The AOP II Cost-effectiveness Study

Part II: The TREMOVE Model 1.3

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EXECUTIVE SUMMARY

TREMOVE is an innovative integrated simulation model developed for the strategic analysis of costs and effects of a wide range of policy instruments applicable to local, regional and European transport markets. The model has been developed to support the policy assessment process within the framework of the second European Auto-Oil Programme (AOPII). To date, it has been used to produce the AOPII transport base case, finalised in June 1999 and presented in Part III of the AOPII Cost-Effectiveness Study report. A number of test scenarios were run using dummy scenario data and the results are presented in Part IV of the AOPII Cost-Effectiveness Study report.

TREMOVE incorporates components of various models previously developed and used at European scale. It includes parts of the TRENEN model (developed for DGVII), EUCARS (developed by DGII), FOREMOVE (developed for DGXI in the context of AOP-I). It also incorporates the COPERT-II methodology (developed by the EEA and its experts). All components were modified to take account of the recent regulatory and market developments and/or to account for newly available research information (e.g. from the MEET program – a further development of the COPERT methodology by DGVII/EEA). TREMOVE incorporates the so-called EPEFE equations (developed by the EUROPIA and ACEA during AOP-I) to account for changes in the average fuel quality over time. The purpose for developing TREMOVE was therefore not to develop a new emission calculation methodology but rather to implement existing well known methodologies in a strategic policy simulation tool.

TREMOVE is used to compute the effects of various types of policy measures – taken in isolation or as packages – on the key drivers of transport emissions. These key drivers include, among others, the size and composition of the vehicle stock and vehicle usage. The model is used to simulate consumer behaviour with regard to the choice of transport modes and vehicle types (i.e. size and technologies), to assess how these choices are affected by the introduction of policy measures, and to estimate what effect these policy measures will have on emissions. The model takes into account a large number of transport modes, and determines the demand for each mode and emissions from road transport by taking into account the many interactions between the various transport modes. TREMOVE also allows for the analysis of local, regional and European policies.

Simultaneously, TREMOVE is used to compute the difference in costs between alternative transport scenarios, and can decompose these costs by category. The cost components modelled in TREMOVE are the cost to transport users, the costs to transport producers, and the cost to governments.

The output of TREMOVE includes, inter alia, annual forecasts of transport flows, vehicle stock size and composition, costs to society from transportation, and emissions from transport both in the base case and in any variant thereof.
TREMOVE can be used to analyse scenarios with or without the use of optimisation tools. Where optimisation is required, TREMOVE can be used in combination with the LEUVEN II model, which has been developed in parallel. LEUVEN II is an optimisation tool designed to support the second European Auto-Oil Programme. The model is described in a separate part of the report. The TREMOVE and LEUVEN II models can also be used in combination with other models such as the RAINS model.

Finally, the TREMOVE model is still subject to further testing in the context of the AOPII cost-effectiveness study and improvements will be made when needed. Until fully tested, due care is recommended when using the model and the related databases. Indeed, whereas the model structure and its related databases can already be considered a major improvement over existing tools, the information on costs and impacts of policy scenarios should be further improved in order to increase the robustness of conclusions that can be drawn before making policy recommendations. A number of directions for future work are summarised in Annex C.
1. INTRODUCTION

This part of the AOPII Cost-effectiveness Study Report provides a technical description of the TREMOVE model. The model has been developed to support the policy assessment process within the framework of the Second European Auto-Oil Programme (AOPII).

A general description of the overall AOPII cost-effectiveness methodology and the scope of the study can be found in Part I of the AOPII Cost-effectiveness study report. A description of the AOPII transport base case, produced using TREMOVE (version1.3), is provided in Part III of the report. Pending the collection of further scenario input data, dummy data have been used to produce a limited number of preliminary test scenarios. These results are summarised in Part IV of the Report.

TREMOVE is a behavioural model designed to analyse cost-effectiveness of a wide range of technical and non-technical measures aimed at reducing emissions from road transport in particular and improving air quality in general. It can be used to simulate consumer behaviour with regard to the choice of transport modes and vehicle types, to assess how these choices are affected by the introduction of various policy measures, and to assess what effects these choices have on emissions from the vehicle fleet.

It should be stressed that TREMOVE is a simulation model, not a transport-forecasting model. The equations in TREMOVE are specifically designed to analyse changes in behaviour as a result of changes in economic conditions, but incorporate few of the “dynamic” change relationships that would be required in a forecasting model. It also incorporates equations to analyse changes in the environmental performance of the vehicle fleet as a result of changes in the technical features of the future fleet. Interactions are accounted for to the extent that the technical conditions influence the economic conditions and vice-versa.

The model describes annual transport flows, vehicle stocks and vehicle usage, and emissions across three modelling domains for each country considered, i.e., a sample-city, the other urban areas and the non-urban

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1 Reference is also made to the First Consolidated Interim Report to WG7 by Standard & Poor’s DRI and KUL, released in February, 1997.

2 A forecasting model for transport demand would, for example, have to include a set of equations explicitly linking the demand for freight transport – in tonnes and in tonne-kilometre, to indicators of economic activity, preferably by sector. It would also have to model new car sales based on income developments, taking into account substitution between vehicle purchases and other durable or non-durable goods categories, or savings, and trends in unemployment and consumer confidence in general. Price trends would have to be modelled by specifying the relationship between fuel prices and crude oil prices, and link overall trends in inflation to labour market developments or expected exchange rate trends. All these “trend relationships” were implicitly used to construct the base case, by taking consistent sets of data from other model forecasts. However, for simulation purposes, the focus here was not on the link between economic activity and transport, but on a good understanding of modal choice and changes within the transport sector, in particular as a result of policy changes.
areas. Currently nine countries and ten so-called AOPII-cities are covered: Finland (Helsinki), France (Lyons), Germany (Berlin and Cologne), Greece (Athens), Ireland (Dublin), Italy (Milan), the Netherlands (Utrecht), Spain (Madrid) and the United Kingdom (London). The time horizon ranges from 1990 through 2020 with annual intervals. Unless otherwise indicated, the base case data include historical data over the period 1990-96 and forecast data for the period 1997-2020.

The transport flows covered by TREMOVE include those for on-road passenger and freight transport, rail (both metro and train) passenger and freight transport, and in-land waterway freight transport. Vehicle stocks and usage are specified for a wide range of passenger and freight vehicles, including motorcycles. The main pollutants covered are CO, NO\(_X\), VOC (broken down into methane and non-methane VOCs), benzene, and PM\(_{10}\). In addition, other emissions can be calculated such as CO\(_2\) and SO\(_2\). TREMOVE computes the effects of various types of individual or combined transport policy measures on the key drivers of transport emissions, i.e. the size and composition of the vehicle stock and vehicle usage. The transport policy measures that can be analysed include emission abatement technologies for vehicles, fuel quality and alternative fuels specifications, inspection and maintenance, non-technical and fiscal measures.

TREMOVE also computes the difference in costs between these alternative transport policy scenarios, and can decompose these costs by category. The cost modelled in TREMOVE is the total cost to society, including the cost to transport users, the costs to transport producers, and the cost to governments.

The description here refers to TREMOVE Version 1.3. This version includes a number of enhancements to previous versions released and discussed within AOPII WG7. These enhancements respond to comments and requests expressed by the members of WG7. They include, among other changes, new functions for the choice of cars by type and fuel, revised scrapping functions for vehicles, the introduction of different load factors for different truck categories, the introduction of a parameter to account for infrastructure enhancements in the congestion function, and important enhancements to the emission calculation block. TREMOVE 1.3 has been used to produce the fourth of the Auto-Oil II base case, finalised in June 1999 and described in Part III of the AOPII Cost-Effectiveness Study Report.

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3 Results for the other EU countries are extrapolated using a simple methodology described in Part III of the AOPII Cost-effectiveness study report.

4 While transport flows for rail and in-land waterways are included, the calculation of emissions from these modes has not yet been included due to data and resource constraints. Air transport is not covered in the present version. Emissions from sources other than those described in this paragraph but still part of the AOP II scope are calculated outside the TREMOVE model. The LEUVEN II model covers all sources, as input into LEUVEN II comes from TREMOVE and other exercises.
Finally, TREMOVE can be used to analyse scenarios with or without the use of optimisation tools. Where optimisation is required, TREMOVE can be used in combination with the LEUVEN II model, which has been developed in parallel. LEUVEN II is an optimisation tool designed to support the second European Auto-Oil Programme. This model is described in a separate Part of the AOPII Cost-effectiveness Study report. The TREMOVE and LEUVEN II models can also be used in combination with other models such as the RAINS model.
2. OVERVIEW

This Chapter provides an overview of the TREMOVE model and its database structure. The overall methodology and model structure is introduced in Section 1. Section 2 provides a brief overview of the data structure and calibration.

A more detailed account of the methodology and structure adopted for the respective modules is provided in the next chapters and related annexes.

2.1. Methodology and model structure

One of the principles adopted for designing the AOPII models that were to support the cost-effectiveness analysis was that they should improve on the tools used in the first AOP, while maintaining a reasonable level of continuity and comparability. Therefore, in many ways, the TREMOVE model can be seen as consisting of three key, inter-linked modules adapted from existing models. A simplified illustration of the TREMOVE modules is provided in Figure 1.

The first module (“TRE”) is adapted from the TRENEN model.\(^5\) It describes a wide range of transport flows and the users’ decision making

process when it comes to making their modal choice. Starting from an initial level of demand for passenger and freight transport (taken from various existing sources), the module describes how the implementation of a policy measure will affect the current allocation of demand across different modes and different vehicle categories. The key assumption here is that the transport users will select their preferred mode based on the relative travelling cost for each mode. For each mode, transport demand is determined by generalised prices, income levels and given consumer preferences. Many transport modes or markets are considered. For passenger transport, these range from non-motorised and motorcycle transport to small and large gasoline or diesel cars, whether transporting only the driver or pooled driving. For freight, transport modes are defined by the vehicle size and the fuel used (gasoline, diesel). Also, a distinction is made between daily peak and off-peak periods.

The total demand for freight transport (in tonnes to be transported) is set by the trend in economic development in the country considered. Changes in user costs for freight transport will lead to changes in load factors of trucks, or shift across truck categories (for instance to larger or smaller-size trucks), or to other transport modes (e.g. rail or waterways in non-urban areas), and ultimately to a reduction in the quantity of freight transport use through a reorganisation of production operations. For passenger transport, there can also be an overall reduction in passenger-kilometres as some measures might discourage people from travelling.

The methodology and model structure related to this module is further explained in Chapters 3 though 6. Chapter 3 describes the modelling of transport demand; Chapter 4 covers the supply of transport services; Chapter 5 describes the transport equilibrium module; Chapter 6 explains the cost concepts used in TREMOVE and the computation of the cost to society due to the introduction of alternative policy scenarios.

The second module shown in Figure 1 (“MOVE”), is adapted from the FOREMOVE and EUCARS models. This vehicle stock and usage module describes how changes in demand for transport across modes or changes in price structure influence the number and types of vehicles in the stock. For each vehicle category, the stock of vehicles in any given year is defined as the stock in the previous year plus new acquisitions of vehicles in the year, minus scrapping (i.e., using a capital-vintage approach). Both new car sales and scrapping are explained by behavioural functions that depend, among other things, on the policy environment and will vary if there is a change in

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6 Zissis Samaras & Theodoros Zachariadis, Foremove emission forecasts for the auto-oil programme --Basic texts, LAT, Aristotle University of Thessaloniki, May 1996.
7 The EUCARS model was developed by EC-DG II. The model has been used for the Auto-Oil I exercise and was subsequently modified. For a description see C. Denis & G.J. Koopman, EUCARS: A partial equilibrium model of European CAR emissions, European Commission Directorate-General for Economic and Financial Affairs, Economic Papers N° 130, November 1998.
the policy – for example increased fuel taxes. The methodology and model structure related to this module is further explained in Chapter 7.

The third module (also referred to as “MOVE”) is also adapted from on the FOREMOVE methodology and includes the COPERT II methodology. This module is used to calculate fuel consumption and emissions, based on the structure of the vehicle stock and the number of kilometres driven by each type of vehicle (i.e. usage). The main pollutants covered are CO, NOX, VOC (broken down into methane and non-methane VOCs), benzene, and PM10. In addition, other emissions can be calculated such as CO2 and SO2 to facilitate the link with related EU exercises. The methodology and model structure related to this module is further explained in Chapter 8.

Interactions between the respective modules are accounted for, acknowledging that transport users base their modal choice of transport on the relative cost of using each mode, taking into account such factors as the user cost of the mode, the travel time and related cost, and other factors explained in more details later. For example, when a policy measure is introduced, such as a fuel tax or a tightening of a speed limit, transport users will adjust their behaviour, some reducing their demand for transport and some switching to a different mode. Based on the total demand for “kilometres” on each mode, the model calculates what the implications will be for the next vehicle stock vintage and the average usage of the vehicles.

Because of the need to account for these important interactions, it should be noted that the three modules in TREMOVE cannot be run separately, as inputs and outputs from both parts are required at all times. Therefore, the structure of the TREMOVE model shown in Figure 2 is more accurate, although slightly more complex. This structure of shown in Figure 2 holds for every year and region considered. Every year from 1990 until 2020 is linked to the previous year via the stock of transport means and the available infrastructure.

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9 The COPERT methodology has been chosen because it has been developed to serve as a European standard for calculating emission inventories (and therefore assumed to be well known). In a number of cases, modifications to the COPERT methodology were required (building further on the methodologies used in the FOREMOVE model), to take account of changes in average fuel qualities (using the so called EPEFE equations) and of anticipated improvements in emission performance of near future vehicles, of which legislative requirements are part of the “base case”, etc. The purpose of TREMOVE is therefore not to develop an additional emission calculation methodology but rather to implement an existing methodology in a policy simulation tool.

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For each country analysed, a distinct model has been built which describes transport flows and emissions in three regions or domains, i.e. a sample city, the other urban areas (considered as a whole) and the non-urban areas (also as a whole). Currently nine countries are covered, i.e. Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Spain and the United Kingdom.\(^\text{10}\) The cities currently modelled in TREMOVE are the ten so-called AOPII-cities, i.e. Athens, Berlin, Cologne, Dublin, Helsinki, Utrecht, London, Lyon, Madrid and Milan. The modelling domains are illustrated in Figure 3.

