urban, Rural & Highway are to be provided. Apart from speed the shares of each vehicle for each driving mode are required as shown in the Figure 16.

Evaporation Data: Fuel tank size (litre), Canister size (litre), percentage of vehicles with fuel injection and evaporation control are also to be provided in the form shown in Figure 17.

Subsector	Legislation Standard	Speed (km/h)			Driving Share (%)		
		Urban	Rural	Highway	Urban	Rural	Highway
Gasoline 0,8 - 1,4 I	PRE ECE	40	60	100	20	40	40
Gasoline 0,8 - 1,4 I	ECE 15/00-01	40	60	100	20	40	40
Gasoline 0,8 - 1,4 I	ECE 15/02	40	60	100	20	40	40
Gasoline 0,8 - 1,4 I	ECE 15/03	40	60	100	20	40	40
Gasoline 0,8 - 1,4 I	ECE 15/04	40	60	100	20	40	40
Gasoline 0,8 - 1,4 I	Improved Conventional	40	60	100	20	40	40
Gasoline 0,8 - 1,4 I	Open Loop	40	60	100	20	40	40
Gasoline 0,8 - 1,4 I	PC Euro 1 - 91/441/EEC	40	60	100	20	40	40
Gasoline 0,8 - 1,4 I	PC Euro 2 - 94/12/EEC	40	60	100	20	40	40
Gasoline 0,8 - 1,4 I	PC Euro 3 - 98/69/EC St	40	60	100	20	40	40
Gasoline 0,8 - 1,4 I	PC Euro 4 - 98/69/EC St	40	60	100	20	40	40
Gasoline 0,8 - 1,4 I	PC Euro 5 - EC 715/200	40	60	100	20	40	40
Gasoline 0,8 - 1,4 I	PC Euro 6 - EC 715/200	40	60	100	20	40	40
Gasoline 1,4 - 2,0 I	PRE ECE	40	60	100	20	40	40
Gasoline 1,4 - 2,0 I	ECE 15/00-01	40	60	100	20	40	40

Figure 16: Screenshot of COPERT 4: Circulation Data (Data source: EMISIA, 2014)

Subsector	Legislation Standard	Fuel Tank Size (lt)	Canister size (lt)	Fuel Injection (%)	Evaporation Control (%)	Evaporation Share (%)		
						Urban	Rural	Highway
Gasoline 0,8 - 1,4 I	PRE ECE	50	N/A	1	0	80	10	10
Gasoline 0,8 - 1,4 I	ECE 15/00-01	50	N/A	1	0	80	10	10
Gasoline 0,8 - 1,4 I	ECE 15/02	50	N/A	1	0	80	10	10
Gasoline 0,8 - 1,4 I	ECE 15/03	50	N/A	1	0	80	10	10
Gasoline 0,8 - 1,4 I	ECE 15/04	50	N/A	1	0	80	10	10
Gasoline 0,8 - 1,4 I	Improved Conventional	50	N/A	1	0	80	10	10
Gasoline 0,8 - 1,4 I	Open Loop	50	N/A	1	0	80	10	10
Gasoline 0,8 - 1,4 I	PC Euro 1 - 91/441/EEC	50	0,5	100	100	80	10	10
Gasoline 0,8 - 1,4 I	PC Euro 2 - 94/12/EEC	50	0,5	100	100	80	10	10
Gasoline 0,8 - 1,4 I	PC Euro 3 - 98/69/EC Stage200	50	1	100	100	80	10	10
Gasoline 0,8 - 1,4 I	PC Euro 4 - 98/69/EC Stage200	50	1	100	100	80	10	10
Gasoline 0,8 - 1,4 I	PC Euro 5 - EC 715/2007	50	1	100	100	80	10	10
Gasoline 0,8 - 1,4 I	PC Euro 6 - EC 715/2007	50	1	100	100	80	10	10
Gasoline 1,4 - 2,0 I	PRE ECE	60	N/A	1	0	80	10	10
Gasoline 1,4 - 2,0 I	ECE 15/00-01	60	N/A	1	0	80	10	10
Gasoline 1,4 - 2,0 I	ECE 15/02	60	N/A	1	0	80	10	10
Gasoline 1,4 - 2,0 I	ECE 15/03	60	N/A	1	0	80	10	10
Gasoline 1,4 - 2,0 I	ECE 15/04	60	N/A	1	0	80	10	10
Gasoline 1,4 - 2,0 I	Improved Conventional	60	N/A	1	0	80	10	10

Figure 17: Screenshot of COPERT 4: Evaporation Data (Data source: EMISIA, 2014)

