Politecnico di Milano
SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING
Master of Science – Energy Engineering

Vehicle consumption detail in modeling the integration between road transport and energy systems: a literature review and further improvements.

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Academic Year 2018 – 2019

Ringraziamenti

Ringrazio coloro che mi hanno aiutato nello svolgimento del presente lavoro di tesi, ma anche tutte quelle persone che hanno creduto in me e che mi hanno sostenuto e supportato durante questi anni al Politecnico di Milano.

Per prima cosa vorrei ringraziare il Professore Matteo Rocco per l'opportunità di sviluppare questo lavoro di tesi.
Un ringraziamento speciale va a Francesco Sanvito per il suo costante e paziente aiuto, per i suoi preziosi consigli e per le conoscenze trasmesse, che hanno contribuito notevolmente allo svolgimento del presente lavoro.

Rivolgo inoltre un pensiero a tutte quelle persone che hanno reso questo periodo al Politecnico più leggero e spensierato, ai miei familiari, alla famiglia di Chiara, a tutti i miei amici e alle persone che hanno condiviso con me un'esperienza unica ed indimenticabile come quella dell'Erasmus in particolare Maurizio, Michele, Michele A. e Jehanzeb.

Il ringraziamento più sentito va a mia mamma Anna, a Silvano, a mio fratello Andrea, a mio nonno Renato e a Chiara, per avermi supportato, ma soprattutto sopportato, in questi anni, e per aver creduto in me e avermi sempre dimostrato il loro importante sostegno e grande affetto.

Per concludere un ringraziamento al Politecnico di Milano per avermi fatto crescere come studente e prima ancora come persona e per avermi dato l'opportunità di confrontarmi con un'ambiente stimolante e di assoluto livello.

Abstract

Road passenger transport sector is on the verge of radical transformations driven by rapid technology advancements in fuels and powertrains. This sector contributes to a significant share of global CO_2 emissions and fuel consumption. Integrated assessment models (IAMs) and sector-coupling models are widely used to explore transport sector decarbonization scenarios. The advantage of using IAMs is that the scenarios derived from them consider interactions of the transport system with other productive sectors linking human activities and environmental impacts. The drawback is the level of detail in representing the transport sector and more in particular the road passenger cars segment. To increase the degree of representation of this sector, exisiting models should be supplemented with other models and approaches like travel based models. Driving cycles (DC) are considered as travel based models used to estimate emission inventories. The present thesis work aims at carring out a literature review of the existing outlooks, transportation models and driving cycles. A classification within each topic is provided, focusing on road passenger transport sector. The work then focuses on comparing the frameworks and scenarios from thirteen global transportation models with a considerable technological detail highlighting modeling structures, data, assumptions, intermediate parameters and projections. The sources of divergence and consistency between models are identified, as well as criticisms. A possible idea to overcome some of the criticisms of model is given by driving cycles, by far used in the validation step of new models. Nevertheless, additional work is required to confirm the solution proposed in this manuscript, and to delineate a methodology to implement the resulting DC into a model framework.

Keywords: Road passenger transport, Energy and transport, Integrated assessment models, Long-term scenarios, Driving cycles, Model comparison, CO_2 emissions, Literature analysis.

Sommario

Il settore trasporti passeggeri su strada è soggetto ad una fase di grande evoluzione guidata dal rapido progresso nei carburanti e nei gruppi propulsori. Questo settore contribuisce ad una quota significativa di emissioni globali di CO_2 e di consumi di carburanti. I modelli di valutazione integrata (IAM) e altri modelli di accoppiamento settoriale sono ampiamente utilizzati per esplorare percorsi di decarbonizzazione del settore dei trasporti. Il grande vantaggio degli IAM è che gli scenari che ne derivano prendono in considerazione le interazioni del sistema dei trasporti con altri settori. Lo svantaggio è il livello di dettaglio di rappresentazione del settore dei trasporti e in particolare il segmento relativo alle autovetture. Per aumentare il livello di dettaglio tecnologico nella rappresentazione di questo settore, i modelli esistenti dovrebbero essere supportati con altri modelli e approcci come ad esempio i modelli basati sui viaggi. I cicli di guida sono considerati come modelli di questo genere e sono utilizzati per stimare gli inventari delle emissioni. Infatti il presente lavoro di tesi mira a realizzare una revisione della letteratura sulle proiezioni, sui modelli legati ai trasporti e sui cicli guida esistenti. Viene fornita una classificazione all’interno di ciascun argomento, incentrata sul settore del trasporto passeggeri stradale. Il lavoro si concentra quindi sul confronto delle strutture e delle proiezioni di tredici modelli di trasporto a livello globale con notevoli dettagli tecnologici evidenziando le strutture, i dati, le ipotesi, i parametri intermedi e le proiezioni. Le fonti di divergenza e congruenza tra i vari modelli sono identificati, nonché le criticità. Una possibile soluzione ad alcune delle critiche rivolte ai modelli è fornita dai cicli di guida, utilizzati fino a questo momento nelle fasi di validazione dei nuovi modelli. Tuttavia, sono necessari ulteriori sviluppi per confermare la soluzione proposta in questo manoscritto e per stabilire una metodologia per implementare questi cicli guida nella struttura dei modelli.