\(^{10}\) Results for the other EU countries are extrapolated using a simple methodology described in Part III of the AOPII Cost-effectiveness study report.
Because each country is specified separately (in fact there are currently 9 TREMOVE models), there are no explicit links between countries, meaning that the policy measures cannot induce a displacement of transport demand from one country to another. The models do, however, take into account international trade and transport, and changes therein, in the base case. For each international trip, the model records the kilometres driven by region in all the regions travelled. Thus, in the case of a journey from Amsterdam to Frankfurt, the kilometres driven in the Netherlands are included in the Netherlands figures, and the kilometres driven in Germany are included in the German data.

Also, within each country, the three domains are modelled separately, so that there are no explicit links between them. This means that, faced with a change in the cost of transport in the city for example, the user will adjust his or her behaviour within the city (reducing his mileage or shifting to another transport mode) but will not exit the city to move into a rural area or another city. Natural migration patterns between cities or between cities and rural areas, are taken into account in the base case. However, these patterns are assumed to be constant and not influenced by the policy measures to be tested.

Within each country domain or regional module, passenger and freight transport is analysed simultaneously. Both use the same road network, and influence each other through congestion. For example, increased road congestion due to heavier truck traffic will influence passenger transport flows, causing some road transport users to shift to another mode, such as trams & metros.

Within the domains of the AOPII-city and the other urban areas, the transport users are divided into 2 groups (i.e., inhabitants and commuters) because they may have different preferences and use the transport modes in different ways. For the non-urban areas that distinction is less relevant and only one consumer group is considered. Within each consumer group, all consumers are assumed to behave in a homogeneous way (i.e., they are assumed to have the same preferences). A demand function can therefore be constructed to describe the demand of a representative consumer for a given transport market, where a transport market corresponds to the use of a given transport mode at a particular point in time (e.g. the use of a small car in the peak period in the city). The transport sector is represented within each modelled region by a set of interrelated transport markets. Demand and supply in each transport market are balanced by the generalised price of transport.

2.2. Data base structure and model calibration

As for all economic models, TREMOVE includes two sets of variables: exogenous variables, which are determined outside the model (they are the

\[11\] Due to lack of data at the desired level of analysis, however, no distinction is made between different purposes of trips (e.g. business, commuting, and leisure).
assumptions) and endogenous variables, determined within the model. This is illustrated in Figure 4.

**Figure 4: Typical Structure of a Model Database**

Exogenous variables are of two types: those which are fixed or predetermined, such as the macroeconomic variables (real GDP, inflation, population, discount rate), and those which can be influenced by policy instruments, i.e. that can be adjusted for the purpose of policy analysis. The latter include vehicle costs (which can be adjusted to reflect price changes due the introduction of new technologies), fuel prices, tax rates, etc. Other parameters that can be modified in scenario analysis include those reflecting infrastructure levels, or the emission performance of vehicle technologies.

Endogenous variables are all the variables computed within the model, making use of pre-specified functions. The vehicle stock, for example, is calculated as the vehicle stock in the previous year minus the scrapping, plus new vehicle sales. Sales and scrapping are also both computed within the model.

Parameters are the coefficients of the behavioural functions (e.g. elasticities of substitution). They do not change over time. They are also not changed in scenario analyses, though sensitivity tests can be undertaken by modifying the coefficients slightly to check the stability of the solution.

Much of the underlying base case data comes from official statistical sources, with gaps filled in by DRI/KUL based on professional judgement on an ad hoc basis. This includes, among other, total traffic (expressed in pkm and tkm) on roads in the base case, as well as the historical vehicle stocks, fuel prices, insurance and vehicle registration costs, and pkm and tkm by mode, for most modes. Where gaps existed in the data, these were filled based on partial information for the country or region considered, or based on data from similar countries or regions, with necessary adjustments made.

Given a pre-determined data set for most endogenous variables in TREMOVE, a first step before undertaking simulation analysis (including the simulation of the base case or reference scenario) is to “calibrate” the model in such way that, in the base case, it exactly reproduces the pre-determined data set. This calibration exercise thus consists in defining the value of a few parameters in TREMOVE that will ensure that the “solution”
calculated by the model for the base case exactly reproduces the data set that has been developed for the base case. The parameters defined in the calibration process are “level” parameters, not behavioural ones. Behavioural parameters, such as the elasticity of substitution between various modes or the value of time, come from economic literature and are not changed in the calibration exercise.

In TREMOVE, the functions to be calibrated are the congestion functions and the transport demand functions. The substitution between modes as a result of, say, a tax change is given by the model, but the model needs to know whether the substitution starts from a level of for example 100 pkm for large gasoline car and 20 pkm for large diesel cars, or from another level. The demand functions for each transport modes are thus calibrated in order to reproduce the base case data, given the assumptions made with respect to prices, income levels and transport demand. The calibration parameters are computed and incorporated explicitly in the model equations.

The coefficients of the congestion functions, which link speed and traffic flows, were computed from the base case assumptions on speed. The calibrated congestion functions are then also incorporated in the model.
3. MODELLING TRANSPORT DEMAND

This Chapter describes the methodology and TREMOVE structure for modelling transport demand. Section 1 contains a brief introduction. The modelling of transport demand for passenger transport and freight transport is discussed in sections 2 and 3 respectively.

3.1. Introduction

The transport demand module measures the number of passenger-kilometres (pkm) or ton-kilometres (tkm) that will be travelled on each mode, in each region of the country considered, in total over a given year as well as the break-down between peak and non-peak periods.

As for all modelling exercises, the transport module is a schematic representation of reality, which relies on certain assumptions of how people (i.e., economic agents) behave “on average”. Because TREMOVE contains a rather detailed breakdown of passenger and freight transport modes (and vehicle categories), or transport markets, more complex assumptions can be modelled (see Appendix 1 for an illustration of the different transport markets considered in TREMOVE).

The key underlying assumption in the transport demand module is that transport users, i.e. the consumers, will select their preferred mode based on the relative cost of travel on each mode. For each mode, transport demand is determined by generalised prices, income levels, and consumer preference patterns. Starting from a given situation, (based on reported transport behaviour as provided by our sources and contained in the base case), consumers will adjust their current demand for that particular transport mode. They will do so, either by changing their demand level altogether, or by shifting onto a different mode – if the user cost of only one of the modes changes. Substitution across modes will occur if, say, insurance fees are raised for certain types of vehicles, or if fuel price changes, or if speed limits are introduced impacting congestion. A change in user cost for a given mode will change demand for that mode, but also for other modes. Thus, if a technical measure is introduced which significantly reduces the number of trucks on the road (e.g. because it encouraged transport service providers to use bigger trucks), this also has an impact on car usage. Indeed, as congestion decreases, driving speed can increase; hence some people previously discouraged from taking their car might switch back from public transport to private cars.

3.2. Passenger transport demand

3.2.1. General discussion

Travellers are assumed to choose between available alternative transport modes based on their income level, the relative prices of all transportation modes supplied, and their subjective preferences (captured in the elasticities
of substitution). Figure 5 presents an overview of the demand for passenger transport module in TREMOVE.

**Figure 5: Flow chart of demand for passenger transport**

The transport sector is modelled as a set of interrelated markets: the consumer has the possibility to substitute one transport mode for another. Since transport markets are interrelated, consumer behaviour (choice of mode + usage) is determined not only by the price level of the mode considered, but also by the price of all the other transport modes.

These interrelations are captured by using nested utility functions or utility trees. A utility tree has several branches and levels, each representing one option that is an aggregate of (at least) two options at the next lower level of the utility tree. A change in the price of one transport mode does not only affect the demand for that transport mode, but, through the utility tree, the demand for all other transport modes as well (because they are in one way or another substitutes of that transport mode).

At each level of the utility tree, a demand function is specified for each option available at that level. These demand functions are CES functions. The CES function has been chosen because it can be calibrated with a minimum of information (one elasticity of substitution per nest describes the case of substitution between two alternatives).

The use of elasticities of substitution is explained in Annex B. The same appendix describes how elasticities of substitution relate to price elasticities, and presents selected values resulting from the base case model.

The utility trees set up for urban and non-urban transport respectively only differ in some transport possibilities. One of these is that TREMOVE...
considers only one consumer category per mode for non-urban areas, but
distinguishes two types of consumers in urban areas: commuters and
inhabitants. Whereas both types of users are confronted to the same set of
choices (i.e. the utility trees corresponding to the two types are identical),
they are assumed to respond in different ways to factors influencing
incomes, prices and preferences. Their utility function differs. Therefore,
estericities of substitution vary for these two consumer types. The difference
between commuters and inhabitants is much less relevant when analysing
non-urban transport and is therefore not made in the non-urban module.

Figure 6 presents the utility tree for urban passenger transport. It is used as
an example to explain the use of nested CES utility functions.

**Figure 6: Utility Tree for Urban Passenger Transport -- Peak**

The branches of the utility tree in Figure 6 represent the choices the
consumer faces. The options that can be recognised at each level of the
utility tree are called utility components.

Starting from a given level, the consumer can make a choice between (at
least) two components at the next lower level. Each component being an
aggregate of the components at the next lower level, is a CES function of
the components at the next lower level.

At each level of the utility tree in Figure 6, the consumer has to make a
choice between two options. For example, after having chosen between
peak and off-peak travelling, the consumer has to choose between the
motorised vs. the non-motorised transport options. At the next level, the
private and public transport branches are indicated separately, because from
then on, options are not equal anymore, unlike e.g. the options available
when having chosen between peak and off-peak transport. After having chosen peak and off-peak transport, options are still equal; indeed, the structure of branches starting from peak transport is equal to the structure of branches starting from off-peak transport.

At the highest level (i.e. the top level) of the utility tree, there is only one utility component: total utility. This is a linear homogeneous CES function of the components at the next lower level. At the nth level below the top level, each utility component $X_{n,i}$ is a CES function of a disjoint group of components at the next lower level (indicated as level $n+1$). Each component can thus be defined as an aggregate of lower level components, called a quantity index:

$$X_{n,i} = \left[ \sum_{j \in i} \alpha_{n+1,j} X_{n+1,j}^{\rho_{n,i}} \right]^{1/\rho_{n,i}}, \quad \rho_{n,i} = \frac{\sigma_{n,i} - 1}{\sigma_{n}},$$

where $X$ is the index for aggregate transport quantity demanded, the parameter $\sigma_{n,i}$ is the elasticity of substitution at that level of the tree, and the parameter $\alpha_{n+1,j}$ is a distribution parameter $^{12}$ (a share of the components) at the next lower level. The letter $n$ indicates the level of the tree on which the utility component is located. The letter $i$ indicates a lower level component, which is an element of the branch starting from the former component. Usually the letter $i$ indicates a transport mode, being a utility component at the lowest level.

Most utility components at higher levels are thus aggregates of different transport modes, hence can be written in different ways: e.g., the overall utility can be written as $X_{0,1}$ and $X_{0,4}$. The description “$j \in i$” means “over all utility components at level $n+1$ which are an element of the aggregate quantity index $X_{n,i}$”. The quantity index $X_{n,i}$ has as a second index $i$, this means that this quantity index incorporates transport mode $i$ (so, this index could also have been called $X_{n,j}$ if transport mode $j$ is incorporated in the quantity index).

For each utility component, an aggregate quantity index, $X_{n,i}$, and the corresponding aggregate price index $P_{n,i}$, can be computed. It is a property of CES functions that the corresponding prices have similar functional forms. Thus, the price index corresponding to $X_{n,i}$ is defined as follows:

$$P_{n,i} = \left[ \sum_{j \in i} \alpha_{n+1,j} P_{n+1,j}^{\rho_{n+1,j}} \right]^{1/\rho_{n,i}}, \quad \rho_{n,i} = \frac{\sigma_{n,i} - 1}{\sigma_{n}}, \quad \sigma = \sigma^{-1}$$

The equilibrium quantities of pkm for every passenger transport mode and the equilibrium quantity of the aggregate of other goods and services purchased by consumers are obtained by maximising overall consumer utility as a function of passenger transport modes and of an aggregate of all

$^{12}$The distribution parameter $\alpha$ is the optimal budget share of utility component $i$ at level $n+1$ in the budget allocated to the aggregate utility component at level $n$ of which it is part.
other goods & services, subject to a budget constraint. This is expressed mathematically as follows:

$$
\text{Max } \omega = X_{0,i} = \left[ \sum_{j \in J} \alpha_i^{1-p_{0,j}} X_{i,j}^{p_{0,j}} \right]^{1/p_{0,i}} = X_{0,i}(X_{6a,i}, \forall i \in Pr; X_{5b,j} \forall j \in Pu, X_{4c,k}, k=NM)
$$

s.t. \( y = P_{0,i}X_{0,i} = \sum_{i \in Pr} P_{6a,i} X_{6a,i} + \sum_{j \in Pu} P_{5b,j} X_{5b,j} + \sum_{k \in NM} P_{4c,k} X_{4c,k} \) (3)

where Pr stands for all private transport modes, Pu stands for all public transport modes, and NM stands for non-motorised transport & motorcycles.

These equilibrium quantities, being functions of income and of consumer prices of all passenger transport modes and of the aggregate price of other goods & services, are the demand functions for the different transport modes. So, for each private passenger transport mode an equation can be computed of the form of:

$$
X_{6a,i} = \frac{y}{P_{0,i}} \prod_{n=a}^{0} \alpha_{n+1,i} \left( \frac{P_{n,i}}{P_{n+1,i}} \right)^{\alpha_{n,i}} \text{ (4)}
$$

where \( P_{n,i} \) is the price index at level n specified above.