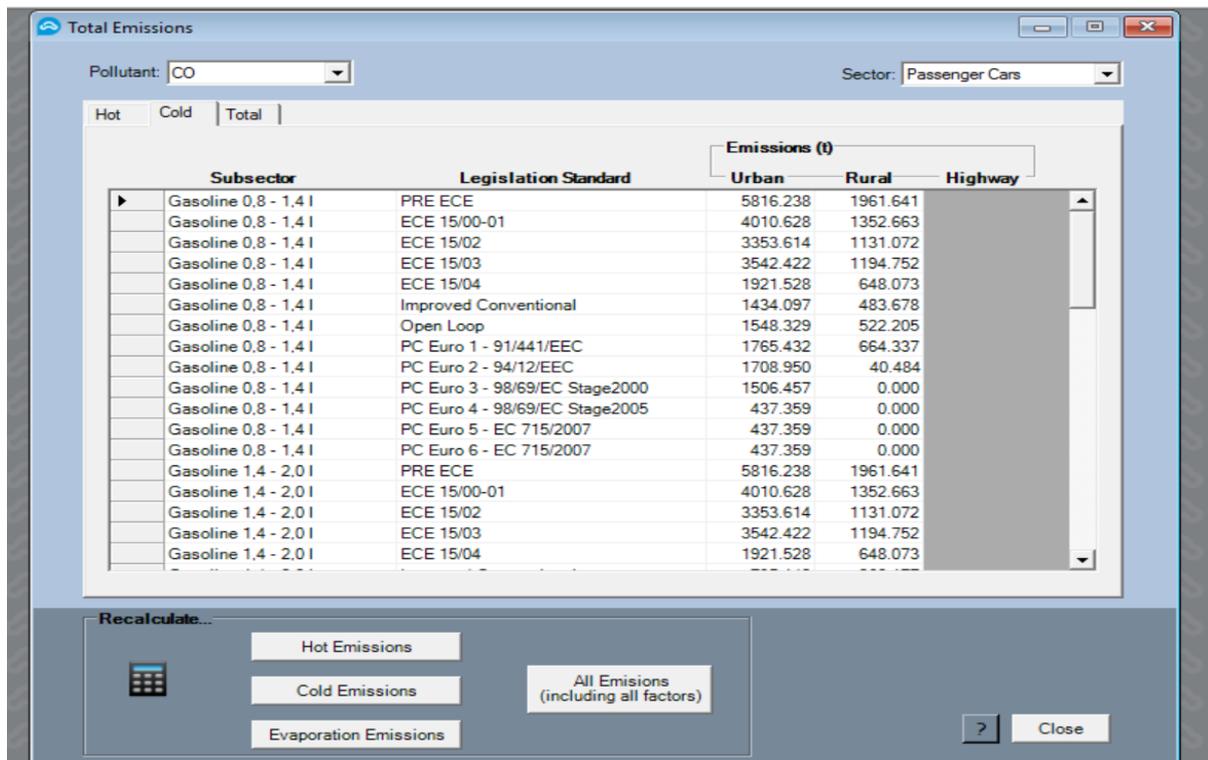
## Output-

The output emissions from COPERT 4 can be obtained in the form of cold start emission and hot exhaust emission (Source Oriented) for each driving mode i.e. Urban, Rural and Highways as shown in the following Figure 18 and Figure 19.

The screenshot displays the 'Total Emissions' window for CO in the Passenger Cars sector. The 'Hot' tab is active, showing a table of emissions (t) for various subsectors and legislation standards, categorized by Urban, Rural, and Highway driving modes. The 'Recalculate...' section shows buttons for Hot, Cold, and Evaporation Emissions, along with an 'All Emissions' button.

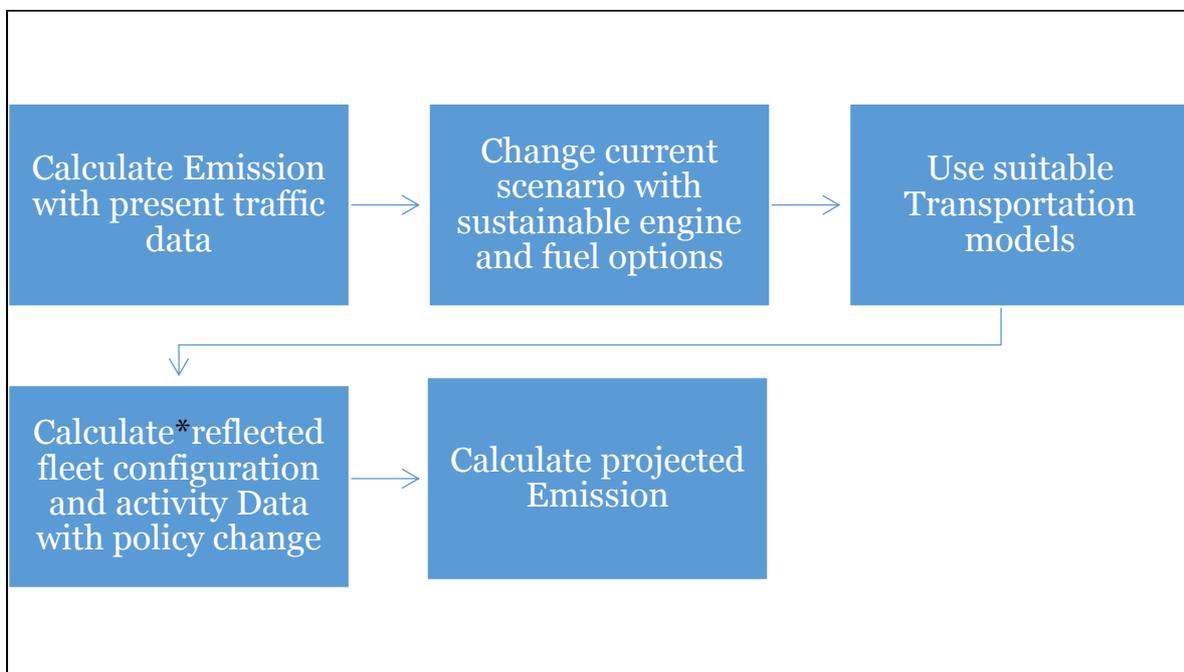
Subsector	Legislation Standard	Emissions (t)		
		Urban	Rural	Highway
Gasoline 0.8 - 1.4 l	PRE ECE	5500.960	8521.794	6208.000
Gasoline 0.8 - 1.4 l	ECE 15/00-01	3793.226	5752.000	7448.000
Gasoline 0.8 - 1.4 l	ECE 15/02	3171.827	3688.000	3304.000
Gasoline 0.8 - 1.4 l	ECE 15/03	3350.400	4276.800	3048.000
Gasoline 0.8 - 1.4 l	ECE 15/04	1817.369	2257.158	1716.640
Gasoline 0.8 - 1.4 l	Improved Conventional	1356.360	2343.120	3982.800
Gasoline 0.8 - 1.4 l	Open Loop	1464.400	2172.800	3372.800
Gasoline 0.8 - 1.4 l	PC Euro 1 - 91/441/EEC	353.018	564.784	706.861
Gasoline 0.8 - 1.4 l	PC Euro 2 - 94/12/EEC	131.824	229.702	299.437
Gasoline 0.8 - 1.4 l	PC Euro 3 - 98/69/EC Stage2000	103.792	246.249	459.380
Gasoline 0.8 - 1.4 l	PC Euro 4 - 98/69/EC Stage2005	39.005	99.246	211.871
Gasoline 0.8 - 1.4 l	PC Euro 5 - EC 715/2007	39.005	99.246	211.871
Gasoline 0.8 - 1.4 l	PC Euro 6 - EC 715/2007	39.005	99.246	211.871
Gasoline 1.4 - 2.0 l	PRE ECE	5500.960	8521.794	6208.000
Gasoline 1.4 - 2.0 l	ECE 15/00-01	3793.226	5752.000	7448.000
Gasoline 1.4 - 2.0 l	ECE 15/02	3171.827	3688.000	3304.000
Gasoline 1.4 - 2.0 l	ECE 15/03	3350.400	4276.800	3048.000
Gasoline 1.4 - 2.0 l	ECE 15/04	1817.369	2513.217	1716.640

Figure 18: Screenshot of COPERT 4: Output forms for Hot exhaust emission (Data source: EMISIA,2014)



**Figure 19: Screenshot of COPERT 4: Output forms for cold start emission (Data source: EMISIA, 2014)**

As a part of Greening Transport project our aim is to calculate emission from transportation at the current situation and with a feasibly changed situation. Figure 20 shows the steps to reach this goal.