Parole chiave: Trasporto passeggeri su strada, Energia e trasporti, Modelli di valutazione integrata, Scenari a lungo termine, Cicli di guida, Confronto di modelli, Emissioni di CO_2, Analisi della letteratura.

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Introduction

Transportation accounts for a significant portion of global fossil fuels use and greenhouse gas (GHG) emissions, and the greatest contribution is given by road passenger cars. Therefore, reductions in road transportation sector emissions will play an important role in any comprehensive carbon reduction strategy. The European Union (EU) recently adopted CO_2 emissions mandates for new passenger cars, requiring steady reductions to 95 gCO_2/km in 2021 [1].

Energy policies accompanying the transition towards a sustainable development process must be supported by technical analysis in which future energy scenarios are modeled and evaluated. This work analyze possible decarbonization scenarios at a global level. Scenarios envisage high electrification of transports, high use of renewable energies and a modal shift towards public transport. A comparison study of global energy scenarios is undertaken in order to provide clearer understanding and new insights on energy transition for road transport sector. By considering different available outlooks from the major organizations, this work gives a general understanding on why scenario analysis is a powerful tool for strategic conversation in energy companies.

Scenarios are based on models. Many modeling frameworks have been developed to provide an understanding of the drivers of climate change and to assist policy formation. Integrated assessment models (IAMs) are used widely for this purpose. In recent years, modelers have started to pay more attention to representing key energy demand sectors in greater detail, including the transport sector. For this reason, IAMs are able to provide insights about possible long-term developments of the global transport sector in the absence of stringent climate policies, but they can also delineate possible pathways for countries transport systems while meeting the deep emission reduction targets in compliance with Paris Climate Agreement. This agreement is expected to set the world on a path towards a substantial GHG emissions decrement [2]. The big advantage of IAMs is that the scenarios derived from them consider interactions of the transport system with other sectors. The drawback is the complexity in IAMs structure and the lower technological detail in representing energy systems and road passenger transport in an integrated way for the evaluation of emissions and fuel consumption.

In this work, some recent model developments of new transport sector models/modules are documented. The considered models are the ones with a high degree of technological detail compared to the major IAMs. The goal is to provide insights that can lead to a better representation of transport in IAMs and other models. The detailed comparison takes in consideration the modeling frameworks, underlying data, assumptions, intermediate parameters and projections to gain a better knowledge of the sources of divergence or consistency between models. As already stated, IAMs cover a crucial role in performing mitigation pathways analysis, but they should increasingly be supplemented with other models and analytical approaches, like driving cycles.

Driving cycles are introduced to describe in a greater detail the vehicle technology. These are considered as travel based models to estimate emission inventories. By supplementing these cycles to IAMs there could be the opportunity to increase the level of technological representation of passenger cars.

In the following sections, the issue concerning the importance of scenario analysis, energy system and transport sector integrated models and driving cycles are discussed. In particular:

- Chapter 1 is dedicated to the description of the Transport sector, and more in particular passenger road transport, nowadays, highlighting past shares, market trends and emission and fuel consumption data;

- Chapter 2; the methodology adopted and the steps followed for exploring and classifiying the different topics are explained;

- Chapter 3 shows the results of the literature review: a description of selected scenarios, models and driving cycles, a comparative analysis of these topics and a final discussion on possible advantages of supplementing driving cycles to transportation models.

Chapter 1
Transport sector in figures

The transport sector involves the movement of passengers and freight by various means, and may be divided into several sub-sectors such as road transport, aviation, shipping and rail. Energy needs subdivision in the transport sector is complex due to the presence of various transport modes, vehicle types, energy carriers, fuels and distribution infrastructure.

Transport is the second largest energy end-use sector, accounting for 29% of final global energy consumption in 2015, and over 75% of this is for road transport. Aviation accounts for 10.7% and shipping for 9.5% of final demand for transport [3]. (Figure 1.1).