3.2.2. Urban passenger transport

The utility tree for urban passenger transport was provided in Figure 6 above. Whereas Figure 6 shows the full utility tree for urban peak transport, Figure 7 elaborates on the off-peak choices. As can be seen, the choices over the off-peak period are equivalent to those in the peak period.
So, for each private passenger transport mode, an equation can be computed of the form:

\[ X_{6a,1} = \frac{y}{gp_{0,1}} \prod_{n=5a}^{0} \alpha_{n+1,j} \left( \frac{gp_{n,j}}{gp_{n+1,j}} \right)^{a_{n,j}} \]  

(5)

where \( gp_{n,i} \) is the price index at level \( n \) specified above. The price concept used is the “generalised price” (cf. infra).

The demand functions for public passenger transport are written as follows:

\[ X_{5b,j} = \frac{y}{gp_{0,j}} \prod_{n=4b}^{0} \alpha_{n+1,j} \left( \frac{gp_{n,j}}{gp_{n+1,j}} \right)^{a_{n,j}} \]  

(6)

And the demand functions for non-motorised transport and motorcycles look like:

\[ X_{4c,k} = \frac{y}{gp_{0,k}} \prod_{n=3}^{0} \alpha_{n+1,k} \left( \frac{gp_{n,k}}{gp_{n+1,k}} \right)^{a_{n,k}} \]  

(7)

\[ X_{6a,1} = \frac{y}{gp_{0,1}} \times \left[ \frac{gp_{5a,1}}{gp_{6a,1}} \right]^{a_{5a,1}} \times \left[ \frac{gp_{4a,1}}{gp_{5a,1}} \right]^{a_{4a,1}} \times \left[ \frac{gp_{3a,1}}{gp_{4a,1}} \right]^{a_{3a,1}} \times \]  

\[ \times \left[ \frac{gp_{2a,1}}{gp_{3a,1}} \right]^{a_{2a,1}} \times \left[ \frac{gp_{1a,1}}{gp_{2a,1}} \right]^{a_{1a,1}} \times \left[ \frac{gp_{0a,1}}{gp_{1a,1}} \right]^{a_{0a,1}} \]  

Examples

At level 6a, the demand function for a big car \( X_{0,1} \) driven alone in the peak period is:
\[
\left[ \alpha_{3,1} \left( \frac{g_{2,1}}{g_{3,1}} \right)^{\sigma_{2,1}} \right] \times \left[ \alpha_{2,1} \left( \frac{g_{1,1}}{g_{2,1}} \right)^{\sigma_{1,1}} \right] \times \left[ \alpha_{1,1} \left( \frac{g_{0,1}}{g_{1,1}} \right)^{\sigma_{0,1}} \right] \quad (8)
\]

where \( g_{n,i} \) \( \forall n \) and \( \forall i \) is the price index corresponding to the quantity index \( X_{n,i} \), as specified above. For all cars, either big or small, either driven alone or by more people, either in the peak or in the off-peak period, a similar demand function can be specified. In (8), it becomes clear that the demand for the use of a big car in the peak period is influenced by its own price but also by the prices of all other modes. The influence of any price change depends on the ease of substitution at the different levels and this is given by the elasticities of substitution (\( \sigma \)).

For all public transport modes, the demand function will look like the demand function of bus transport in the peak period:

\[
\frac{y}{g_{0,5}} \times \left[ \alpha_{5b,5} \left( \frac{g_{4b,5}}{g_{5b,5}} \right)^{\sigma_{4b,5}} \right] \times \left[ \alpha_{4b,5} \left( \frac{g_{3b,5}}{g_{4b,5}} \right)^{\sigma_{3b,5}} \right] \times \left[ \alpha_{3b,5} \left( \frac{g_{2b,5}}{g_{3b,5}} \right)^{\sigma_{2b,5}} \right] = \left[ \alpha_{2b,5} \left( \frac{g_{1b,5}}{g_{2b,5}} \right)^{\sigma_{1b,5}} \right] \times \left[ \alpha_{1b,5} \left( \frac{g_{0b,5}}{g_{1b,5}} \right)^{\sigma_{0b,5}} \right] \quad (9)
\]

Finally, the demand function for non-motorised transport (and that for motorcycle transport) in the peak period can be written as follows:

\[
\frac{y}{g_{0,7}} \times \left[ \alpha_{4c,7} \left( \frac{g_{3c,7}}{g_{4c,7}} \right)^{\sigma_{3c,7}} \right] \times \left[ \alpha_{3c,7} \left( \frac{g_{2c,7}}{g_{3c,7}} \right)^{\sigma_{2c,7}} \right] \times \left[ \alpha_{2c,7} \left( \frac{g_{1c,7}}{g_{2c,7}} \right)^{\sigma_{1c,7}} \right] \times \left[ \alpha_{1c,7} \left( \frac{g_{0c,7}}{g_{1c,7}} \right)^{\sigma_{0c,7}} \right] = \left[ \alpha_{2c,7} \left( \frac{g_{1c,7}}{g_{2c,7}} \right)^{\sigma_{1c,7}} \right] \times \left[ \alpha_{1c,7} \left( \frac{g_{0c,7}}{g_{1c,7}} \right)^{\sigma_{0c,7}} \right] \quad (10)
\]

### 3.2.3. Non-urban passenger transport

Again, in the case on non-urban passenger transport, the consumer has to choose between two options at each level of the utility tree, represented in Figure 8 and Figure 9.
Demand equations for all non-urban transport modes, equivalent to those for all urban transport modes, can be computed, using the same method. Private passenger transport demand functions equal:

\[
X_{7_{a,i}} = \frac{y}{g_{P_{0,i}}} \prod_{n=6a}^{0} \alpha_{n+1,i} \left( \frac{g_{P_{n,i}}}{g_{P_{n+1,i}}} \right)^{\sigma_{n,i}}.
\]  

(11)

The demand functions for the different public transport modes do not look completely alike.

At level 6b the demand functions for bus transport either on the motorway or on other road types look like:

\[
X_{6_{b,j}} = \frac{y}{g_{P_{0,j}}} \left[ \prod_{n=5b}^{0} \alpha_{n+1,j} \left( \frac{g_{P_{n,j}}}{g_{P_{n+1,j}}} \right)^{\sigma_{n,j}} \right].
\]  

(12)

The demand functions for train transport are:
\[ X_{s_h,k} = \frac{y}{gP_{0,k}} \left[ \prod_{n=4}^{0} \alpha_{n+1,k} \left( \frac{gP_{n,k}}{gP_{n+1,k}} \right)^{\sigma_{v,k}} \right] , \]  

And the demand functions for motorcycle transport (either on the motorway or on other rural roads) is written:

\[ X_{4c,m} = \frac{y}{gP_{0,m}} \left[ \prod_{n=3}^{0} \alpha_{n+1,m} \left( \frac{gP_{n,m}}{gP_{n+1,m}} \right)^{\sigma_{v,m}} \right] \]

### 3.3. Freight transport demand

#### 3.3.1. General discussion

This module computes, for given fixed exogenous production levels and given generalised prices, the freight transport flows per mode, as presented in Figure 10.

The substitution possibilities in freight transport are represented by nested CES cost functions. Again, two specifications are given: one for urban transport and one for non-urban transport. The nested CES cost functions are similar to the CES utility functions for passenger transport: they have a similar structure (and are used for the same reasons) and the same properties: constant elasticities of substitution and constant returns to scale.
### 3.3.2. Urban freight transport

The nested CES cost function used in the urban freight transport specification is represented in Figure 11. This cost function is used as an example to explain the methodology.