**Figure 20: Flowchart of Transportation Emissions Model**

\*Predicted input dataset required for COPERT 4

Table 9 presents the sources of essential data required for GHG calculation and its latest availability.

**Table 9: Sources of COPERT 4 input data**

Required data (as input)	Source (to calculate emission in present scenario)	Models to be used to get the information in the projected future scenario
Temperature and relative humidity	European Climate Assessment & Dataset	The suitable transportation model will be used
Fleet Data	POWSCAR Irish Tax & Customs Department of transport, tourism & sports	
Passenger car kilometre	CSO employment statistics & National Travel survey, National Car Test database	

The report by Environmental Protection Agency (EPA), Ireland (Alam et al., 2015) discuss on available input data for COPERT and effect of disaggregated mileage values on emission estimates. Table 10 presents the effective years of vehicle emission standards for different vehicle classes. Speed data were taken as Urban- 50 kmph; Rural roads- 120 kmph; 100 kmph otherwise (Road Safety Authority). Disaggregated vehicle mileage information were obtained from National Car Testing database.

**Table 10: Technology class vehicle active years (Alam et al., 2015)**

Technology	Passenger car	LDV	HDV	Buses/Coaches	Moped and Motorcycle
Pre-ECE	Up to 1969	--			
ECE 15/00-01	1970-1978				
ECE 15/02	1979-1980				
ECE 15/03	1981-1985				
ECE 15/04	1986-1991				
Conventional vehicles*	--	Upto 1993	Upto 1994	Upto 1993	Upto 1999
Euro-I	1992-1996	1994-1997	1995-1997	1994-1996	2000-2003
Euro-II	1997-2001	1998-2001	1998-2001	1997-2001	2004-2006
Euro-III	2002-2005	2002-2005	2002-2005	2002-2006	2007-to date
Euro-IV	2006-2010	2006-2010	2006-2010	2007-2009	--
Euro-V	2011-todate	2011-todate	todate	2010-to date	--

\*Before introduction of emission standards

For engine size it was assumed that 5% is the total passenger cars are of engine size <1.4 L. Rest are equally divided between 1.4-2 L and >2.0 L. Petrol and gas, petrol and electric, and petrol and ethanol powered vehicles were included in the petrol category. Small public service vehicles were included in the passenger car category for the distribution.

Brady and O'Mahony (2011) used COPERT 4 in their research to calculate emission from passenger cars for home to work trips and assumed average speeds for Rural, urban, highway as 40kmph, 60kmph, and 100kmph respectively. The driving share were assumed to be 9% (rural), 14% (urban), and 76% (highway). Table 11 summarizes the importance of input parameters in COPERT 4 in calculating emission along with availability and issues with them.

**Table 11: Importance and availability of statistics of different parameters (Fameli and Assimakopoulos, 2012)**

Parameter	Importance	Notes/Particular Issues with availability
Number of vehicles per class	High	Question is the scooter and mopeds registration availability
Distinction of vehicle to fuel used	High	Question is the availability of records for vehicles retrofitted for alternative fuel use
Distribution of cars/motorcycles to engine classes	Medium*	Not important for conventional pollutants, more important for CO2 emission estimates
Distribution of heavy duty vehicles to weight classes	High	Vehicle size important both for conventional pollutant and CO2 emissions
Distinction of vehicles to technology level	High	Imported, second-hand cars and scrappage rates are an issue
Annual mileage driven	High	Can be estimated from fuel consumption. The effect of mileage with age requires attention.
Urban driving speed	Medium**	Affects the emission factors
Rural, highway driving speeds	Less	Little affect the emission factors, with their expected range of variation
Mileage share in different driving modes	Less	Little affect emissions, within their expected range of variation

\*as emission is not a direct function of engine size

\*\*speed fluctuation is there and thus contribution to emission

#### 2.4.5 Expected Results:

COPERT 4 estimates emissions of all major air pollutants (CO, NOx, Volatile Organic Carbon (VOC), PM, Ammonia (NH3), SO2, heavy metals) produced by different vehicle categories (passenger cars, light commercial vehicles, heavy duty trucks, busses, motorcycles, and mopeds) as well as greenhouse gas emissions (CO2, Nitrous Oxide (N2O), Methane (CH4)). It also provides speciation for NO/NO2, elemental carbon (EC) and organic matter (OM) of PM and non-methane VOCs, including PAHs and POPs. The output i.e. transportation emissions are obtained in tonnes.

#### **2.4.6 Additions in COPERT 5 (EMISIA, 2015):**

- Includes additional Euro classes e.g. Euro7, Euro8.
- Includes alternative vehicle options like, electric, plug-in hybrids.
- Includes alternative fuel options (Blends, H2 etc.)

Though COPERT 5 seems to be most suitable for the research question, it is not available for use yet. After detailed review of available emission models COPERT 4 deemed to suit best for the research.

#### **2.5 Validation of COPERT**

There are many methods for validating environmental models, such as, Laboratory validation, On board validation, Tunnel validation, Remote Sensing validation, Ambient Concentration Measurements and Ambient Mass Balance Method (Smit et al., 2010). Every method has its pros and cons. However, very few studies have been carried out so far to validate COPERT. As mentioned previously, Borge et al. (2012) has used COPERT and HBEFA to calculate NO<sub>x</sub> emission and compared values with observed values from the air quality monitoring network. The author reported that the emission values from COPERT gives more realistic results. According to Funk et al. (2001) and Mellios et al. (2006), a method to validate road traffic urban emission inventories is to perform a comparison between emission estimates and ambient air quality data by using CO/NO<sub>x</sub> ratio. As reported previously, Ong et al. (2011), Pouliot et al. (2012), Brady and O'Mahony (2011) has also used COPERT for their research.