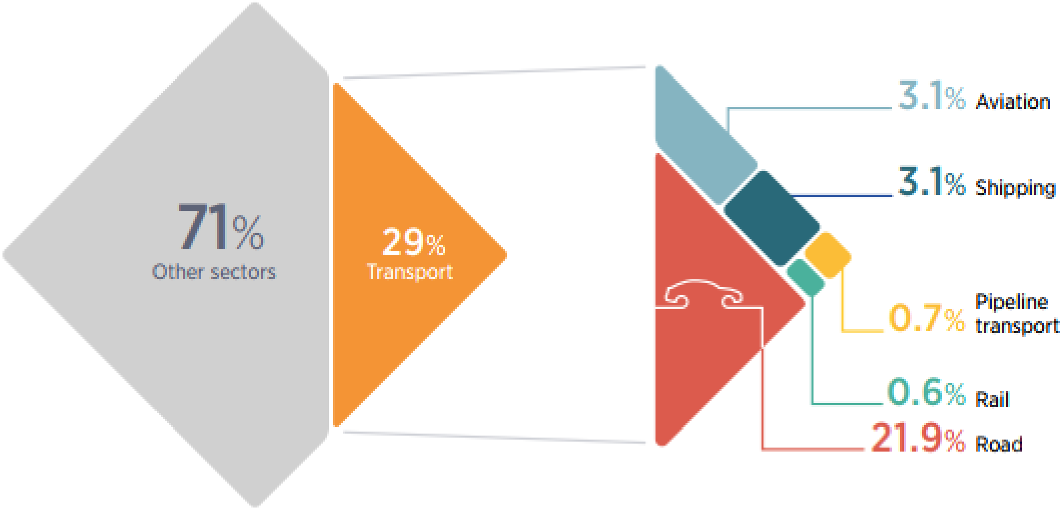


Figure 1.1. The role of transport in total final energy consumption [3]

Transport remains heavily reliant on fossil fuels. In 2015, 96% of the sector's energy use came from petroleum products, representing 64.7% of world oil consumption, and only 3.1% from renewable energy, significantly lower than that for electricity and heat [4].

The transport sector is a significant contributor to global carbon dioxide (CO_2) emissions, representing 23% of all such such global energy-related emissions, and almost 80% of that is from road transport. Passenger cars are the major polluter, accounting for two-thirds of total CO_2 emissions from road transport [3], consequently they are the main focus of this work. (Figure 1.2).

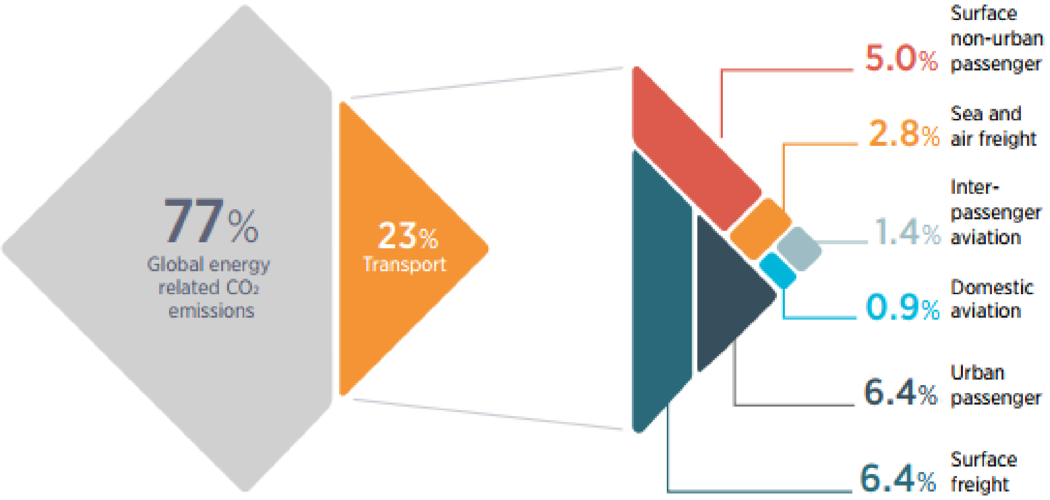


Figure 1.2. global CO_2 emissions by transport mode [3]

1.1 Number of vehicles

In the European Union (EU), around 82.9% of the vehicles moving on road in 2017 correspond to passenger cars [5].

New car registrations increased to 15.2 million [6], which is the highest level since 2007. In the previous years, due to economic crisis, sales had reached a bottom point in 2013, with 11.8 million sales. Registrations in the EU are dominated by the larger Member States; the three largest alone (Germany, France and United Kingdom) account for nearly 60% of the total. (Figure 1.3).

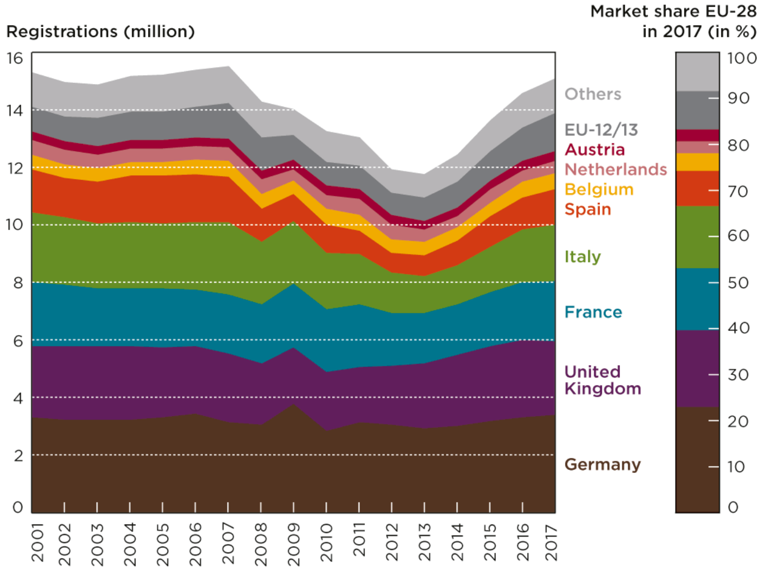


Figure 1.3. Passenger cars registrations by Member State [6]