#### Figure 11: The CES Cost Function for Urban Freight Transport

```
Production cost
  /       \
Freight transport  Other inputs
    /     \        /  \      
  Peak    Off-peak  Big trucks  Small trucks
    \     /    /            /  \        
      Big trucks  Small trucks  Big trucks  Small trucks
```

```
Production Y is a CES function of inputs at level UF1. Freight transport is itself a CES function of peak and off-peak freight transport, which are also CES functions of big and small trucks at level UF3.

\[
Y = X_{0,f} = \left[ \sum_{j \neq f} \kappa_{1,j}^{1-p_{0,j}} X_{1,j}^{p_{0,j}} \right]^{1/p_{0,f}}
\]  

(15)

which in this case equals:

\[
Y = X_{0,f} = \left[ \kappa_{1,fr}^{1-p_{0,fr}} X_{1,fr}^{p_{0,fr}} + \kappa_{1,IOI}^{1-p_{0,IOI}} X_{1,IOI}^{p_{0,IOI}} \right]^{1/p_{2,f}}
\]  

(16)

where \( \kappa_{n,f} \) is, like \( \alpha \) for passenger transport, a distribution parameter, \( X_{1,fr} \) is quantity of freight transport and \( X_{1,IOI} \) is quantity of other inputs.

\[
X_{1,fr} = \left[ \kappa_{2,p}^{1-p_{1,p}} X_{2,p}^{p_{1,p}} + \kappa_{2,op}^{1-p_{1,op}} X_{2,op}^{p_{1,op}} \right]^{1/p_{1,p}}
\]  

(17)

with \( X_{2,p} \) is quantity of peak transport and \( X_{2,op} \) is quantity of off-peak transport, which themselves can also be written as CES functions of the urban freight transport modes, big and small trucks.

The demand functions for freight transport can be obtained by minimising the costs needed to produce the production level as given by the base case:

\[
\text{Min } C(g_{p_1}, Y) = g_{p_{1,1}} X_{3,1} + g_{p_{3,2}} X_{3,2} + g_{p_{3,3}} X_{3,3} + g_{p_{3,4}} X_{3,4} + g_{p_{1,IOI}} X_{1,IOI}
\]

s.t. \( Y = X_{0,f} \)

(18)

where \( X_{3,1} \) is quantity of big trucks in peak period, \( X_{3,2} \) is quantity of small trucks in peak period, \( X_{3,3} \) is quantity of big trucks in off-peak period, \( X_{3,4} \) is quantity of small trucks in off-peak period and \( X_{1,IOI} \) is quantity of other inputs, and the price concept used is again generalised price. The production function \( X_{0,f} \) is defined by (16) and describes all the substitution possibilities between inputs (transport and others).

This minimisation leads to demand functions for urban freight transport modes that are very similar to the demand functions for urban passenger transport modes:

\[
X_{3,f} = \frac{Y}{g_{p_{0,f}}} \left[ \kappa_{3,f} \left( \frac{g_{p_{1,fr}}}{g_{p_{3,f}}} \right)^{\sigma_{2,p}} \kappa_{2,p} \left( \frac{g_{p_{1,fr}}}{g_{p_{2,p}}} \right)^{\sigma_{1,p}} \kappa_{1,fr} \left( \frac{g_{p_{0,fr}}}{g_{p_{1,fr}}} \right)^{\sigma_{1,f}} \right], \quad f = 1, \ldots, 4
\]

(19)

with price indices equalling:

---

13 One of the characteristics of a CES cost function is that it corresponds to a CES production function.
\[ g_{n,f} = \left( \sum_{j \in f} \kappa_{n+1,j} g_{P,n+1,j} \right)^{1/\rho_{n,f}}, \quad \rho_{n,f} = \frac{\sigma' - 1}{\sigma'}, \quad \sigma' = \sigma^{-1} \]  

(20)

3.3.3. Non-urban freight transport

Non-urban freight transport is also represented using a CES cost function, but with five levels of nests. This is shown in Figure 12 below.

Equations similar to those for the urban freight transport modes can be computed. The private freight transport mode demand functions can be written:

\[ X_{5a,f} = \frac{Y}{g_{P_{0,f}}} \prod_{n=4a}^{0} \kappa_{n+1,f} \left( \frac{g_{P_{n,f}}}{g_{P_{n+1,f}}} \right)^{\sigma_{n,f}} \]  

(21)

and public freight transport mode demand functions is defined by:

\[ X_{3b,h} = \frac{Y}{g_{P_{0,h}}} \prod_{n=2b}^{0} \kappa_{n+1,h} \left( \frac{g_{P_{n,h}}}{g_{P_{n+1,g-h}}} \right)^{\sigma_{n,h}} \]  

(22)

3.4. Calibration of demand functions

The demand functions described in section 3.2 and 3.3 above are calibrated against the base case data before being used in scenario analyses.

Calibrating the demand functions means assigning a value for the unknown parameters of these functions, such that the result of the function, once calculated with the values of the exogenous variables in the base case, exactly replicates the base case transport demand figure.

The unknown parameters are the shares (\( \alpha \)) of the components at each level of the nested CES utility (or cost) functions in the component at the next higher level. These shares can be computed, making use of the base case, i.e. the known demand levels for each of the transport modes as well as the...
generalised prices of all transport modes and preferences (as captured in the elasticities of substitution). Once computed, the demand functions are fully specified and can be used to compute the demand levels of the transport modes, in new situations (scenarios).
Appendix 3.1: Transport markets considered in TREMOVE

This appendix provides an illustration of many different traffic flows modelled in TREMOVE. As can be seen in the table below, some 252 different transport markets are considered—of which 144 related to passenger cars.

<table>
<thead>
<tr>
<th>Table 1: Transport markets considered in TREMOVE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle type</strong></td>
</tr>
<tr>
<td>Cars, small</td>
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<td>Cars, large</td>
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<td>Light trucks, &lt; 3.5T</td>
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<td>Heavy trucks, 16T-32T</td>
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<td>Buses &amp; coaches</td>
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<td>Trains, passenger</td>
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<td>Mopeds</td>
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<td>Motorcycles, 4 str., 250-750cc</td>
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<td>Motorcycles, 4 str., &gt;750cc</td>
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<td>Trains, freight</td>
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<td>Waterways</td>
</tr>
</tbody>
</table>
4. Modelling supply of transport services

The supply side in TREMOVE is assumed to follow demand. The supply module determines the producer price of all inputs necessary for transport services (cars, fuels, maintenance, etc.). Producer prices are used as an input to determine the equilibrium price in each transport market, where equilibrium prices are stated in terms of generalised prices. The producer price is determined by the resource cost and the market structure. In TREMOVE, constant returns to scale and perfect competition are assumed. This result in producer prices, equal to marginal costs plus producer taxes. The computation of the generalised price is discussed in the equilibrium section further in this document.

The transport markets for which producer prices need to be collected and/or computed are those that were defined at the lowest levels of the utility and production trees described in the previous section. Those markets are listed by way of example for urban transport in Table 2.

<table>
<thead>
<tr>
<th>Tpt Market</th>
<th>Tpt Mode</th>
<th>Residence User 1</th>
<th>Occupancy User 2</th>
<th>Period User 3</th>
<th>Type User 4</th>
<th>Means User 5</th>
<th>Subject User 6</th>
<th>Surface Infra 1</th>
<th>Region Infra 2</th>
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<tbody>
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<td>1</td>
<td>car, big</td>
<td>inhabitants</td>
<td>alone</td>
<td>peak</td>
<td>private</td>
<td>motorised</td>
<td>Passengers</td>
<td>Road</td>
<td>urban</td>
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<tr>
<td>2</td>
<td>car, big</td>
<td>inhabitants</td>
<td>alone</td>
<td>off-peak</td>
<td>private</td>
<td>motorised</td>
<td>Passengers</td>
<td>Road</td>
<td>urban</td>
</tr>
<tr>
<td>3</td>
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<td>commuters</td>
<td>alone</td>
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<td>motorised</td>
<td>Passengers</td>
<td>Road</td>
<td>urban</td>
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<tr>
<td>4</td>
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<td>commuters</td>
<td>alone</td>
<td>off-peak</td>
<td>private</td>
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<td>Passengers</td>
<td>Road</td>
<td>urban</td>
</tr>
<tr>
<td>5</td>
<td>car, big</td>
<td>inhabitants</td>
<td>pool</td>
<td>peak</td>
<td>private</td>
<td>motorised</td>
<td>Passengers</td>
<td>Road</td>
<td>urban</td>
</tr>
<tr>
<td>6</td>
<td>car, big</td>
<td>commuters</td>
<td>pool</td>
<td>off-peak</td>
<td>private</td>
<td>motorised</td>
<td>Passengers</td>
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<td>urban</td>
</tr>
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<td>7</td>
<td>car, big</td>
<td>commuters</td>
<td>pool</td>
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<td>Passengers</td>
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<td>8</td>
<td>car, big</td>
<td>commuters</td>
<td>pool</td>
<td>off-peak</td>
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<td>motorised</td>
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<td>9</td>
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<td>Passengers</td>
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<td>10</td>
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<td>11</td>
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<td>pool</td>
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<td>Passengers</td>
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<td>Passengers</td>
<td>Road</td>
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</tr>
<tr>
<td>17</td>
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<td>-</td>
<td>peak</td>
<td>public</td>
<td>motorised</td>
<td>Passengers</td>
<td>Road</td>
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</tr>
<tr>
<td>18</td>
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<td>-</td>
<td>off-peak</td>
<td>public</td>
<td>motorised</td>
<td>Passengers</td>
<td>Road</td>
<td>urban</td>
</tr>
<tr>
<td>19</td>
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<td>-</td>
<td>peak</td>
<td>public</td>
<td>motorised</td>
<td>Passengers</td>
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<td>-</td>
<td>off-peak</td>
<td>public</td>
<td>motorised</td>
<td>Passengers</td>
<td>Road</td>
<td>urban</td>
</tr>
<tr>
<td>21</td>
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<td>-</td>
<td>peak</td>
<td>public</td>
<td>motorised</td>
<td>Passengers</td>
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<td>off-peak</td>
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<td>motorised</td>
<td>Passengers</td>
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<td>urban</td>
</tr>
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<td>peak</td>
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<td>motorised</td>
<td>Passengers</td>
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<tr>
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<td>Passengers</td>
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<tr>
<td>29</td>
<td>Walking &amp; Biking</td>
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<td>-</td>
<td>peak</td>
<td>non-motorised</td>
<td>Passengers</td>
<td>Road</td>
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</tr>
<tr>
<td>30</td>
<td>Walking &amp; Biking</td>
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<td>-</td>
<td>off-peak</td>
<td>non-motorised</td>
<td>Passengers</td>
<td>Road</td>
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<tr>
<td>31</td>
<td>Walking &amp; Biking</td>
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<td>-</td>
<td>peak</td>
<td>non-motorised</td>
<td>Passengers</td>
<td>Road</td>
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<tr>
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<td>off-peak</td>
<td>non-motorised</td>
<td>Passengers</td>
<td>Road</td>
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<td>33</td>
<td>HGV Business</td>
<td>-</td>
<td>peak</td>
<td>Freight</td>
<td>Road</td>
<td>urban</td>
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<td>Freight</td>
<td>Road</td>
<td>urban</td>
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</table>
The vehicle categories listed in Table 2 are further broken down according to technology criteria for the purpose of calculating emissions. This is described in Chapter 8 and in Annex A of this report.

4.1. **Private passenger and freight transport costs**

The producer price for each transport mode (or market) considered in TREMOVE is the sum of the following components (all expressed in ECU per vehicle kilometre):

- Purchase cost
- Maintenance cost
- Insurance cost
- Fuel cost

The *purchase cost* component is given in terms of constant 1998 ECU per vehicle and therefore needs to be translated first in terms of 1998 ECU per vehicle kilometre. This is done using the following annuity formula:

\[
\text{Purchase cost per vkm} = \frac{\text{Purchase cost per vehicle}}{\text{annual mileage}} \left[ \frac{i (1+i)^n}{(1+i)^n - 1} \right]
\]

where the real interest rate \(i\) is 4\%, and the average lifetime \(n\) and average annual mileage of the vehicle are determined exogenously.

*Maintenance* and *insurance costs* are given in constant 98 ECU per year and are converted into constant 98 ECU per vehicle kilometres by dividing the annual cost by the average annual mileage determined exogenously.

The *fuel cost* component of the producer price on a constant 98 ECU per vehicle kilometre basis is computed based on a number of variables that are calculated in other TREMOVE modules. The fuel cost is, indeed, a function of fuel prices and fuel consumption. The fuel price is given in constant 98 ECU per litre, and is exogenous. Average fuel consumption per vehicle kilometre, however, is a function of the technology-related fuel efficiency (in terms of litres per kilometre) and the traffic demand-related average speed (in hours per kilometre).

4.2. **Public passenger transport**

For public transport, a linear cost function has been used. The total cost of supplying XP passenger-kilometre in the peak period and XOP passenger-kilometre in the off-peak period is given by:

\[ TC = FC + \text{vcp. XP + vcop. XOP} \]

Where:

- \(FC\) represents the fixed costs
- \(vcp\) represents the variable operations costs (including capacity costs of carriages or busses) of transporting passengers in the
peak period; this cost is computed using a fixed occupancy factor per bus or rail carriage.

\( \text{vcop} \) represents the variable operation costs (excluding capacity costs of carriages and buses) of transporting passengers in the off-peak period; this cost is computed using a fixed occupancy factor different from the one used for the peak period.

For public transport, a *Mohring effect* has been included. This means that the waiting time for public transport users is a decreasing function of the total demand for public transport.
5. MODELLING EQUILIBRIUM

In the equilibrium module the demand side and the supply side are equalled, i.e. the equilibrium prices for all transport modes are computed, making use of the producer prices (i.e. the supply side), the demand functions (i.e. the demand side) and the (demand related) speed functions (congestion functions). This is illustrated in Figure 13.

The respective steps to model the transport demand and supply equilibrium are discussed next.

5.1. The generalised price

As already explained, the price concept used when considering transport market equilibrium is the generalised price. The generalised price is the sum of three elements:

- the producer price \( p_i \) per vkm travelled by mode \( i \) : The producer price \( p_i \) is determined in the supply module. Under the assumption of perfect competition, this producer price equals the marginal cost to the producer of supplying one vkm of that transport mode. This marginal production cost is equal to the resource cost.

- a tax (or subsidy) \( \tau_i \) : On top of the resource cost the consumer usually has to pay taxes or receives a subsidy, both of which have to be taken into account to calculate the market price.

- a transportation time cost \( t_{ci} \) for a km travelled by transport mode \( i \) (this includes waiting and walking time for public transport)
The generalised price for a passenger km travelled by mode $i$ is thus defined as:

$$\text{generalised price } i = gp_i = q_i + tc_i$$

where $q_i$ is the consumer price (the monetary part of the generalised price): $q_i = p_i + \tau_i$;

and $tc_i = \rho_i^* t_i$, with $\rho_i$ being the value of time for mode $i$ in that particular situation (e.g. peak or off-peak) and $t_i$ the time needed to travel one km by mode $i$.

$$gp_i = p_i + \tau_i + tc_i \quad (23)$$

where

$p_i$ = producer price for a km by transport mode $i$ (fixed in the supply module)

$= \text{vehicle cost}_i + \text{fuel cost}_i + \text{maintenance cost}_i + \text{insurance cost}_i$

$\tau_i$ = tax levied on a km by transport mode $i$ (fixed exogenously by the government)

$= \text{tax on vehicle cost}_i + \text{tax on fuel cost}_i + \text{tax on maintenance cost}_i + \text{tax on insurance cost}_i$