Broderick et al. (2007) measured emission by dispersion modelling and concluded that COPERT III shows good agreement with the composite emission factors but has a tendency to underestimate the evaporative emissions. The evaluation of COPERT III was done by Ekstrom et al. (2004) with the data collected using remote sensing method. The dataset contained emission measurements of CO, Nitric Oxide (NO), HC for gasoline passenger cars and diesel passenger cars and heavy duty vehicles. For gasoline passenger cars the model showed good agreement for NO<sub>x</sub> emission but overpredicted the CO emission and HC prediction was reasonably good. For diesel passenger cars there was also a relatively good agreement for NO<sub>x</sub> emission factors but for heavy-duty vehicles NO<sub>x</sub> emission factors were lower than those from the remote sensing measurements.

López et al. (2011) conducted tests on buses using Horiba OBS 2200 on board emission measurement system. The buses were then driven through two predefined roads in Madrid. It was observed that emission values calculated from COPERT 4 were systematically lower than those from experimental tests, especially for CO, HC and NO<sub>x</sub>. Achour et al. (2011) used a portable Gas Analyzer to calculate real emission and the measured data were compared with the emission obtained from COPERT 4. It was found that COPERT 4 overestimated the CO emissions while it underestimated the NO emissions. Berkowicz et al. (2006) evaluated COPERT for Danish condition. Street level concentrations of NO<sub>x</sub> and CO are calculated using Operational Street Pollution Model (OSPM) as the dispersion model and the results were compared with emission data estimated by the COPERT methodology. It was reported that there is significant underestimation of pollution concentration (especially for NO<sub>x</sub> and CO) calculated by COPERT.

Kousoulidou et al. (2010) has validated COPERT with real world data with the help of Portable Emissions Measurement Systems (PEMS). PEMS are very useful and valuable tools for validating emission factors. In order to validate COPERT, a Euro 5 diesel passenger car (equipped with a particulate filter) was fitted with a Portable Emission Measurement System. The vehicle was then driven over three predefined routes designed to incorporate a variety of driving conditions. The concentration of the tailpipe emission were measured on a second-by-second basis. Engine speed, torque and other data readings of the test vehicle were also recorded from the ECU (Engine Control Unit). GPS position and vehicle-mounted weather station data were also recorded. The results were compared to the emission factors provided by the COPERT emission model for validation purpose. Emissions of CO<sub>2</sub>, HC and CO correlated well with COPERT values but NO<sub>x</sub> emission levels were

consistently higher than the COPERT emission factors. The following figure shows the instrumental setup used for validating COPERT.



(a) Semtech-DS mobile emission analyser (manufactured by Sensors, Inc.)



(b) Stock Fiat Bravo 1.6 JTD (DPF Diesel) 88 kW  
300 N·m @ 1500 rpm , 300 N·m @ 1500 rpm

**Figure 21: Instrumental set up** (Kousoulidou et al., 2010)

This type of study is beyond the scope of our research and if those kind of data is provided, the validation of COPERT 4 can be done. COPERT 4 was originally planned to be validated using air quality model for Ireland. However, due to lack of availability of this model the validation exercise cannot be performed appropriately. As COPERT 4 is applicable for Irish conditions (EMISIA, 2014), COPERT 4 is chosen as the preferred vehicle emission model.

Moreover, from the available literature on use of COPERT 4 for European countries and also from the validation studies conducted so far, it is quite visible that COPERT 4 is the most relevant available emission modelling tool for this study. Even though various researchers have reported that COPERT 4 underestimates or overestimates some major pollutants, there is not enough information given on the input information provided to calculate emissions from COEPRT in those evaluation studies. Alam et al. (2015) compared the emissions estimated from COPERT 4 with aggregated and disaggregated vehicle mileage data and significant differences were found in the emission values between the two cases. Thus, it is also very important to use the input parameters as accurately as possible in order to have promising results.

### 3.1 Discussion and Conclusion:

This deliverable has provided an executive review and critical analysis of the current transportation and emissions models that are available to Ireland which are of particular interest to the research aims of the Greening Transport project.

From the literature review the following points can be concluded:

The NTA model has been reviewed as being the most suitable transportation model currently available in Ireland for the following reasons:

- It's adaptability and functionality meet the aims of the project,
- It provides the most extensive bank of data in the country that deals with all transport modes including cycling and walking
- It acknowledges travel behaviour as a significant determinant of modal shifts
- As it focuses on the GDA it provides a significant level detail to assess travel in a region that is essential to economic performance nationally and internationally

COPERT 4 has been found suitable for our research for the following reasons,

- It calculates emission of all (important) pollutants from road transport.
- It covers all (major) vehicle classes.
- It can be applied in all EU member countries (European Environment Agency (EEA); EMISIA, 2014).
- COPERT 4 can be used to calculate transportation emission from 1970 to 2030 (Kouridis et al., 2014).
- It provides a user-friendly graphical user interface to introduce, view and export data (Kouridis et al., 2014).

These models present the foundation of the research that will be conducted in the following deliverables in examining; the benefits of increased walking, cycling and public transport as well as sustainable usage of the private car (WP3), emission reductions as a result of changes in the private car fleet and public transport bus fleet (WP4) and finally in the examination of bio fuel and electrification growth scenarios and alternative vehicle tax scenarios (WP5).

### **3.2 The Transport Emissions Model**

The Transport Emission Model is displayed below in Figure 22 and 23 comprises of a Current Scenario and Projected Scenario. The Current Scenario acts as a 'business as usual' situation that feeds fleet and passenger car mileage data into COPERT 4 which is then used to generate emissions calculations associated with current fleet statistics. The Projected Scenario will be used to forecast emissions levels to 2020 and 2030 in line EU targets. Outputs from the chosen transportation model, the NTA model, will be fed into COPERT to generate emissions predictions into the future based on specific modal shifts taking place and possible varying levels of car ownership. The ISus Car Stock Model will similarly be used to derive assumptions about the future composition of the private car fleet, as well as aiding the consideration of fiscal changes to promote sustainable car use and how such changes could possibly impact on car ownership/ usership which may potentially result in emissions reductions.