Germany is the largest market, with a 23% share of the overall European market. Registrations in Germany dropped in 2006-2008, then rose in 2009 thanks to the government scrappage scheme, and from that point on increased again to around 3.4 million vehicles per year. By contrast, in Spain fewer than half as many new vehicles were registred in 2012 as in 2001-2007. Since 2014 sales in Spain and Italy are again trending upward sharply. In Italy total registrations in 2017 are 1.9 milions.

A notable exception to the upwards trend is the United Kingdom (UK), which is the only larger country in which registrations decreased by 6% between 2016 and 2017.

Concerning the technologies, despite the attention paid to alternative modes of road transportation in recent years, oil demand in road transportation has grown by around 11 mb/d since 2000, the largest increase in any sector over this period. Around half of this increase come from cars, nearly 40% from road freight and the remainder from two/three wheelers and buses [4]. (Figure 1.4).

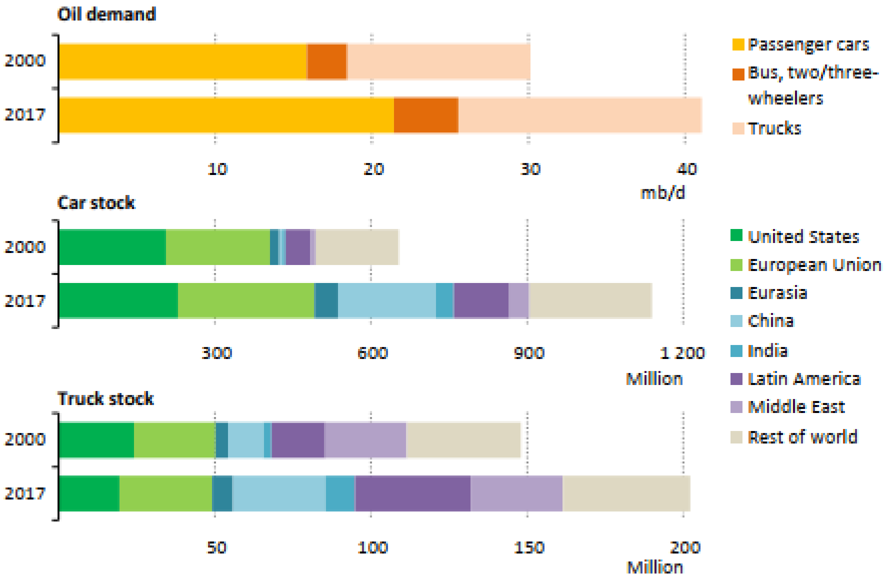


Figure 1.4. Oil demand by road vehicles by region [4]

The share of diesel cars dropped notably in 2017. In 2012 about 55% of newly registered cars in the EU were powered by diesel fuel, still now an all time high. Since then, the market share of diesel decreased, first slowly to 49% in 2016, then more speedily to 44% in 2017. However, market developments vary by Member State. For example, in France the market share of diesel cars dropped from 77% in 2008 to 47% by 2017, related to the fact that the French government is levelling out taxes on diesel and gasoline fuel [6]. (Figure 1.5).

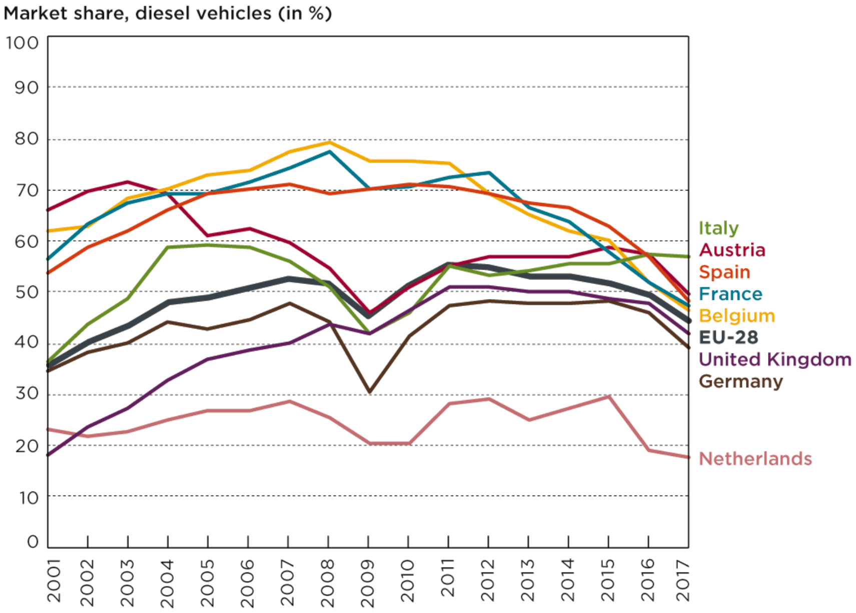


Figure 1.5. Market share of diesel passenger cars by Member State [6]

On the other hand, in Germany, the market share remained stable over the past five years at about 48% but began to drop noticeably towards the end of 2016, reaching a level of 33% in December 2017.