$tc_i$ = time cost spent on one km by mode $i$ (determined endogenously in the model)

$= \rho_i^* t_i$ ($\rho_i$ = time value of mode $i$, $t_i$ = time spent on one km by mode $i$); $t_i = 1/\text{speed}$ (in terms of time per km)

### 5.2. Travel time and Speed-flow relationships

In TREMOVE, travel time is calculated endogenously: it is a function of the total volume of traffic. Given the time needed to travel one km, or $t_i = 1/\text{speed}$, where speed depends on the level of congestion, one sees that speed is directly related to the traffic flow. The relationship between the traffic speed and the traffic flow is expressed by a congestion function, which is assumed to be exponential based on extensive tests analysed in the context of the TRENEN exercise.

Because the speed on the road is a function of the total traffic flow, the speed-flow relation or congestion function is also used to provide the link between the different transport categories, i.e. between passenger (commuters and inhabitants) and freight transport:

$$\text{speed} = F(\text{commuters transport demand, inhabitants transport demand, freight transport demand})^{14}$$

---

14 In TRENEN II URBAN the Brussels congestion function (speed-flow relation) is:

$$Scar = 1.19461337 + 0.00538663 * \text{(EXP}(7.9528754*\text{PCU}))$$
In Tremove, we model the speed/flow relationship per road class \( r \) as follows:

\[
\text{Speed}_r = a + b \cdot \exp(c \cdot \text{PCU}_r)
\]

(24)

where

- \( \text{Speed}_r \) is the speed on road class \( r \) (in minute per km)
- \( a, b, c \) are coefficients that have to be estimated for each equation
- \( \text{PCU}_r \) is number of passenger car units per hour. A car corresponds to 1 PCU, buses and trucks to 2 PCU.

### 5.3. Equilibrium prices and quantities

We have previously identified a demand function for all passenger transport modes \( i \) (and for both types of consumers, commuters and inhabitants) and all freight transport modes \( f \), of the following type:

\[
X_i = X_i(g_{p1}, \ldots, g_{pI}; y_i), \text{ with } I \text{ the number of passenger transport modes}
\]

\[
X_f = X_f(g_{p1}, \ldots, g_{pH}; y_f), \text{ with } H \text{ the number of freight transport modes}
\]

Indeed, demand for one particular transport mode depends on generalised prices of all transport modes of that particular transport type (passenger or freight); passenger transport demand depends also on income \( y_i \), and freight transport demand depends on the fixed production level \( y_f \).

We have also identified that the generalised price is a function of the producer prices, taxes or subsidies and time costs. Part of the producer price (i.e., the fuel cost) and the time cost are a function of speed. Speed itself is, however, a function of transport demand (or transport flows). After several iterations, the equilibrium prices and quantities of transport (pkm) are obtained.

---

where Scar, speed of cars, is in minutes per km, and PCU is millions of passenger car units per hour. A car corresponds to 1 PCU, buses and trucks to 2.
6. COMPUTING THE COSTS TO SOCIETY

One of the purposes of TREMOVE is to provide a consistent basis for computing the cost to society associated with emission reduction scenarios in European urban and non-urban areas.

In this Chapter, we first restate briefly the cost definition that has been used in AOP-I. Next, we introduce the broader cost-concepts used in TREMOVE. As this cost-concept is rather abstract its different elements are introduced step by step, starting with the simplest case. Finally, we summarise the different elements discussed on a conceptual basis and explain how the costs to society are computed using TREMOVE.

6.1. The cost concept used in AOP-I

In the AOP-I the welfare cost concept used for measures on vehicles and fuels equalled changes in resource costs, i.e., changes in capital and operating costs before taxes and subsidies, taking the volume of car use as given.

This is an obvious way to compute the total costs to society: in an economy with full employment, higher production costs for a cleaner car mean that productive resources have been withdrawn from other sectors that produced useful consumption goods. Foregoing these other consumption goods is the welfare cost of a cleaner car. Capital as well as operating costs are relevant. Taxes and subsidies have to be eliminated because they are transfers between different groups of the population of a given region. Whenever the measures imposed do not affect the consumer prices significantly, there will be no important effects on the volume of transport. Under these conditions the cost concept previously used in AOP-I is appropriate. There are, however, four problems with the AOP-I cost definition. Indeed, a broader and more complex cost concept needed to be introduced because the AOP-I cost definition was not anymore appropriate to deal with the wide range of policy measures that had to be evaluated in AOP-II. The problem with the AOP-I cost definition are below.

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15 The cost concepts used in AOP-II have been extensively debated in the initial stages of the programme. These discussions also took into account the comments made by the European Parliament included in their reports related to the conciliation procedure of the AOP-I Directives. The outcome of these discussions has been reported in the First Consolidated Interim Report, released in February 1998. This section mainly restates these concepts whilst providing more detail or slightly modifying some terms to improve the overall consistency and to take account of comments and suggestions received in later stages.

16 By welfare cost we mean the sum of costs to society. Here we work with representative individuals so that we take a unweighted sum of costs over individuals. The cost concept for one individual corresponds to the compensating income variation concept: what change in income is needed to make the individual accept the new prices and quality offered to him in the new equilibrium.
Firstly, the AOP-I cost definition cannot cope satisfactorily with the transport measures that need to be evaluated in the AOP-II Programme. Reducing emissions by reducing the volume of car transport (e.g. in some highly polluted area) and by modal changes would not fit into the AOP-I definition. Indeed if one used only the change in resource cost as cost-element, the reduction of the volume of car transport or a transfer to cheaper modes (put 1000 car-users into 1 train) would save resources and would be a negative cost option!

Secondly, the AOP-I cost definition cannot discriminate between different instruments, such as taxes, subsidies or regulations, that aim at introducing the same cleaner car or fuel. One knows that the three measures have a slightly different impact but this can not be measured in terms of direct resource costs, one needs a more general cost definition.

Thirdly, the AOP-I definition cannot deal with travel time issues (which is an essential component of mobility) and with other side effects (other air pollutants, noise, and accidents).

The final problem is that the change in resource costs does not tell us who bears the costs of the measure. Whether a cleaner car is adopted via subsidies or via taxes will make a difference for the distribution of costs over economic agents.

It was agreed that the AOP-II cost definition, explained in the next paragraph, had to be more general whilst including the AOP-I definition as a special case.

6.2. Cost to society – methodology and concepts used in AOP-II

This section explains the more general AOP II cost-definition on a step by step basis. Readers with good economic background can skip the step.\textsuperscript{17}

6.2.1. Considering one transport market and ignoring taxes

Take the simple transport market of Figure 15. We assume that that there is only one type of standard car of a given age. In this figure, we represent for a given area with given infrastructure, the demand for car use. The demand curve is a function of different elements including the generalised price of car use. If we assume perfect competition, no taxes and no distortions on the input markets, the money cost of car use will equal the sum of resource costs of car use. To obtain the generalised cost we add the average time cost that increases with the volume of car use on a given road infrastructure. One obtains an equilibrium car use $X_0$ where the demand

\textsuperscript{17} Given the structure of the TREMOVE model explained in previous chapters, it should be noted that the cost to society of a policy measure in one country is the sum of the costs to society as calculated for the three different regions and within each region, the total cost to society is the sum of the cost to society of passenger transport and the cost to society of freight transport.
function crosses the generalised cost function. In this point the willingness to pay of the last road user equals the generalised cost.

Assume that we impose the use of a cleaner car that drives up resource costs from \( r \) to \( r' \). We assume that this cost is passed on fully into an increase in producer prices. The new generalised cost curve starts now in point \( t' \) and we obtain a new equilibrium \( X_1 \) and \( g_{p_1} \).

In the AOP I definition, the welfare cost definition used equals the increased resource cost of making available the same volume of car use: the area \( r' f g r \) in Figure 13.

**FIGURE 14: ONE TRANSPORT MARKET AND NO TAXES**

The more general definition we use starts from the idea that the more expensive car use makes individuals reduce their car use. Some car users find it more profitable for them to forego their car use and spend the money differently. As they prefer the latter option, this means that the total cost to society is smaller than the initial volume times the increased resource cost. Economists measure the welfare loss via the change in *consumer surplus*. The consumer surplus is by definition the difference between the willingness to pay of the consumer (area under the demand function) and what he actually pays. In this case the initial consumer surplus equalled \( h e g_{p_0} \), after the imposition of a clean car, the consumer surplus equals \( h d g_{p_1} \).
The welfare cost equals the difference between the two areas, here \( gp_1 \) d e gp0.

The welfare cost can be decomposed into three components:

- increased money cost of remaining car users \( X_1 \) times \( r' - r \) (area gp1 d b gp2)
- the lost welfare of the diverted car users: area d a e
- the gain in time costs of the remaining car users (area gp\(_n\) a b gp2)

If the extra resource costs were not passed through completely to the consumer, the losses of the producer would have to be included in the welfare cost definition. This change in real profit is called *producer surplus*.

The welfare cost depends on the slope of the demand function and the speed-flow relationship. The steeper (the less price-elastic) the demand curve, the less car users can switch to other options and the higher will be the welfare cost. The flatter the speed flow relation, the flatter the average time cost curve, the smaller will be the time gains for the remaining users.

The previous argument not only holds for passenger car transport, but can also be transplanted to other modes and to freight transport. Take the case of truck transport. The demand function for truck use is also downward sloping. When the generalised price of truck use decreases, it translates the possibilities to reduce total production costs by switching from other transport modes or other production factors to a greater truck use and vice-versa. This can be seen as an increase in consumer surplus for the production sector as a whole and thus ultimately as a welfare gain for households paying less for their consumption goods.

The concepts of Figure 13 can be used to analyse other policy measures than the imposition of the use of a cleaner car. The net welfare cost of a reduction in the maximal speed can be measured by the consumer surplus change of an upward shift in the average time cost curve. Improvements of road infrastructure capacity have the reverse effect: they decrease average time costs and the volume of car use. Obviously for both cases we have to add to the cost side the specific costs attached to that instrument (i.e., monitoring costs and infrastructure extension).

### 6.2.2. Considering several transport markets

Some policy measures reduce emissions indirectly. This is typically the case for public transport policies. By decreasing the generalised cost of public transport (via improved frequency, subsidies, improved comfort, etc...), one wants to make car users switch to the public transport mode hoping to decrease congestion, may be total emissions, etc.

The welfare cost of such a policy can not be measured on the public transport market alone as it is the purpose to affect the car transport market. One wants the demand curve for car use to shift inwards (to the left) so that the volume of car use and the emissions of car use are decreased.
In principle one could measure the welfare cost of a public transport policy by adding the changes in consumer surplus on both markets. This becomes a rather cumbersome and less precise method as demand curves on both markets shift: the demand for car use shifts because of the price reduction in bus use; the demand for bus use could shift inwards too because the reduced car use leads to a lower generalised price of car use (via reduced time costs), etc.

For the welfare cost measurement of simultaneous price changes, economists return to the use of utility functions that is the concept underlying the demand functions.

In TREMOVE we use as measure for the sum of consumer surpluses the indirect utility function divided by the marginal utility of income in the base case \( \mu(0) \):

\[
\frac{1}{\mu(0)} V(p_0, g_{p1}, \ldots, g_{pn}, \text{INC} + \text{PS}_{\text{transport supply}} + \text{net tax revenue}) + C(g_{p1}, \ldots, g_{pn}, Y)
\]

(25)

The function \( V \) has the dimension of utility and is constructed by taking the direct utility function in (3) and substituting all the quantities by their demand functions. This gives a function in generalised prices and income, which is called the indirect utility function. As we want to measure welfare changes in money terms we divide the utility function by the marginal utility of income in the base case \( \mu(0) \).

The advantage of expression (25) is that we can plug in any set of new equilibrium prices, new values for producer surplus and net tax revenues. The difference of the function (25) with the value obtained in the base case gives the welfare cost of this complex change.

In (25) it has been assumed that all changes in producer surpluses (net profits of suppliers of cars, fuel, and car services plus the profit of public transport) as well as all net changes in tax revenue are returned to the representative households. These elements need to be present in (25) in order to represent correctly subsidy or tax policies that affect the generalised prices but need to be financed via other levies on the consumer.

The last term in (25) represents the production cost of users of freight transport taking the production level \( Y \) constant. This term fulfils the same role as the indirect utility function for the consumer of passenger transport. This cost function equals the cost function (18) in which all factor demand functions have been introduced.

6.2.3. Considering the marginal cost of public funds

In expression (25) the net changes in taxes, subsidies and public transport profits are by assumption returned to the representative household. This is the reason why in a cost-effectiveness analysis taxes cannot be fully counted as costs. In fact this is a shortcut that is based on two assumptions. First there is the assumption that there are no existing taxes, secondly that all
changes in taxes are changes in lump-sum taxes. Lump-sum taxes are taxes that do not distort prices e.g. a head tax.

Both assumptions are heroic and therefore we need to give a different weight to changes in consumer surplus and producer surplus and changes in net tax revenue. The extra weight given to tax revenue is called the marginal cost of public funds. The extra tax revenue will in principle be returned to the taxpayers and therefore one finds in (25) the Tax Revenue term in the income of the consumers. What is still missing in (25) is the specific efficiency loss or gain associated to changes in tax revenue because of the extra price distortions that a higher tax generates on the market where the additional tax revenue is collected. We add therefore an extra term $\lambda \, \text{dTR}$ to the welfare cost function (25). $\lambda$ is the extra efficiency loss associated to raising one extra Euro of tax revenue on the transport market.

\[