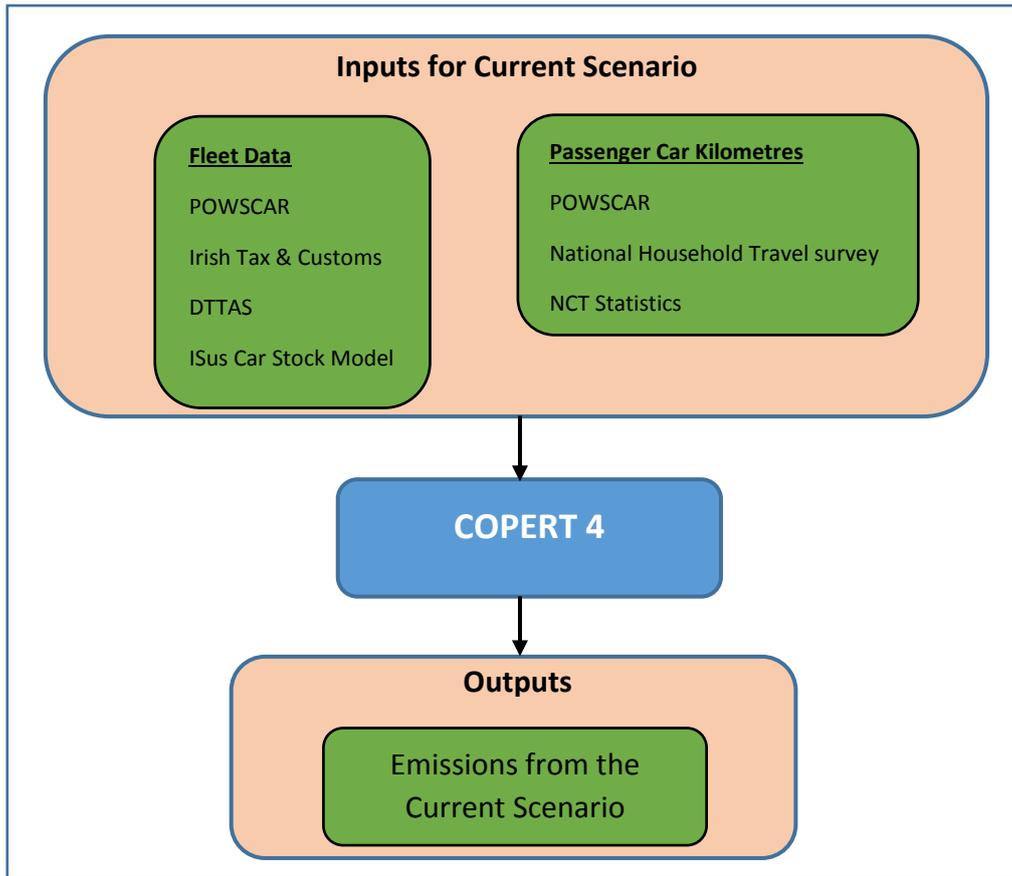


Figure 22: Current Scenario

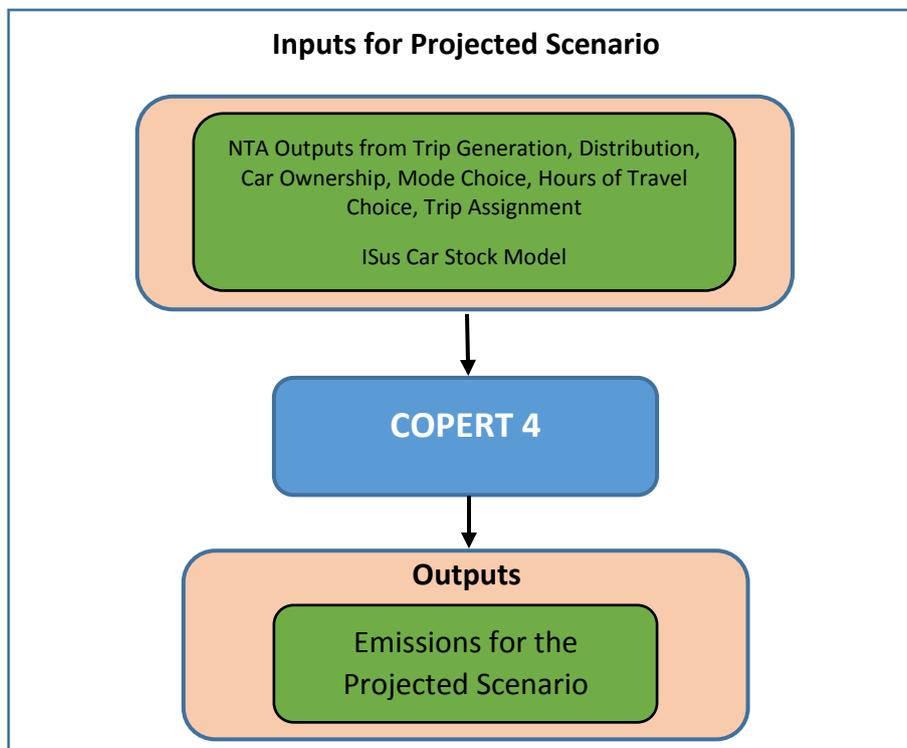


Figure 23: Projected Scenario

### **WP3: Examining Smarter Travel Options to Reduce Emissions (October, 2016)**

- An examination of the benefits of increased usage of active travel modes such as walking, cycling and an outright reduction in ownership or usership of privately-owned cars will be conducted in order to provide guidance on feasible steps that can be taken to achieve a modal shift, especially with regards work trips under 15 minutes. These trips account for over 50% of all work trips in Ireland (CSO, 2012). Viable actions that can be made to reward cyclists, pedestrians and public transport users are: walkability analyses and plans to expand and declutter footpaths, priority routes and schemes for traffic management of public transport especially at junctions, greater segregation of cyclists from mainstream traffic and safe cycling infrastructure (bicycle parking, early starts at traffic lights and safe road surfaces). Impediments to car usage such as: greater pedestrianisation of streets, congestion charging, creation of more park and ride facilities and movement car parks away from city centre areas, can similarly be put in place to deter people from driving to and from work in order to ease congestion and ultimately result in a reduction in emissions. The influence of these measures will be analysed in the context of ultimately reducing emissions due to increasing numbers of commuters opting to walk, cycle or take public transport to work.
- Aside from public transport and active travel, smart alternatives to ownership (i.e. car sharing, carpooling, bike sharing, on-demand taxi services (Hailo, Uber) and telecommuting) provide cost and time efficient benefits that can be a real substitute to car usage, these will be also studied to build a case for a reduction in the car dependency in the Greater Dublin Area (GDA). These innovations in the transportation sector are being driven by a recognition that cars are becoming victims of their own success, in terms of their effect on the environment. Ways to accelerate these smart options will be looked at to support their modal share.