Amongst the largest markets, Italy is the only one where the diesel share remained relatively constant at 57% market share in 2017.

The vast majority of Europe's new cars remain powered by gasoline or diesel motors [7]. In particular diesel tends to be the preferred fuel for the larger segments, while for mini/small and sport vehicles gasoline dominates [6].

Electric mobility is expanding at a rapid pace, due to technology improvement, cost reduction, infrastructure development and increasing environmental awareness [8]. In 2018, the global electric car fleet exceeded 5.1 million, up 2 million from the previous year and almost doubling the number of new electric car sales [9]. Europe is the second largest leader in terms of electric car market share. There are three main types of electric vehicles (EVs), classed by the degree that electricity is used as their energy source: battery electric vehicle (BEV), plug-in hybrid electric vehicles (PHEV) and hybrid electric vehicles (HEV).

The market share of HEVs in the EU was 2.7% of all new cars sales in 2017 [6]. Sales of hybrid-electric cars went up in particular in Spain with an increase in the market share from 1.8% in 2015 to 4.5% in 2017. This is even higher than in Netherlands (4.2%) which used to be the EU's leading country in terms of hybrid-electric car sales for many years. (Figure 1.6).

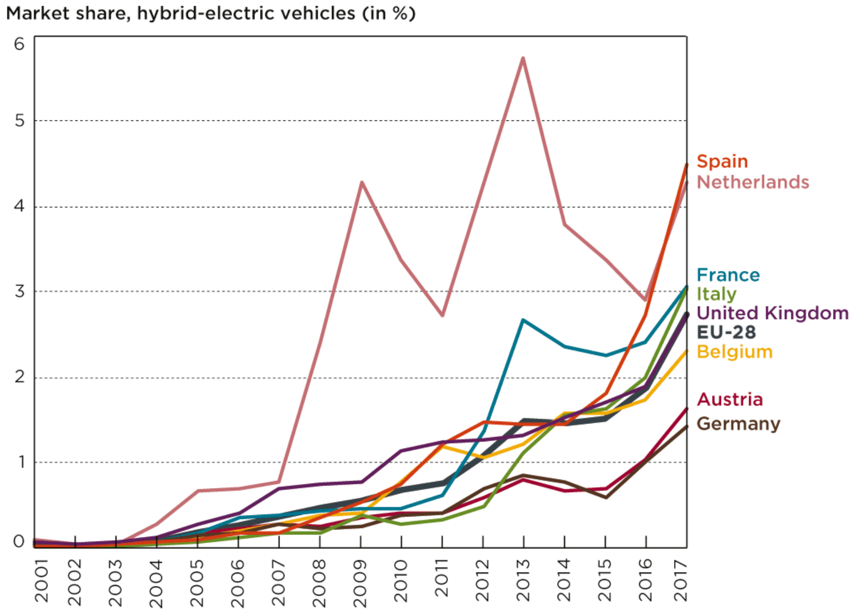


Figure 1.6. Market share of HEV by Member States [6]

In 2017, plug-in hybrid (PHEV) and battery electric vehicles (BEV) made up about 1.4% of vehicle registrations in the EU. This is a slight increase compared to the previous years. Outside the EU, sales of electric vehicles are particularly high in Norway. 39% of new cars sold there in 2017 were electric, and an additional 13% were hybrid-electric vehicles [9]. Such high market shares are attributable at least in part to generous fiscal incentives provided by the Norwegian government.

Electric vehicles are making headlines, but fuel cells are gaining momentum. Hydrogen could play a vital role in the renewable-energy system and in future mobility. Major international automotive companies have launched demonstration vehicles and plan to place fuel cell electric vehicles (FCEVs) powered by hydrogen on the market. These vehicles and the hydrogen infrastructure to fuel them are in the early stages of implementation. In Japan, South Korea, the United States and Germany three models of FCEVs are already commercially offered for passenger cars. Ten additional models are slated for release by 2020 [10].

1.2 CO_2 emissions and fuel consumption

Average CO_2 emissions of newly registered passenger cars in the EU, measured over the New European Driving Cycle (NEDC), were 119 g/km in 2017, 1 g/km higher than in 2016 but still lower than the world average of 139 g/km [6].