\frac{1}{\mu(0)} \left( V(p_0, gp_1, \ldots, gp_n, \text{INC} + \text{PS}_{\text{Transport supply}} + \text{net tax revenue}) + C(gp_n, \ldots, gp^t, Y) + \lambda \, \text{dTR} \right)
\]

To compute the value $\lambda$ we need to make two types of assumptions:

Assumptions on how the change in tax revenue is used:

As default assumption we will have that the net change in tax revenue from the transport sector is used to reduce social security contributions or income taxes in general. Taxes on income are indeed the major sources of government income. Other assumptions could be used and this will affect the use of the $\lambda \, \text{dTR}$ term.

In some projects the changes in revenue are earmarked to a particular purpose and this needs to be taken into account. Assume by way of example that the project consists in raising taxes on automobile use in the peak and to use the tax receipts to cut registration taxes on cars. There will be no net increase in tax revenue but there will be a change in the relative prices of car use in the peak and in the off-peak periods, the welfare effects of this are taken into account in the changes in the generalised prices of expression (26).

One can imagine other examples. The government could impose a special tax on say environmental pollution and promise to return the funds via extra investments into protection of the environment. In this case the project needs to be redefined as follows: impose a pollution tax and reduce emissions via an investment, the net tax receipt is zero and the $\lambda \, \text{dTR}$ term disappears in (26).

Assumptions related to existing labour tax rates and the price elasticity of labour supply

Consider first a project that raises the average tax rate on transport and where the net tax revenue is used to reduce existing labour taxes. We have to consider two effects: one effect on the transport market and one effect on the labour market.
The effect on the transport market is predictable: there will be a loss in consumer surplus that is due to the increase in generalised prices. The effect on the labour market is less easy to grasp. There are two conflicting effects: the transport tax goes up and this decreases the purchasing power of the wage. This comes down to an implicit increase of the labour tax. The second effect is the reduction of the labour tax made possible by the extra revenue coming from transport taxes. If there is only one individual and only one source of income (labour), we will assume that both effects cancel out and in this case we chose a value of $\lambda$ equal to 0. The value of $\lambda$ will be different if another use is made of the transport tax revenues.

As default value we will assume that there are also other sources of income that are taxed but that only taxes on labour income are reduced. This amounts to a shift of the tax burden from labour to non-labour income. In this case there will be a net efficiency gain of raising taxes in the transport sector and reducing labour taxes that equals:

$$ (\text{MCPF}_{\text{labour}} - 1) \ k \ d\text{TR} = \lambda \ d\text{TR} \quad (27) $$

In this expression, MCPF$_{\text{labour}}$ stands for the marginal cost of raising tax revenue via labour taxes (a value of approx. 1.2 is used here$^{18}$), k stands for the share of non-labour income (typically equal to 0.3). The value of $\lambda$ used here (approx. 0.07) represents the efficiency gain of lowering labour taxes through a shift of taxes (via higher transport taxes) to non-labour income taxes.

One can imagine less efficient uses of recycling tax revenue, imagine a reduction of taxes under the form of a head tax. In this case (27) becomes

$$ (1 - \text{MCPF}_{\text{labour}}) \ (1-k) \ d\text{TR} = \lambda \ d\text{TR} \quad (28) $$

Now the increase in transport taxes that is not used to reduce labour taxes means that the real wage has been reduced and that implicitly the labour tax has been increased (the tax income is returned to the individual but he has now a smaller incentive to work. This causes an efficiency loss and the resulting $\lambda$ is now negative (-0.14) and this will increase the costs of all policies that raise taxes on the transport sector and not returning them as reduced labour taxes.

6.2.4. Consider other side effects

It has been agreed in AOPII to also use an alternative cost definition compared to the one defined in expression (26) to account for so-called side effects. With side-effects we mean effects other impacts associated with transport causing external costs. It was decided to include the external costs

---

$^{18}$ The value of MCPF of labour taxes will be a function of the existing tax rates and the elasticity of labour supply. For Belgium we computed a value of 1.2 (Ochelen, Proost, Van Dender, 1998).
of accidents and noise in an alternative cost-function to test the sensitivity of the cost-effectiveness calculations using expression (26).19

The cost of noise and accidents has been estimated using a simple procedure. From previous TRENEN studies, we had an estimate of the cost of noise and accident per vehicle-kilometre, as shown in Tables 3 and 4. These figures are expressed in constant 1990 ECU per thousand vkm, and were computed for 2005. We converted them into 1998 ECU by using CPI inflation in EU15, and assumed, following TRENEN, that the cost changes over time at the same pace than income per capita.

These values were computed for Brussels and for interregional traffic in Belgium. We will apply Brussels’ values for all urban areas in all countries, and the interregional values for non-urban areas in all countries.

The method used here to estimate the cost of noise and accidents is taken from Chapter 7 of Reforming transport pricing in the European Union – a modelling approach, a publication – not yet published – by the Centre for Economic Research of the K.U. Leuven.

The estimation of the cost of noise is based on the “hedonic housing market method”. This method assumes, that, everything else being equal, the value of a house will depend on environmental factors, such as noise (see Pearce D.W. and Markandia A. (1989), Environmental policy benefits: monetary valuation, Paris, OECD). One key assumption of this methodology is that the real price of houses is constant over time. This assumption is consistent with other price assumption made in this study.

The estimation of the cost of accidents is taken from an article from J.O. Jansson (Accident externality charges, 1994, Journal of Transport Economics). The main assumption is that the risk of accident (per vehicle kilometre) is not dependant on the level of traffic.

<table>
<thead>
<tr>
<th>TABLE 3: MARGINAL EXTERNAL NOISE COST (1990 ECU PER T’VKM) IN 2005</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Peak</td>
</tr>
<tr>
<td>Off-peak</td>
</tr>
</tbody>
</table>

Source: TRENEN

19 Although included in TREMOVE, the this alternative cost function has not been discussed in detail to date.
<table>
<thead>
<tr>
<th>Mode of Transport</th>
<th>Brussels</th>
<th>Inter-regional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars</td>
<td>32.65</td>
<td>45.7</td>
</tr>
<tr>
<td>Trucks</td>
<td>96.42</td>
<td>47.63</td>
</tr>
<tr>
<td>Buses</td>
<td>23.47</td>
<td>62.64</td>
</tr>
<tr>
<td>Tram</td>
<td>25.53</td>
<td>--</td>
</tr>
<tr>
<td>Metro</td>
<td>2.62</td>
<td>--</td>
</tr>
</tbody>
</table>

Source: TRENEN
7. MODELLING VEHICLE STOCK AND USAGE

7.1. Overview

This module calculates the size and structure of the vehicle stock, based on a capital-vintage approach. The output of the module is a full description of the vehicle stock every year, by vehicle type and by age of the vehicle. The age structure of the vehicle stock is an essential variable to assess the impact of emission reduction policies, since technology - hence emission profiles - differ significantly across vintages. The structure of this module is illustrated in Figure 15.

The key input variables of this module are:
- road transport demand by mode,
- vehicle costs,
- fuel prices, and
- policy measures that affect vehicle choice.

This module also calculates the usage for each category of vehicles, from which the usage cost can be derived.
Usually the type and age of a vehicle determine its technical characteristics, i.e. its fuel efficiency and emission characteristics. In this, TREMOVE follows the COPERT II methodology for current and near future vehicles. Figure 16 provides a summary of the vehicle categories included in TREMOVE.

Figure 16: Vehicles type included in TREMOVE

- Cars:
  - gasoline-small (< 1.4l)
  - gasoline-medium (1.4l - 2.0l)
  - gasoline-large (> 2.0l)
  - diesel-medium (< 2.0l)
  - diesel-large (> 2.0l)
  - LPG
  - CNG
  - other AFV (for future introduction)
  - two stroke

- Light duty vehicles:
  - gasoline
  - diesel
  - AFV

- Heavy duty vehicles:
  - gasoline
  - diesel 3.5 - 7.5T
  - diesel 7.5 - 16T
  - diesel 16 - 32T
  - diesel > 32T
  - AFV

- Buses and coaches:
  - Buses & coaches
  - AFV buses

- Motorcycles:
  - 2 strokes<50cc
  - 2 strokes>50cc
  - 4 strokes 50-250cc
  - 4 strokes 250-750cc
  - 4 strokes>750cc

A full list of technologies, fuel consumption, and emission factors is given in the COPERT II methodology manual (see references in the section on the emission module).\(^{20}\)

The vehicle stock is broken down by:

- type of vehicle
- age of vehicle

Within TREMOVE, a distinction is made between the modelling of transport activity (the transport module of TREMOVE) and the modelling of vehicle stock and emissions (the stock, usage and emissions module of TREMOVE). In the case of traffic, the emphasis is put on the substitution between transport modes and on characteristics such as the period (peak or off-peak), the type of road (urban, highway, other), or the region (urban, non-urban). However, to compute vehicle stocks and emissions, the key factor is a detailed description of the stock. In the stock, usage and emissions module, the transport module categories are thus split according

\(^{20}\) However, following the adoption of the so called AOP-I Directives related to emission limit values of passenger cars, light duty vehicles and heavy duty vehicles, a number of updates have been added to COPERT II, following the advice of vehicle technology experts that were members of the Auto-Oil II Working Groups.
to detailed vehicle categories rather than according to traffic characteristics. The correspondence is shown on Figure 17.

**Figure 17: Correspondence between TRE and MOVE categories**

<table>
<thead>
<tr>
<th>SC</th>
<th>Small Cars</th>
<th>gasoline - small (&lt; 1.4l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>Big Cars</td>
<td>gasoline - medium (1.4l - 2.0l)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>gasoline - large (&gt; 2.0l)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>diesel - medium (1.4l - 2.0l)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>diesel - large (&gt; 2.0l)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LPG</td>
</tr>
<tr>
<td>MC</td>
<td>Motorcycles</td>
<td>2 strokes&lt;50cc</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 strokes&gt;50cc</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 strokes 50-250cc</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 strokes 250-750cc</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 strokes&gt;750cc</td>
</tr>
<tr>
<td>ST</td>
<td>Small trucks</td>
<td>LCV - gasoline</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LCV - diesel</td>
</tr>
<tr>
<td>BT</td>
<td>Big Trucks</td>
<td>HDV - gasoline</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HDV - diesel 3.5T - 7.5T</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HDV - diesel 7.5T – 16T</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HDV - diesel 16T - 32T</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HDV - diesel &gt;32 T</td>
</tr>
<tr>
<td>B</td>
<td>Buses and coaches</td>
<td>Buses and coaches</td>
</tr>
</tbody>
</table>

The assumptions behind the linking of vehicle categories shown in Figure 17 is that transport users derive the same utility from driving in different vehicles (i.e. in different stock, usage and emissions module categories), as long as they are in the same transport module category. For example, a transport user will derive the same utility from driving a big gasoline car or a big diesel car, as long as it is a big car. It is this utility that the transport module considers to analyse substitution between modes. The transport user will choose between the different stock, usage and emissions module categories (within a transport module category) on the basis of lifetime costs.

In addition to a breakdown of the vehicle stock based on vehicle types, vehicles are categorized by age, ranging between zero and fifteen years old (the last category containing all vehicles aged fifteen years and older).

The vehicle stock consists of annual vintages that are handed over from period to period. The vehicle stock size in a given year t is a function of:

- the vehicle stock size in the previous year
- retirements, or scrapping of vehicles
- new vehicle sales

Hence, for a given vehicle category i:

$$\text{Stock}_i(t) = \text{Stock}_i(t-1) - \text{Scrap}_i(t) + \text{Sale}_i(t)$$  \hspace{1cm} (29)

where:

$$\text{Stock}_i(t): \quad \text{number of vehicles of type } i \text{ at the end of period } t$$
7.2. Vehicle stocks

In TREMOVE, we first consider the stock of vehicle for each TRE category. Each year, the stock of vehicles desired by transport users in each category is computed as the ratio of demand of vkm by category divided by its average annual mileage.

\[ \text{Desired stock}_{i}(t) = \frac{\text{transport demand}_{i}(t)}{\text{annual mileage}_{i}(t)} \]

In TREMOVE, the stock of vehicle is actually described by generation, with a variable \( \text{Stock}_{i}(t, T) \), which represents the stock of vehicle of category \( i \), in year \( t \) and of age \( T \). A variable \( \text{Scrap}_{i}(t, T) \) is also introduced. To account for the description of the age structure, equation (29) is thus modified as follows.

\[ \text{Stock}_{i}(t, 0) = \text{Sale}_{i}(t) \quad (30) \]

\[ \text{Stock}_{i}(t, T) = \text{Stock}_{i}(t-1, T-1) - \text{Scrap}_{i}(t, T) \quad (31) \]

The newest generation of vehicle is equal to the new sales (equation 30). For older generations, the number of vehicles of age \( T \) in period \( t \) is the number of vehicles of age \( T-1 \) in period \( t-1 \) reduced by the number of vehicles of this generation that have been scrapped (equation 31).

Let us look at the different elements of these equations, i.e. scrapping, and sales. Technology turn-over and vehicle usage issues are addressed afterwards.

7.3. Scrapping

The scrapping rate is computed in TREMOVE for each year (year \( t \)), for each \( stock, usage and emissions \) module category of vehicle (category \( i \)), and for each generation (age \( T \)): \( \text{Scrap}_{i}(t, T) \).

Scrapping is a function of the technical life of a vehicle, the probability of breakdown before the end of the life and policies that directly or indirectly affect car costs such as purchase taxes and scrapping incentives.

TREMOVE follows the approach applied in EUCARS 2.0\textsuperscript{21}. Scrapping is partly endogenous, partly exogenous. The final scrapping rate is computed as the combination of endogenous and exogenous scrapping rates, with weights respectively at 2/3 and 1/3.

\textsuperscript{21} Cécile Denis, Gert Jan Koopman, Henk Mees, \textit{EUCARS, a partial equilibrium European CAR emissions Simulation model. Model description of versions 1.0 and 2.}
The endogenous scrapping is based on the idea that there is an age dependant probability of breakdown. Following breakdown, repair expenditures are needed to restore vehicles to operating conditions. The required repair expenditures are assumed to follow a normal distribution. This assumes that vehicles are homogenous, i.e. that, after a repair, a vehicle cannot be distinguished from other vehicles of the same generation. Non repaired vehicles cannot be used and have a market value of zero.

\[
\text{Enscrap}_i(T) = \beta \left[ 1 - F\left( \frac{MV_i(T) - RC_i(T)}{\sigma_{RC_i}(T)} \right) \right] \tag{32}
\]

where

- \( F \): normal cumulative distribution
- \( \beta \): annual breakdown probability
- \( RC_i \): average repair cost
- \( \sigma_{RC_i} \): standard deviation of the repair cost, assumed to be one third of \( RC \).
- \( MV_i \): average market value (residual value).

**Repair costs** are computed in a simple way. They increase linearly over the first 5 or 6 years of the vehicle, and then remain stable (in constant price).

\[
RC_i(T) = a_i + b_i * T \quad \text{if } T \leq 6 \tag{33}
\]

\[
RC_i(T) = RC_i(6) \quad \text{if } T > 6
\]

Where \( a_i \) and \( b_i \) are constants which depend on the purchase value of the vehicle class, and \( T \) the age of the vehicle.

The market value of a vehicle is a function of its age \( T \). We have modelled this by assuming that, in real terms, the market value of the vehicle declines rapidly in its first year (for example around 35% for a medium gasoline car), and then declines by a constant percentage rate every year (around 20% for a medium gasoline car).