### **WP4: Examining emissions reductions from changes in the Private Car Fleet and Public Transport Bus Fleet (November, 2016)**

- Possible changes in the private car fleet and public transport bus fleet that potentially lead to emissions reductions will be estimated using COPERT 4. Different electric vehicle market penetration scenarios for a range of electric vehicle options (EVs, plug-in hybrids (PHEV) and hybrids (HEV)) will also be examined, owing to the Irish target of 10% of all passenger vehicles being electric by 2020. The ESRI ISus private car stock model (Hennessy and Tol, 2011) will be used to derive assumptions about the future composition of the private car fleet.
- The decarbonisation of bus transport will similarly be explored using COPERT to estimate the emissions from bio-fuel Euro VI compliant buses for varying percentages of the bus fleet. Emissions scenarios will then be extrapolated to 2020 and 2030 using time series modelling. Backcasting approaches (Banister and Hickman, 2013) will be employed to recommend a range of interventions in terms of road transport emissions regulations be ensure Ireland complies with 2020 and 2030 EU targets.

### **WP5: Measuring the impacts of fiscal changes on promoting sustainable car use (July, 2017)**

- Bio fuel and electrification growth scenarios and alternative vehicle tax scenarios will be conducted using the ISus model to consider how these measures could impact on car ownership/ usership decision making which may potentially result in emissions reductions. These scenarios will be modelled up to 2030 in line with EU targets.

The growth scenarios will look at how alternative pricing frameworks based on usage of renewable fuels will influence purchase trends of sustainable vehicles up to 2030 and the effects of such developments on emissions targets. The alternative tax scenarios will study the effects of road user

charging/ congestion charging, tax relief, grants and subsidies and other possible fiscal measures on potential reductions in emissions. Equitability of such actions will be considered so that those living in areas of poor public transport accessibility will not be unfairly penalised.

By merging the technical evaluation of emissions from transport with necessary behavioural change analyses the Transportation Emissions Model aims to achieve what past attempts to measure emissions reductions have failed to do. The model is designed to provide the EPA with concrete emissions forecasts which take account of specific action being taken to induce shifts in the private car and public transportation fleets, in the uptake of renewable fuels and fiscal change scenarios, as well as there being an emphasis being placed on addressing travel behaviour change.

With the assistance of the NTA and ESRI, the project team are confident that by merging transportation and emission modelling techniques to produce emissions projections, we can offer valuable guidance to policy makers and stakeholders in relation to tackling emissions levels from transport in Ireland.

## References

- Achour, H., Olabi, A., G., Carton, J., G., (2011) 'Estimating Vehicle Emissions from Road Transport, Case study: Dublin City', *Applied Energy*, Vol. 88, pp1957-1964.
- AECOM, Roughan & O'Donovan, Goodbody Economic Consultants (2012) '*National Transport Model: Variable Demand Model – Model Documentation*'. Dublin: AECOM, Roughan & O'Donovan, Goodbody Economic Consultants.
- Ahn, K., Rakha, H., Trani, A., & Aerde, M., V. (2002) 'Estimating Vehicle Fuel Consumption and Emissions Based on Instantaneous Speed and Acceleration Levels', *Journal of Transportation Engineering*, Vol 128, pp182-190.
- André, M., Keller, M., Sjodin, A., Gadrat, M., & Mc C, I. (2009) 'The artemis european tools for estimating the transport pollutant emissions', [EPA] *Proceedings of the 18th International Emission Inventories Conference*, pp1-10.
- Alam, Md., S., Duffy, P., Hyde, B., & McNabola, A. (2015) '*Restructuring, estimation and back extrapolation of road transport activity data for emissions estimation: 1987-2013*', Environmental Protection Agency.
- Banister, D., Hickman, R. (2013) 'Transport Futures: Thinking the Unthinkable', *Transport Policy*, Vol. 29, pp283-293.
- Bergin, A., Conefrey, T., FitzGerald, J., Kearney, I., Znyderl, N. (2013) '*The HERMES-13 macroeconomic model of the Irish economy – ESRI Working Paper Number 460*'. Dublin: Economic and Social Research Institute.
- Berkowicz, R., Winther, M., M. Ketzel, (2006) '*Traffic pollution modelling and emission data*', Environmental Modelling & Software, Vol. 21, pp454-460.
- Borge, R., Miguel, I., D., Paz, D., D., L., Lumbreras, J., Pérez, J., & Rodríguez, E. (2012) '*Comparison of road traffic emission models in Madrid (Spain)*', Atmospheric Environment, Vol. 62, pp461-471.
- Brady, J., and O'Mahony, M. (2011) '*Travel to work in Dublin. The potential impacts of electric vehicles on climate change and urban air quality*', Transportation Research Part D, Vol. 16, pp188-193.
- Broderick, B., M., O'Donoghue, R., T., (2007) '*Spatial variation of roadside C2–C6 hydrocarbon concentrations during low wind speeds: Validation of CALINE4 and COPERT III modelling*', Transportation Research Part D, Vol. 12, pp537–547.
- Caulfield, B. (2009) '*Estimating the environmental benefits of ride-sharing: a case study of Dublin*', *Transportation Research Part D: Transport and Environment*, Vol. 14, pp. 527 – 531.
- Convery, S., Williams, B (2013) Applications of the MOLAND model in the GDA [PowerPoint Presentation], Available at: [https://www.ucd.ie/t4cms/MOLAND\\_Application\\_for\\_GDR.pdf](https://www.ucd.ie/t4cms/MOLAND_Application_for_GDR.pdf), [Accessed on: 11/01/2016].
- CSO (2012) '*National Travel Survey, 2012*'. Dublin: Central Statistics Office.
- Curtis, J. (2012) '*Environment Review 2012 – ESRI Research Series Number 26*'. Dublin: Economic and Social Research Institute.
- Department of Finance (2014) '*Quantification of the Economic Impacts of Selected Structural Reforms in Ireland – Irish Government Economic and Evaluation Service: Working Paper*'. Dublin: Department of Finance.