CO_2 emissions and fuel consumption are directly linked, so the current level of emissions amounts to about 5 liters/100 km.

The EU’s overall 2015 target of 130 g/km was met in 2013, two years ahead of schedule. Emission levels vary widely among Member States. For example Germany is at the upper end (126 g/km) and France at the lower end (110 g/km) of the spectrum. Italy has a low average of 113 g/km. The Netherlands have one of the lowest emission levels (109 g/km), even though the average new-car emission level increased in 2016 and 2017. (Figure 1.7).

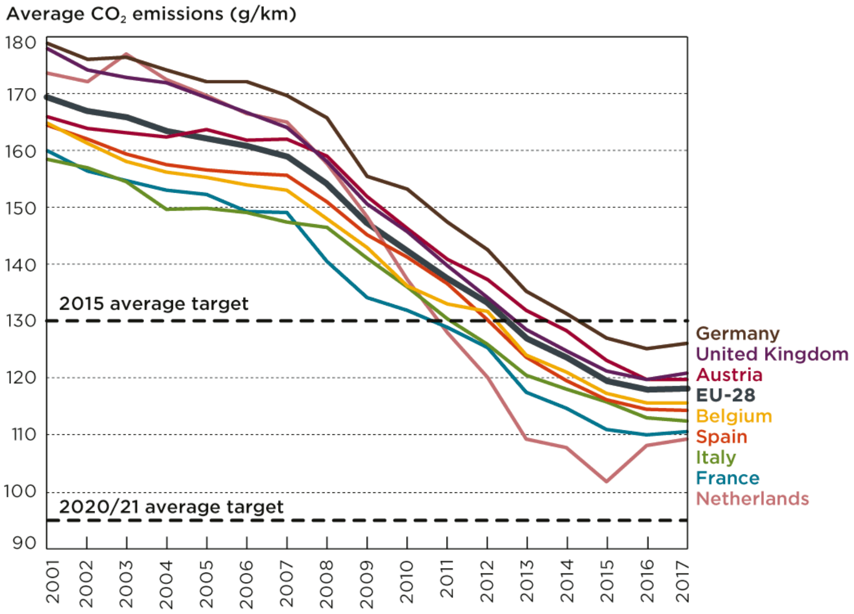


Figure 1.7. CO_2 passenger cars emissions by Member State [6]

In an international context, the EU has historically been a leader in implementing vehicle CO_2 emission standards. However, in recent years, most large economies have set converging CO_2 emission targets for new vehicles. In 2012 the European Commission formally proposed an average CO_2 emissions target of 95 g/km for 2020, which in terms of fuel consumption equates to about 4 liters/100 km. In March 2014, the regulation was formally adopted. (Figure 1.8).

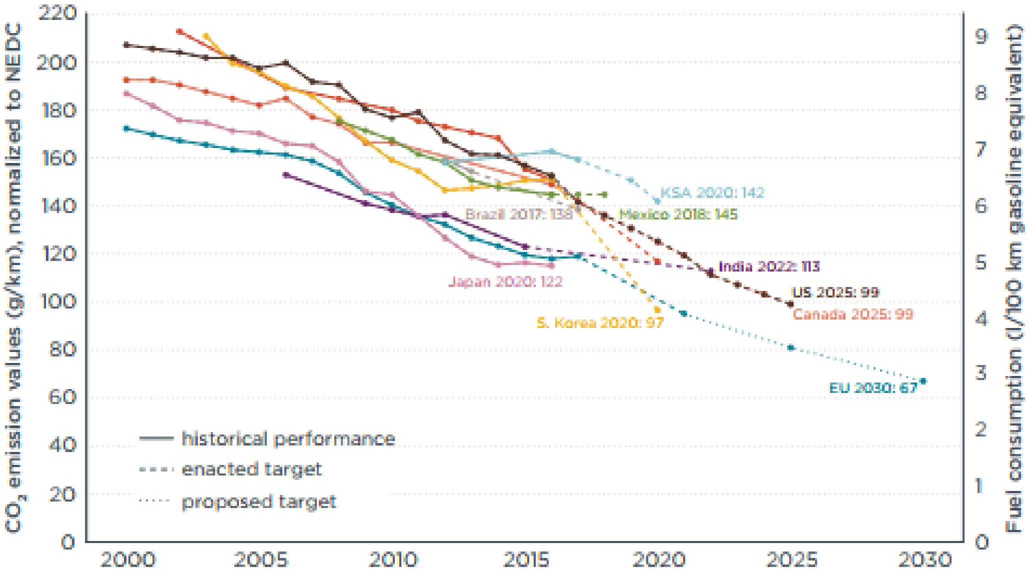


Figure 1.8. Comparison of global CO_2 regulations for passenger cars [11]

Compared to the EU's 2020/21 target, the United States (99 g CO_2/km for 2025 passenger cars), South Korea (97 g CO_2/km by 2020) and Canada (99 g CO_2/km by 2025) have set similar targets.