We thus have an equation such as (with \( D2 \) being the annual rate of decline after the first year):

\[
MV_i(T) = \text{Purchase Price}_i * D1 * \exp^{-D2 * T} \tag{34}
\]

This endogenous scrapping enables to assess the long term impact of scrapping schemes, i.e. of scrapping schemes which are set up and remain in place over the forecast interval. Scrapping scheme such as those implemented recently in a number of countries cannot be accurately simulated with this approach, as the impact of such schemes depend on a number of other factors not taken into account here (for example, consumers anticipate that the scheme will not last).

There is also a fixed proportion of exogenous scrapping, representing car that can no longer be repaired. As in EUCARS, we have modelled this using
the FOREMOVE\textsuperscript{22} approach. The presence probability $PP_i(T)$ of vehicle category $i$ and age $T$ is the share of vehicles that remain operating $T$ years after being sold.

$$PP_i(T) = \exp \left[ - \left( \frac{T + b_i}{L_i} \right)^{b_i} \right]$$ \hspace{1cm} (35)

where

- $b_i$: failure steepness for vehicle type $i$
- $L_i$: characteristic technical life for vehicle type $I$

The exogenous scrapping rate for the vehicle category $i$, as a function of age $T$, is directly derived from this presence probability:

$$\text{Exscrap}_i(T) = 1 - \left[ \frac{PP_i(T)}{PP_i(T-1)} \right]$$ \hspace{1cm} (36)

Thus total scrapping for a given vehicle category $i$ of age $T$ is:

$$\text{Scrap}_i(t, T) = \left[ 1 - \left( 1 - \frac{2}{3} \times \text{Enscrap}_i(T) \right) \times \left( 1 - \frac{1}{3} \times \text{Exscrap}_i(T) \right) \right] \times \text{Stock}_i(t-1, T-1)$$ \hspace{1cm} (37)

$$\text{Scrap}_i(t) = \sum_T \text{Scrap}_i(t, T)$$ \hspace{1cm} (38)

where

- $\text{Scrap}_i(t)$: number of vehicles of type $i$ scrapped during period $t$
- $\text{Scrap}_i(t, T)$: number of vehicles of type $i$ and age $T$ scrapped during period $t$
- $\text{Enscrap}_i(T)$: endogenous scrapping rate for vehicle type $i$ of age $T$
- $\text{Exscrap}_i(T)$: exogenous scrapping rate for vehicle type $i$ of age $T$

7.4. Sales

The stock of vehicles surviving from the year before:

$$\text{Surviving Stock}_i(t) = \text{stock}_i(t-1) - \text{Scrap}_i(t)$$ \hspace{1cm} (39)

will in general be lower then the stock of vehicles desired by the transport users. The difference between the desired stock and the surviving stock will be the sales. Thus, for each category $i$ and year $t$, we have

$$\text{Sale}_i(t) = \text{Stock}_i(t) - \left[ \text{Stock}_i(t-1) - \text{Scrap}_i(t) \right]$$ \hspace{1cm} (40)

The above computation is done for each transport module category. The split of new sales between the corresponding stock, usage and emissions module categories, is based on lifetime cost of each type of vehicle, through

\textsuperscript{22} Although in FOREMOVE, scrapping is only exogenous, i.e. it is not linked to costs.
a logit-type function. Consumers buying a vehicle of the aggregate (TRE) category C will choose between the different vehicle types (the stock, usage and emissions module types) which constitute the aggregate category, according to the different lifetime costs. For these choices, two logit-type functions are used. A first version is used for trucks and motorcycles. A second, more integrated approach is followed for cars.

7.4.1. Trucks and motorcycles

The probability that a given buyer choose alternative $i$ within category C is given by:

$$P_{C,i} = \frac{V_i^\mu}{\sum_{k \in C} V_k^\mu} \quad (41)$$

with $V_k$ is a function of the lifetime cost of vehicle type $k$:

$$V_k = f_k \times \exp(\text{lifetime cost}_k) \quad (42)$$

In this case, we have set the parameter $\mu$ to 1, and computed $f_k$ on the basis of the market share in 1996.

When required, the shares of alternatively-fuelled vehicles in new sales are specified with reference to legislative requirements, and these percentages are applied to their respective classes, yielding alternatively-fuelled vehicle sales for each class. Alternatively-fuelled vehicles (AFVs) are likely to be separated into electric and non-electric vehicles based on the assumption that electric vehicles will only penetrate the market to the extent that legislative mandates require, at least over the near to medium term. Other types of AFVs, such as compressed natural gas (CNG), ethanol, propane, methanol, M85 (85% methanol/15% gasoline) and flex-fuelled (M85/gasoline) vehicles, are assumed to compete with each other to comply with legislative mandates based on relative economics and also with gasoline and diesel vehicles in some markets, depending on refined fuel and gas prices.

7.4.2. Cars

The TRE-category of small cars corresponds to the next level – MOVE – category of small gasoline cars. There is thus no further choice to be made by the consumer in this category. The TRE-category of big cars, however, corresponds to several MOVE categories: medium and big cars, using either gasoline, diesel or LPG (other fuels can be introduced in scenarios).

In this category, the choice of the consumer purchasing a car will be divided into 2 steps. First, the consumer will decide between a medium car (below 2000cc) and a large car (above 2000cc). Then, the consumer will decide which fuel will be used. This structure is shown on Figure 18.
As we already have the absolute figure of cars in the aggregated TRE-category (big cars), it is enough to know which share will have each MOVE sub-category. We use logit functions to compute those shares. Logit functions are a well-established way of modelling consumer choice concerning car ownership\textsuperscript{23}.

We assume that the consumer will make its decision based on the lifetime cost per kilometre in each category. In order to compare lifetime costs over the different countries and over categories, a constant life expectancy (12.5 years) and a constant mileage (18,000 km per year) have been assumed. It has also been assumed that the sensitivity towards price is constant across Europe (so the coefficient of lifetime cost is constant over categories and over countries).

**First step: choice between medium and large cars**

The shares of medium and of large cars in country $l$ at time $T$ are computed respectively as:

$$\text{shareML}(\text{medium},l,T) = \frac{e^{\alpha * \text{LFC}(\text{medium},l,T) + \beta (\text{medium},l) + \gamma (\text{medium},l)}}{e^{\alpha * \text{LFC}(\text{medium},l,T) + \beta (\text{medium},l) + \gamma (\text{medium},l)} + e^{\alpha * \text{LFC}(\text{large},l,T)}}$$

\textsuperscript{23} Some references are:


shareML(large,l,T) = \frac{e^{\alpha*\text{LFC}(\text{large},l,T) + \beta(\text{medium},l) \cdot \text{INC}(l) + \gamma(\text{medium},l)}}{e^{\alpha*\text{LFC}(\text{large},l,T)}}

where LFC stands for the lifetime cost per kilometre and INC for the income per capita. These two shares add up (identically) to 1.

In this function \( \alpha \) - the coefficient of the lifetime cost – is the effect of a change in the (relative) lifetime cost on the shares of medium and large cars, which is assumed constant over the countries.

The \( \beta \) coefficient, normalised to zero for large cars, expresses the effect of a change in the per capita income on the share of medium cars. Our assumption is that \( \beta \) is negative, and thus that the larger the income per capita is, the smaller is the share of medium-sized cars. This \( \beta \) coefficient is assumed constant across countries.

The \( \gamma \) coefficient, normalised to zero for large cars, expresses the (positive or negative) preference for medium-sized cars, which cannot be explained by difference in (lifetime) costs. This \( \gamma \) is assumed country-dependent, since the preference for medium-sized cars differs from country to country.

The lifetime cost of a medium-sized car is the weighted average of the lifetime costs of a medium gasoline, a medium diesel and a medium LPG car. The weights are the shares of the latter categories within the medium-sized car category.

Similarly, the lifetime cost of a large car is the weighted average of the lifetime costs of a large gasoline and a large diesel car. All LPG cars are accounted for in the medium category.

Second step for large cars: choice between gasoline and diesel

Once the size of the car is chosen, the consumer must choose the fuel used by the vehicle. Two types of fuels are recognised for large cars: gasoline and diesel. These shares of gasoline and diesel engines in large cars are:

\[
\text{shareL(gasol.,l,T)} = \frac{e^{\alpha*\text{LFC}(\text{L, gasoline},l,T) + \beta(\text{L, gasoline},l)}}{e^{\alpha*\text{LFC}(\text{large},l,T)}} + e^{\alpha*\text{LFC}(\text{L,diesel},l,T)}
\]

\[
\text{shareL(diesel,l,T)} = \frac{e^{\alpha*\text{LFC}(\text{L, gasoline},l,T) + \beta(\text{L, gasoline},l)}}{e^{\alpha*\text{LFC}(\text{large},l,T)}} + e^{\alpha*\text{LFC}(\text{L,diesel},l,T)}
\]

Note: the \( \alpha \) coefficient is not necessarily equal to the \( \alpha \) in the logit function of the choice between medium and large cars.

Second step for medium cars: choice between gasoline, diesel and LPG

Similar functions are estimated for the choice between diesel, gasoline and LPG within the medium-sized car category\(^{24}\).

\[^{24}\text{In some countries the number of LPG cars is negligible, and so the share of LPG cars is set to 0. These countries are: Finland, France, Germany and the United Kingdom.}\]
shareM(gasol.,l,T) = \frac{e^{\alpha \text{LFC}(M, \text{gasoline},l,T) + \beta (M, \text{gasoline},l)}}{e^{\alpha \text{LFC}(M, \text{gasoline},l,T) + \beta (M, \text{gasoline},l)} + e^{\alpha \text{LFC}(M, \text{diesel},l,T) + \beta (M, \text{diesel},l,T)} + e^{\alpha \text{LFC}(M, \text{LPG},l,T) + \beta (M, \text{LPG},l)}}

shareM(diesel,l,T) = \frac{e^{\alpha \text{LFC}(M, \text{diesel},l,T)}}{e^{\alpha \text{LFC}(M, \text{gasoline},l,T) + \beta (M, \text{gasoline},l)} + e^{\alpha \text{LFC}(M, \text{diesel},l,T) + \beta (M, \text{diesel},l,T)} + e^{\alpha \text{LFC}(M, \text{LPG},l,T) + \beta (M, \text{LPG},l)}}

shareM(LPG,l,T) = \frac{e^{\alpha \text{LFC}(M, \text{LPG},l,T) + \beta (M, \text{LPG},l)}}{e^{\alpha \text{LFC}(M, \text{gasoline},l,T) + \beta (M, \text{gasoline},l)} + e^{\alpha \text{LFC}(M, \text{diesel},l,T) + \beta (M, \text{diesel},l,T)} + e^{\alpha \text{LFC}(M, \text{LPG},l,T) + \beta (M, \text{LPG},l)}}

The estimations of the coefficients of the different functions – method and values – are given in Annex C.

7.5. Technology turnover

The approach described so far is age-driven. However, the emission behaviour is dependent on the technology, for each of which COPERT II provides a set of emission factors. For this reason, the age distribution of vehicles is transformed into a technology distribution showing the technology mix of a vehicle class for each consecutive period.

To this aim, we created a technology implementation matrix TECHM_i (TC, RY), that indicates, for each MOVE vehicle category i and each registration year RY, the share of each technology TC for the vehicle sold that year (see Appendix 7.1). In any given year t, we thus have the stock of vehicle (of type i) for each technology:

\[
\text{Stock}_{TC_i}(t, \text{TC}) = \sum_T \text{TECHM}_i (\text{TC}, t-T) \times \text{Stock}_i(t, T)
\]  

7.6. Vehicle usage

Average vehicle usage depends in large part upon the vehicle’s age and class. Usually, the smaller the vehicle, the fewer kilometres are driven each year; similarly, the older the vehicle, the fewer kilometres are driven each year. Aggregated vehicle usage (in terms of vkm) for the TRE vehicle categories is transmitted from the passenger and freight transport demand modules. On the basis of historic usage rates for all vehicle types that are available in CORINAIR/COPERT and of simple assumptions with regard to the future evolution of vehicle usage parameters, aggregate vehicle usage is disaggregated between the different vehicle class according to type and age. While each category has an overall average annual mileage, we have assumed, using data from MEET deliverable 21, an age (T) distribution, so that new vehicles are driven more than older ones.

\[
\text{Usage}_i(t, T) = \frac{M_i(t)}{T^{0.37}}
\]
where $M_i(t)$ is the mileage for a new vehicle of category $i$ and year $t$. 
### Appendix 7.1: Vehicle Technology Matrices

#### Correspondence between registration year and emission standards (part 1 - passenger cars)

<table>
<thead>
<tr>
<th>Country</th>
<th>1997 to 2020</th>
<th>1999 to 2020</th>
<th>2006 to 2020</th>
</tr>
</thead>
</table>

#### Correspondence between registration year and emission standards (part 2 - other road vehicles)

<table>
<thead>
<tr>
<th>Type</th>
<th>1970 to 1996</th>
<th>1970 to 2005</th>
<th>1970 to 2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euro III</td>
<td>2001 to 2005</td>
<td>2001 to 2005</td>
<td>2001 to 2005</td>
</tr>
<tr>
<td>Euro IV</td>
<td>2006 to 2006</td>
<td>2006 to 2006</td>
<td>2006 to 2006</td>
</tr>
</tbody>
</table>

| Euro III | 2001 to 2005 | 2001 to 2005 | 2001 to 2005 |
| Euro IV | 2006 to 2006 | 2006 to 2006 | 2006 to 2006 |

| Euro III | 2001 to 2005 | 2001 to 2005 | 2001 to 2005 |
| Euro IV | 2006 to 2006 | 2006 to 2006 | 2006 to 2006 |

| Euro III | 2001 to 2005 | 2001 to 2005 | 2001 to 2005 |
| Euro IV | 2006 to 2006 | 2006 to 2006 | 2006 to 2006 |

| Euro III | 2001 to 2005 | 2001 to 2005 | 2001 to 2005 |
| Euro IV | 2006 to 2006 | 2006 to 2006 | 2006 to 2006 |
8. MODELLING FUEL CONSUMPTION AND EMISSIONS

This module calculates fuel consumption and vehicle emissions for each year of the forecast period, based on vehicle use, driving modes, the structure of the vehicle stock, vehicle characteristics and fuel characteristics.

The calculation of emissions applies the COPERT II methodology\textsuperscript{25,26} (COPERT = COmputer Programme to calculate Emissions from Road Traffic, a computer programme developed in the framework of the European Environment Agency’s CORINAIR project). This methodology is also the basic methodology used in the FOREMOVE model\textsuperscript{27,28}. TREMOVE thus ensures consistency with the CORINAIR inventory.

The emission calculation is done for each of the pollutants selected within the Auto-Oil II Programme, i.e. NO\textsubscript{x}, VOC, CO, particulate matter (PM\textsubscript{10}), benzene (C\textsubscript{6}H\textsubscript{6}). VOC, together with NO\textsubscript{x} emissions are also computed, as these two pollutants enter in the formation of tropospheric ozone (O\textsubscript{3}). However, ozone concentration is not computed by TREMOVE. Benzene is computed as a share of all non-methane VOC emissions. Methane emissions are thus also computed in TREMOVE.

Emissions of CO\textsubscript{2}, SO\textsubscript{2} and N\textsubscript{2}O are also included in TREMOVE, following a much simpler methodology, as described in COPERT II.

CO\textsubscript{2} emissions are directly linked with the carbon content of the fuel.

SO\textsubscript{2}, emissions are directly proportional to the fuel consumption and the sulphur content of the fuel.

For methane and N\textsubscript{2}O, COPERT II provides emission factors that include all emissions. Additional cold start emissions are thus not taken into account separately, but are assumed to be included into the published emission factor. According to COPERT II, N\textsubscript{2}O emission factors are rough estimates, and need confirmation with further measurements. Figures for this pollutant have thus to be treated with great care.


\textsuperscript{28} Zachariadis, (1992), FOREMOVE Forecast of Emissions from Motor Vehicles, User’s Manual, Thessaloniki
The reader is referred to the COPERT II\textsuperscript{29} methodology manual for further details. We summarise below (section 9.2.) the COPERT II methodology to compute emissions of the main regulated pollutants: NO\textsubscript{x}, CO, particulate matter (PM\textsubscript{10}) and VOC.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{flow-chart}
\caption{Flow chart of fuel use and emission module}
\end{figure}

8.1. Fuel consumption

For a particular class of vehicle i, fuel consumption is determined by multiplying the vehicle stock for that class by the average kilometres travelled per vehicle and by the average fuel efficiency of that class.

\[
FC_i = \sum_{TC} \text{Stock}_{TC_i}(t, TC) \times \text{Usage}_i \times FE_{TC} \tag{45}
\]

where

- \(FC_i\): fuel consumption of vehicle category i
- Usage\(_i\): average annual mileage of vehicle of category\(_i\) (as a function of age)
- FE\(_{TC}\): fuel efficiency of technology TC

Information on vehicle stocks and usage are computed in the vehicle stock module of MOVE. Average fuel efficiency for a given year for a given class is a weighted average of the efficiency of each of the vintage years (and thus technologies) comprising the vehicle stock. It takes into account the

\textsuperscript{29} See reference to COPERT II above.