Department of Transport, Tourism and Sport (2016) *'Common Appraisal Framework for Transport Projects and Programmes'*. Dublin: DTTaS.

Department of transport, tourism & Sport (2015) *'Irish Bulletin of Vehicle and Driver Statistics'*. Dublin: DTTaS.

Devitt, C., Hennessy, H., Lyons, S., Murphy, L., Tol, S., J., R. (2010) *'The Energy and Environment Review 2010 – ESRI Research Series Number 19'*. Dublin: Economic and Social Research Institute.

Doorley, R., Pakrashi, V., & Ghosh, B. (2015) 'Quantification of the Potential Health and Environmental Impacts of Active Travel in Dublin, Ireland'. *Transportation Research Record: Journal of the Transportation Research Board*, (2531), pp129-136.

DTO, Steer Davies Gleave (2009) *'DTO Model Calibration: Highway and PT Assignment Model, Calibration and Validation Report'*. London: Steer Davies Gleave.

EEA (European Environment Agency), COPERT 4, Available at: <http://www.eea.europa.eu/data-and-maps/data/external/copert-4>, [Accessed on: 18/04/16].

Elkafoury, A., Negm, A., M., Bady, M., & Aly, M., H., (2014) *'Review of transport emission modeling and monitoring in urban areas – Challenge for developing countries'*, International Conference on Advanced Logistics and Transport.

Ekstrom, M., Sjo din, A., Andreasson, K., (2004) 'Evaluation of the COPERT III emission model with on-road optical remote sensing measurements', *Atmospheric Environment*, Vol.38, pp 6631 6641.

EMISIA (2014), COPERT Countries data, [Emisia Website]. Available at: <http://emisiam.com/products/copert-data>, [Accessed on: 20/04/16].

EMISIA (2014) *'The Popular, straightforward and simple to use emissions calculator'* [Emisia Website]. Available at: <http://emisiam.com/products/copert-4>, [Accessed on: 18/04/16].

EMISIA, (2015) *'COPERT 5: status and new features'* [Presentation]. Available at: <http://www.tfeip-secretariat.org/assets/Transport/Expert-Meetings/TFEIP-Meeting-of-Transport-Expert-Panel-2015-11-May-Milan/6COPERT5.pdf>, [Accessed on 18/04/2016].

ERMES (2013) *'Overview of the European Research Group on Mobile Emission Sources'*, [Ermes Group Website] Available at:

[http://ermes-group.eu/web/system/files/filedepot/11/ERMES\\_presentation\\_Dec2013.pdf](http://ermes-group.eu/web/system/files/filedepot/11/ERMES_presentation_Dec2013.pdf) [Accessed on: 18/04/16].

ERMES (2016) *'European Research on Mobile Emission Sources'*, [Ermes Group Website]. Available at: [http://www.ermes-group.eu/web/leading\\_EU\\_models](http://www.ermes-group.eu/web/leading_EU_models), [Accessed on: 18/04/16].

Farrell, S., McNamara, D. and Caulfield, B. (2010) 'Estimating the Potential Success of Sustainable Transport Measures for a Small Town', *Transportation Research Record: Journal of the Transportation Research Board*, 2163, pp97 – 102.

Farrell, E. (2013) *'An Introduction to the Use of Transport Modelling by the NTA, and a Framework for Modelling Nationally'*, NTA: Dublin, [PowerPoint Presentation]. Available at: [https://www.ucd.ie/t4cms/Farrel\\_National\\_Transport\\_Model.pdf](https://www.ucd.ie/t4cms/Farrel_National_Transport_Model.pdf), [Accessed on: 29/01/2016].

Fameli, K., M., & Assimakopoulos, V., D. (2015) *'Development of a road transport emission inventory for Greece and the Greater Athens Area: Effects of important parameters'*, *Science of the Total Environment* 505, pp770–786.

Franco, V., Dilara, P., Kousoulidou, M., Ntziachristos, L., Gkeivanidis, S., Samaras, Z. (2010) *'Validation of the COPERT road emission inventory model with real-use data'*, [Presentation]. Available at: [https://www3.epa.gov/ttnchie1/conference/ei19/session6/dilara\\_pres.pdf](https://www3.epa.gov/ttnchie1/conference/ei19/session6/dilara_pres.pdf), [Accessed on: 21/04/16]