Under the new EU regulation, only 95% of new vehicle fleet must comply with the 95 g/km target by 2020. It sets individual targets for manufacturers, depending on the average vehicle weight of a manufacturer's fleet, and requires all manufacturers to reduce CO_2 emissions by 27% compared to their individual 2015 targets [12]. After one year of phase-in, from 2021 all new vehicles will be taken into account for calculating manufacturers fleet average.

Light commercial vehicles have their own CO_2 emission standards (147 g/km by 2020 with respect to the average fleet emission level of 175 g/km of 2017) [13].

In November 2017, the European Commission came forward with a regulatory proposal for CO_2 emissions of new passenger cars and light commercial vehicles for the time period up to 2030. The proposal includes a fleet-wide CO_2 reduction target of 15% for 2025 and 30% for 2030, but it is expected that the European Parliament and the Council (the EU member state governments) will strengthen the regulatory proposal before it will get adopted [14].

While average CO_2 emissions have dropped for all engine technologies, the decline in emission levels since 2005 has been particularly steep for gasoline vehicles. This is in part due to changes in the market, but also to the fact that the CO_2 efficiency gap between gasoline and diesel engines continues to narrow (123 g/km vs. 118 g/km in 2017). Hybrid-electric vehicles show a lower CO_2 emission level (90 g/km in 2017) [6]. (Figure 1.9).

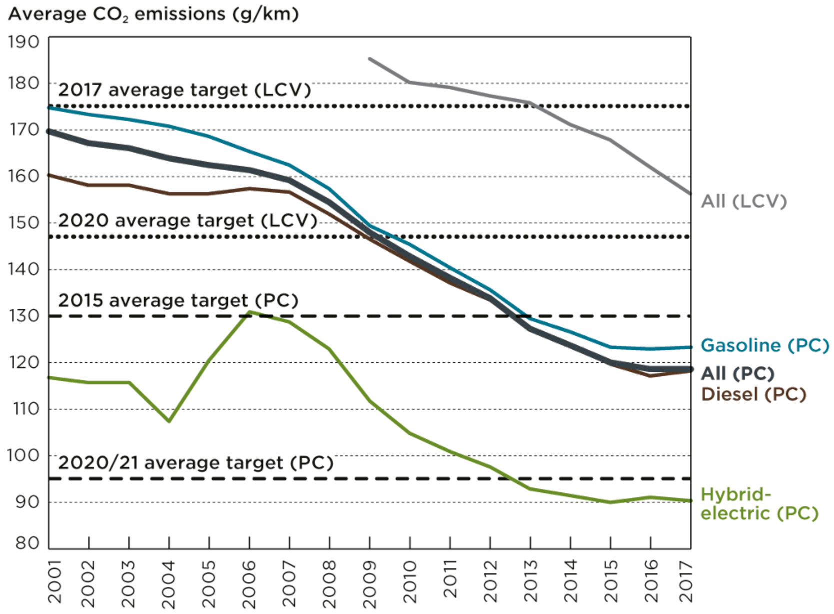


Figure 1.9. Passenger car CO_2 emissions by technology [6]

When comparing the environmental performance of vehicles with different powertrains it is important to consider the whole vehicle life cycle and fuel cycle, because CO_2 emissions and other greenhouse gas (GHG) emissions are not only produced when vehicles are driving but also by the processes used to manufacture, dispose of and recycle the vehicles, produce their fuels and provide the infrastructure to supply them with fuel (embedded emissions) [15].

Life-cycle assessment is particularly important for new technologies such as electric vehicles because their emissions vary depending on how the electricity is generated in a specific country (if it is generated mainly using coal or other fossil fuels). Embedded emissions also depend on the total distance that the vehicle is able to drive during its lifetime. (Figure 1.10).