efficiency of the cars that remain in the stock from one year to the next and the efficiency of new cars, which itself depends on policies and regulations. Policies that affect the retirement rate can therefore have a significant impact on average fuel efficiency.

In the COPERT II methodology, fuel efficiency remain constant after the introduction of Euro I vehicles. To take account of the future improvements of fuel efficiency on fuel consumption and CO₂ emissions, we have introduced improvements of fuel efficiency in TREMOVE on the basis of discussions with vehicle experts.

8.2. Emissions

There are three categories of emissions from road transport:

- hot emissions (emissions from vehicles after they have warmed up)
- cold start emissions (emissions from vehicles while they are warming up)
- evaporative emissions (for gasoline engines only, in the form of NMVOC emissions).

Exhaust (hot and cold start) and evaporative emissions are computed separately. Extra emissions due to cold start are added to hot emissions. In addition to the emission factors provided by COPERT II (which are technology specific), degradation or improvement factors are included to take into account the age structure of the fleet, together with possible inspection and maintenance schemes. The basic formulae for the three categories of emissions are as follows.

**Hot emissions**

Emission factors for the different pollutants are technology specific and speed dependent. Therefore, they vary with the class of vehicle (type/size/fuel) and technology, as well as with the road classes (urban, rural, highway), as average speeds differ across the three infrastructure networks. For each class of vehicle i and class of road r, the speed is provided by the equilibrium module. Hot emission factors are expressed in g/km. Total emissions are measures in tonnes.

For each pollutant, total emissions are the sum of all emissions for all vehicle types on all road categories. Each vehicle category is to be further detailed by its age T and technology TC.

\[ EM_{hot} = \sum_{i,r} EM_{hot,i,r} \]

Each vehicle category is to be further detailed by its age T and technology TC. The age dependence is implicit in the usage variable, and the emission factor if there is an age-dependant degradation factor.

\[ EM_{hot,i,r} = \sum_{TC} e_{hot,i,r,TC} * StockTC_i(t, TC) * Usage_i * Share_{i,r} \] (46)
where

\[ EM^{\text{hot}} \] : total ‘hot’ emissions in tonnes

\[ EM^{\text{hot}}_{i,r} \] : total ‘hot’ emissions in tonnes for vehicle category i and technology TC

\[ e^{\text{hot}}_{i,r,TC} \] : hot emission factor (as a function of speed/road class), in g/km, for vehicle category i and technology TC

\[ \text{Usage}_i \] : annual mileage of vehicle category i (as a function of vehicle age)

\[ \text{Share}_{i,r} \] : share of usage of vehicle category i on road class r

**Cold start emissions**

Cold starts of vehicles result in cold emissions, in addition to the ‘normal’, hot emissions. They take place under all three driving conditions (urban, rural and highway). However, they are most likely to occur in urban driving. In principle they occur for all vehicle categories, but emission factors are only available or can be reasonably estimated for gasoline, diesel and LPG passenger cars and light duty vehicles, so that only these categories are covered by the COPERT II methodology. Moreover, cold emissions are considered not to be a function of vehicle age.

These additional emissions are taken into account by adding to the hot emissions for urban driving. Cold start emissions are calculated by making an assumption on the proportion of usage with a cold engine.

For each pollutant:

\[ EM^{\text{cold}}_i = \beta \cdot \left\{ \left( \frac{e^{\text{cold}}}{e^{\text{hot}}} \right)_c - 1 \right\} \cdot e^{\text{hot}}_{i,\text{urban}} \cdot \text{Usage}_i \quad (47) \]

where

\[ \beta \] : fraction of mileage driven with cold engines or catalyst operated below the light-off temperature

\[ \left( \frac{e^{\text{cold}}}{e^{\text{hot}}} \right)_c \] : cold to hot ratio of emissions

The parameter \( \beta \) depends on ambient temperature \( t_a \) (varying from country to country) and pattern of vehicle use, in particular the average trip length \( l_{\text{trip}} \). The cold to hot ratio of emissions also depends on the ambient temperature and pollutant considered. For each country, it is proposed to use COPERT II or FOREMOVE estimations of these parameters.

For each pollutant, TREMOVE also computes total exhaust emissions, the sum of hot and cold start emissions.

**Evaporative emissions**

Evaporative emissions concern only VOC emissions. They are calculated for all gasoline engines vehicle category i as the sum of diurnal emissions, hot soak emissions and running losses.
\[ \text{EM}^{\text{em}}_{\text{VOC}} = \sum \{ 365 \times \text{Stock}_i \times e^{\text{diurn/soak}}_i + e^{\text{runn}}_i \times \text{Usage}_i \} \] (48)

The average emission factor for diurnal and hot soak losses depends on average ambient temperature \( t_a \), average daily temperature variation, fuel volatility (RVP), fraction of gasoline powered engines equipped with fuel injection and driving pattern. The average emission factor for running losses depends on average monthly ambient temperature \( t_a \), fuel volatility (RVP), and driving pattern. Concerning driving pattern, the COPERT II methodology\(^{30}\) requires a number of statistical data, which, in many countries, are not available. COPERT II also proposes a number of simplification and estimation that will also be adopted in Tremove.

In addition, due to the lack of test data on evaporative emissions of gasoline light duty vehicles and two wheelers, the complete methodology can only be fully applied for gasoline passenger cars. For the two other categories, rough assumptions have been used in COPERT II/FOREMOVE and have been applied in Tremove as well: gasoline light duty vehicles are considered like uncontrolled gasoline passengers cars with regard to emission factors and driving pattern; two wheelers are treated like uncontrolled gasoline passengers cars with regard to driving pattern, but, due to their smaller fuel tanks, it is assumed that emission factors are 0.2 times those of passenger cars for motor cycles <50 cm³ and 0.4 times those of passenger cars for motor cycles >50 cm³.

8.3. Additions to COPERT II methodology

A number of improvements have been brought to COPERT II to take account of developments that occurred since the publication of this methodology (such as the continuation of the MEET programme or the publication of the Auto Oil I Directive). These changes were proposed by Prof. Samaras, of the Aristotle University of Thessaloniki, one of the authors of COPET II. These changes have been discussed with experts from Auto-Oil II Working Groups 2 and 3\(^{31}\)

Emission factors for future technology (Euro II, III IV and V)

- Emission factors for future technology (Euro II, III IV and V) have been included. It should be noted however that these emission factors are provided as reduction factors to be applied to EURO-I emission factors, which were actually sampled. Until more recent sample data is considered in future updated of the COPERT methodology, these effects need to be seen as “best available estimates” only.

Cold start emissions for gasoline engines

- Parameters used in the computation of cold start emissions for gasoline engines have been changed, to take account of the shorter light off time

\(^{30}\) based itself on CONCAWE’s methodology for evaporative emissions (1990).

\(^{31}\) We are grateful for the constructive comments provided by Prof. Samaras and Dr. White whose expertise was made available though ACEA and EUROPIA.
for catalysts. This concerns two parameters: $\beta$ and the ratio of cold to hot emissions. The value of $\beta$ for Euro II, III and IV is equal to the value for EURO I multiplied respectively by a factor of 0.72 (EURO II), 0.32 (EURO III) and 0.18 (EURO IV). The ratio of cold to hot emissions, a linear function of ambient temperature in COPERT II, is now a linear function of both ambient temperature and speed (for EURO I and II). For EURO III and IV, this ratio is further multiplied by 0.49 (for CO) or 0.47 (for VOC’s).

**Evaporative emissions for Euro III and Euro IV**
- Evaporative emissions for Euro III and Euro IV will to be much smaller than for previous vehicles. We assumed them to be 20% of EURO II evaporative emissions.

**Impact of fuel specifications: the EPEFE equations**
- The impact of changes in fuel specification from the Auto Oil I average have been taken into account by introducing the EPEFE equations, as described in Auto-Oil I. The applicability of these functions in relation to near future technology is currently under discussion and thus needs to be treated with care. The results of these discussion were not available at the time the TREMOVE model was released to WG7.

**Degradation factors for catalysts in gasoline vehicles**
- Degradation factors for catalysts in gasoline vehicles have been introduced.

The test data which support COPERT II correlations for conventional vehicles consist of measurements conducted on in-use vehicles of different ages and maintenance levels, since all these categories (pre Euro I vehicles) were widely in circulation at the time of testing. In the case of the newest categories of vehicles (Euro I and after), the database of measured emissions was constructed using relatively new vehicles. COPERT II emission factors for conventional vehicles have thus to be considered as representative of the full lifetime of a vehicle, while emission factors for the newest categories of catalyst cars have to be considered as the “starting” point. Therefore, to account for degradation of this category of the vehicle fleet, the emission factors are adjusted by a factor (greater than unity) which is linearly dependent on mileage. The slope of the degradation depends on the type of inspection and maintenance scheme adopted.

**Methane emissions**
- Currently, COPERT II does not include methane emission factors for catalyst cars. Measurements are under way to improve this situation. For these vehicles, preliminary data show that the methane content of total VOC emissions (both hot and cold) is around 15%.

Using this crude estimate leads to a risk of underestimating methane emissions from catalyst cars. However, road transport is only a minor contributor to methane emissions, and methane is not used (as is the
case in the original COPERT II) to compute benzene emissions. This approximation should thus be acceptable in the framework of Auto-Oil II.

**Benzene emissions**

- Benzene exhaust emissions are computed as a share of total VOC emissions, this share being computed by one of the EPEFE equations in the case of gasoline vehicles. Evaporative emissions are computed as in Auto Oil I (page 50 of the *Air Quality Report of the Auto-Oil Programme*), using the formula:

\[
\text{EVAP}_{\text{benzene}} = 1.173 \times \text{EVAP}_{\text{VOC}} \times \text{Vol\%}(\text{benzene})
\]

**Fuel efficiency improvements**

- In COPERT II, no improvement in fuel efficiency is provided after the EURO I vehicles (arriving on the market in the mid-nineties). The forecast of total fuel consumption and CO2 emissions would thus be higher than in forecasts including an improvement in fuel efficiency. The pre-Kyoto scenario, for example, assumes that fuel efficiency will improve at an annual rate of about 0.9% per year, due to changes in the vehicle stock, in the transport system, (both taken into account in this scenario), and due to technological improvement (not accounted for here). In this basecase scenario, following discussions with ACEA and WG7, we have assumed new cars would see improvements of fuel efficiency of 1.3% per year until 2003, 3.5% per year between 2003 and 2008, and 1% per year thereafter.

**Experimental emission factors for gasoline and non-exhaust particulate matter**

COPERT II only accounts for particulate emissions of diesel engines. Other sources suggest that particulate are also emitted by gasoline engines. Even if particulate emission factors are smaller for gasoline engines, the sheer number of these vehicles implies that their contribution might not be neglected. Other sources of particulates in the air is the wear of tyres and brakes of all vehicles, the damage caused to the road surface and the resuspension of dust on the ground that is caused by traffic. We have regrouped these sources in a category named non-exhaust emissions of particulates.

Information is limited on these topics. Senco, consultant of Working Group 1, has collected the available information from existing sources. The following emission factors have been suggested (Table 5).

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Emission factor g/km</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars</td>
<td>1990 : 0.046</td>
<td>UK NETCEN/NAEI</td>
</tr>
<tr>
<td></td>
<td>1991 : 0.043</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1992 : 0.040</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1993 : 0.037</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1994 : 0.034</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1995 : 0.032</td>
<td></td>
</tr>
</tbody>
</table>
## Light commercial vehicles

<table>
<thead>
<tr>
<th>Year</th>
<th>Emission Factor (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>0.066</td>
</tr>
<tr>
<td>1991</td>
<td>0.063</td>
</tr>
<tr>
<td>1992</td>
<td>0.060</td>
</tr>
<tr>
<td>1993</td>
<td>0.057</td>
</tr>
<tr>
<td>1994</td>
<td>0.053</td>
</tr>
<tr>
<td>1995</td>
<td>0.049</td>
</tr>
<tr>
<td>1996</td>
<td>0.045</td>
</tr>
<tr>
<td>1997</td>
<td>0.040</td>
</tr>
<tr>
<td>1998</td>
<td>0.035</td>
</tr>
<tr>
<td>1999</td>
<td>0.031</td>
</tr>
<tr>
<td>2000</td>
<td>0.028</td>
</tr>
<tr>
<td>2001</td>
<td>0.025</td>
</tr>
<tr>
<td>2002</td>
<td>0.024</td>
</tr>
<tr>
<td>2003</td>
<td>0.022</td>
</tr>
<tr>
<td>2004</td>
<td>0.022</td>
</tr>
<tr>
<td>2005</td>
<td>0.021</td>
</tr>
<tr>
<td>2006 and after</td>
<td>0.010</td>
</tr>
</tbody>
</table>

**Note:** The Dutch inventory uses a factor of 0.026 g/km for gasoline car exhaust and 0.055 g/km for gasoline LDV exhaust in their 1990 inventory. These are similar to the figures from the UK for the mid 1990s, and probably is due to the more rapid introduction of three way catalyst petrol cars due to the use of fiscal incentives in the Netherlands to encourage the purchase of cleaner cars.


Dutch data come from two sources: Emissions of selected heavy metals and persistent organic pollutants in Europe and urban emission inventories, (August 1998), from TNO, and National total PM10 emissions used for urban stress air quality calculations, (1999), RIVM. These two studies were done in the framework of SoER98 (European Environmental Agency) and EU priority study reports (DGXI).

We used the UK data, which allowed us the modelling of an evolution of emission factors over time, for cars and light duty vehicles. For the other vehicles, we used the Dutch data: the UK data did not include figures on gasoline HDV, and used the same data as TNO for motorcycles.
Non-exhaust emission factors come from the TNO study.

**Table 6: Non-exhaust PM\textsubscript{10} Emission Factors (excl. resuspension)**

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Emission factor g/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy duty vehicles</td>
<td>0.038</td>
</tr>
<tr>
<td>Light commercial vehicles</td>
<td>0.009</td>
</tr>
<tr>
<td>Cars</td>
<td>0.007</td>
</tr>
<tr>
<td>Motorcycles &lt;50cc</td>
<td>0.002</td>
</tr>
<tr>
<td>Motorcycles &gt;50 cc</td>
<td>0.004</td>
</tr>
</tbody>
</table>

Source: RIVM/Dutch inventory. These factors only include tyre and brake wear, and road-surface damage. They exclude the re-suspension of dust. UK uses 0.0089 g/km PM\textsubscript{10} for 4 wheeled vehicles from tyre and brake wear.

These first figures for exhaust and non-exhaust were used to run the basecase. However, at the request of Working Group 7, who found that the reliability of these data was not as scientifically founded as that of the COPERT II methodology, these additional PM emissions are reported separately, and are not aggregated with diesel particle emissions.

At the request of WG1, we used another set of emission factors for non-exhaust particle emissions. This new set of data includes the effect of the resuspension of dust by traffic. They are thus much higher than the previous figures. These new figures for the “High PM scenario”, detailed in the scenario section of the final report.

**Table 7: Non-exhaust PM\textsubscript{10} Emission Factors (incl. resuspension)**

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Emission factor g/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy duty vehicles</td>
<td>1.170</td>
</tr>
<tr>
<td>Light commercial vehicles</td>
<td>0.070</td>
</tr>
<tr>
<td>Cars</td>
<td>0.070</td>
</tr>
<tr>
<td>Motorcycles</td>
<td>0.023</td>
</tr>
</tbody>
</table>

Source: TNO