- Gkatzoflias, D., Kouridis, C., Ntziachristos, L., & Samaras, Z. (2012) '*COPERT 4, User manual*'. Available at: [http://emisias.com/sites/default/files/COPERT4v9\\_manual.pdf](http://emisias.com/sites/default/files/COPERT4v9_manual.pdf), [Accessed on: 17/04/16]
- Graz University of Technology (2009) '*Emission Factors from the Model PHEM for the HBEFA*'. Graz: Graz University of Technology.
- HBEFA Introduction (2014), [HBEFA Website]. Available at: <http://www.hbefa.net/e/index.html>, [Accessed on: 18/04/16].
- Hennessy, H., Tol, R., S.J. (2011) '*The impact of tax reform on new car purchases in Ireland*', *Energy Policy*, Vol. 39, pp7059-7067.
- Hennessy H., FitzGerald, J. (2011) '*The HERMES Model of the Irish Energy Sector – ESRI Working Paper Number 396*'. Dublin: Economic and Social Research Institute.
- Jonsson, D., Berglund, S., Almstrom, P., Algers, S. (2011) '*The Usefulness of Transport Models in Swedish Planning Practice*', *Transport Reviews*, Vol. 31, Issue 2, pp251-265.
- Kouridis, C., Mellios, G., & Ntziachristos, L. (2014) '*COPERT 4 main elements*'. [PowerPoint Presentation], Available at [http://emisias.com/sites/default/files/COPERT\\_4\\_Statistics.ppt](http://emisias.com/sites/default/files/COPERT_4_Statistics.ppt), [Accessed on 18/04/2016].
- Kousoulidou, M., Ntziachristos, L., Gkeivanidis, S., Samaras, Z., Franco, V., Dilara, P. (2010) '*Validation of the COPERT road emission inventory model with real-use data*', Laboratory of Applied Thermodynamics, Dept. of Mechanical Engineering, Aristotle & Institute for Environment and Sustainability, Transport and Air Quality Unit.
- López, J., M., Flores, N., Lumbreras, J., Villimar, R., (2011) '*Comparison of the emission factors measured in real world driving with those of COPERT 4*', *WIT Transactions on The Built Environment*, Vol 116, pp655-664
- Lundqvist, L., Mattsson, L., G. (eds.) (2001) '*National Transport Models: Recent Development and Prospects*'. Berlin: Springer-Verlag.
- Lyons, S., Tol, S., J., R. (2006) '*Ireland's Sustainable Development Model –EPA STRIVE Report Series Number 47*'. Wexford: Environmental Protection Agency.
- Martin S. (2014) '*The European Handbook of Emission Factor for Road Transport (HBEFA)*', Leipzig: HBEFA.
- Mellios, G., Aalst, R., V., Samaras, Z. (2006) '*Validation of road traffic urban emission inventories by means of concentration data measured at air quality monitoring stations in Europe*', *Atmospheric Environment*, pp7362–77.
- National Atmospheric Emissions Inventory (2014), Available at: <http://naei.defra.gov.uk/>, [Accessed on 20/04/2016].
- NTA (2012) '*Transport Modelling Report – GDA Draft Transport Strategy 2011-2030*'. Dublin: National Transport Authority.
- NRA (2014) '*The National Transport Model Brochure*'. Dublin: National Roads Authority, Transport Infrastructure Ireland.
- NZ Transport Agency (2013), Transport and Air Quality Information, Resources and Tools, Available at: <https://air.nzta.govt.nz/vehicle-emissions-prediction-model>, [Accessed on: 21/04/16].
- NZ Transport Agency (2013) '*Vehicle emissions prediction model (VEPM 5.1) user guide*'. Available at: [https://air.nzta.govt.nz/sites/default/files/NZTA\\_VEPM\\_Guide\\_v1.0\\_FINAL\\_270214.pdf](https://air.nzta.govt.nz/sites/default/files/NZTA_VEPM_Guide_v1.0_FINAL_270214.pdf), [Accessed on: 21/04/16].

O'Doherty, J., Mayor, K., Tol, S., J., R. (2007) *'Irish Sustainable Development Model (ISus) Literature Review, Data Availability and Model Design - ESRI Working Paper No. 186'*. Dublin: Economic and Social Research Institute.

Ong, H., C., Mahlia, T., M., I., & Masjuki, H., H. (2011) *'A review on emissions and mitigation strategies for road transport in Malaysia'*, *Renewable and Sustainable Energy Reviews*, Vol. 15, pp3516–3522.

Petrov, L. O., Shahumyan, H., Williams, B., Convery, S. (2011) *'Scenarios and Indicators Supporting Urban Regional Planning'*, *Procedia – Social and Behavioural Sciences*, Vol. 21, pp243-252.

Pouliot, G., Pierce, T., van der Gon, H., D., Schaap, M., Moran, M., Nopmongcol, U. (2012) *'Comparing emission inventories and model-ready emission datasets between Europe and North America for the AQMEII project'*, *Atmospheric Environment*, Vol. 53, pp4-14.

Sillaparcharn, P. (2005) *'National Transport Modelling – General Approach and Application to Thailand'*, Paper presented at the *Universities Transport Study Group (UTSG) Conference: Bristol 2005*.

Smith, R. (2014) *'Australian Motor Vehicle Emission Inventory for the National Pollutant Inventory (NPI)'*. Queensland: University of Queensland.

Smith, R. (2014) *'Estimation of road transport emission for Australia'*, *26<sup>th</sup> ARRB Conference-Research driving efficiency*, Sydney, New South Wales.

Smit, R., Ntziachristos, L., Paul Boulter, P. (2010) *'Validation of road vehicle and traffic emission models e A review and meta-analysis'*, *Atmospheric Environment*, Vol. 44, pp2943-2953.

Smit, R., Smokers, R., Rabe, E. (2007) *'A new modelling approach for road traffic emissions: VERSIT+'*, *Transportation Research Part D*, Vol. 12, pp414–422.

Smit, R., Ntziachristos, L. (2013) *'COPERT Australia: a new software to estimate vehicle emissions in Australia'*, *Australasian Transport Research Forum*, Brisbane, Australia.

TREMOD (2015) *'Transport Emission Model'* Available at: [https://www.ifeu.org/english/index.php?bereich=ver&seite=projekt\\_tremod](https://www.ifeu.org/english/index.php?bereich=ver&seite=projekt_tremod), [Accessed on: 18/04/16].

UK Department of Transport (2003) *'National Transport Model (NTM): Summary'*. London: Department of Transport.

United Nations Economic Commission for Europe (UNECE) Transport Division (2012) *'Development and implementation of a monitoring and assessment tool for CO2 emissions in inland transport to facilitate climate change mitigation'*. [Accessed on: 15/12/15]. Geneva: UNECE.

United States Environmental Protection Agency (2003) *'User's Guide to MOBILE6.1 and MOBILE6.2 Printed on Recycled Paper Mobile Source Emission Factor Model'*. Washington: US EPA.

U.S. Environmental Protection Agency (2012) *'Using MOVES for Estimating State and Local Inventories of On-Road Greenhouse Gas Emissions and Energy Consumption'*, Transportation and Climate Division Office of Transportation and Air Quality. Washington: US EPA.

USEPA (2016), *Motor Vehicle Emission Simulator (MOVES)*, Available at: <https://www3.epa.gov/otaq/models/moves/>, [Accessed on: 18/04/16].

USEPA (2016), *'MOBILE6 Vehicle Emission Modelling Software'*, Available at: <https://www3.epa.gov/otaq/m6.html>, [Accessed on: 18/04/16].

Wang, H., & McGlinchy, I. (2009) *'Review of vehicle emission modelling and the issues for New Zealand'*, 32<sup>nd</sup> Australasian Transport Research Forum.

Williams, B., Convery, S. (2012) *'Decision Support Tools for Managing the Urban Environment in Ireland. STRIVE Report Number 92'*. Wexford- Environmental Protection Agency.

WSP (2011) *'Irish National Transport Model Feasibility Study'*. Dublin: WSP.