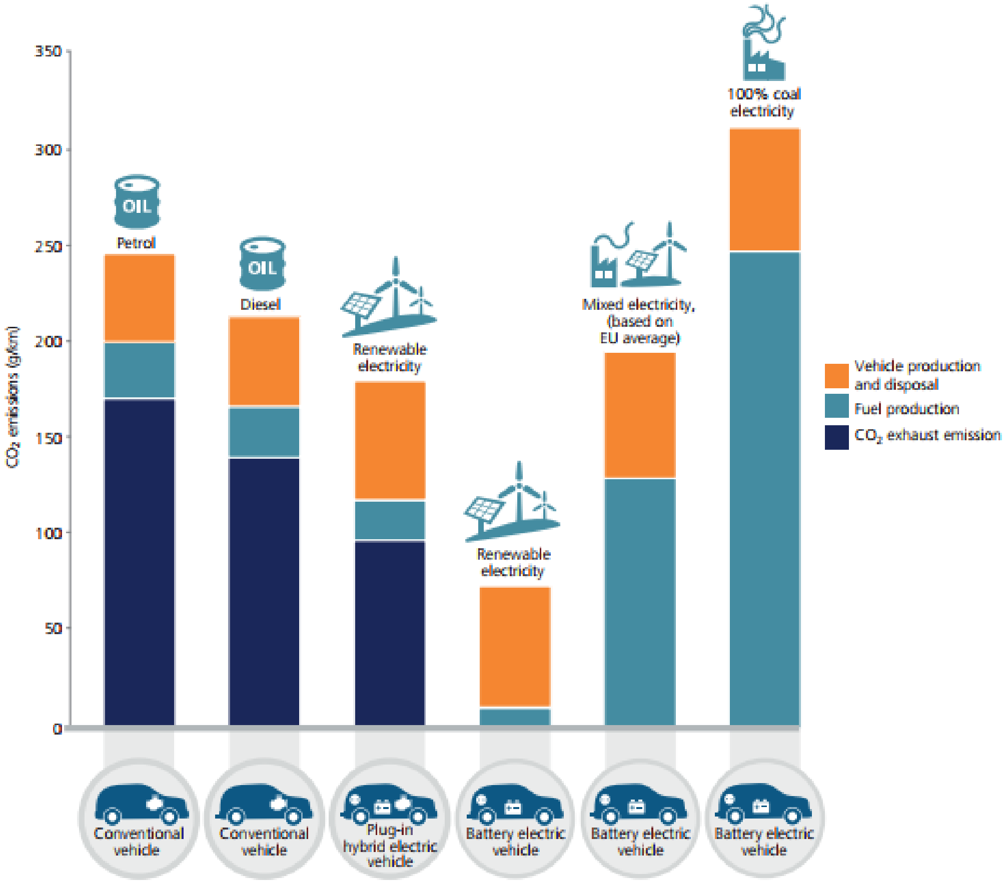


Figure 1.10. Range of life cycle CO_2 emissions for different vehicle and fuel types, based on 220,000 km [16]

Based on a life-cycle assessment, a typical battery electric vehicle emits less CO_2 than the most efficient combustion engine vehicle of the same size [6].

A comparative assessment of five powertrains (ICE, HEV, PHEV, BEV and FCEV) for a mid-size car with a GHG emissions intensity in the electricity mix that is representative of the global average (i.e. with a CO_2 emissions intensity of 518 g CO_2/kWh when including trasmissions and distribution losses) can be found in [9] and shows that EVs, FCEVs and HEVs all exhibit similar performance.

Chapter 2
Methodology

After over a century of petroleum dominance, the transportation sector is on the verge of radical evolution and transformations driven by rapid technology advancement of alternative fuels, powertrain technologies, climate changes and policies at all levels of government. Reductions in transportation sector emissions will play an important role in any comprehensive carbon reduction strategy.

This work starts from adressing the importance of the coupling between energy sector and passenger road transport, highlighting in particular the limit of this integration: the technological detail.

The main objective of the work is to analyise and assess the technological detail in modeling the integration between energy system and passenger road transport for emissions and fuel consumption.

To face this problem, a deep evaluation of the main approaches and tools used for this type of analysis is performed.

The methodology follows three main steps with an increasingly level of detail in the vehicle representation. (Figure 2.1).

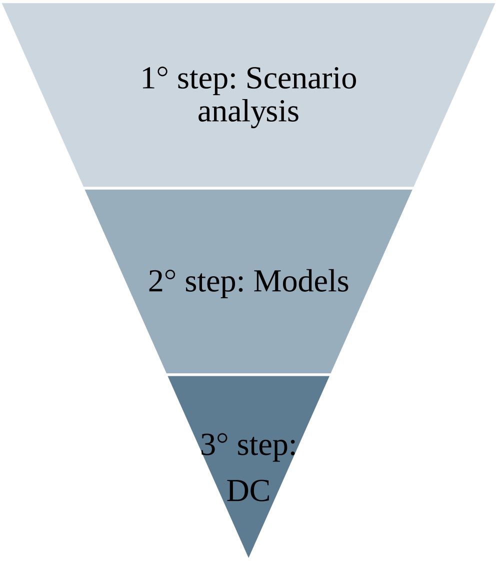


Figure 2.1. Structure of the analysis

All the work is based on a comprehensive literature review, to support the identification of the most suitable tool for specific purposes and needs.

For all the different steps this work wants to focus the attention on main characteristics in order to have a classification and a detailed analysis of the degree of detail.

Now the selected approach for each section is described in detail.

2.1 Scenario analysis

Scenarios are based on models that are key tools to explore different decarbonisation strategies. The anayisis of future energy scenarios is driven in particular by the need for evaluating the impacts of energy efficiency and decarbonization policies.

Energy scenarios are the technical basis to assess the impacts of different developments under assumptions of certain outcomes [17]. Thus, scenarios, does not try to show an exact picture of the future but instead it presents several alternative future developments in order to answer the “what if” questions [18].

It is useful to know that scenarios are typically coordinated and commissioned by the ministry in charge of energy policy, conducted in cooperation with state-affiliated research institutes, and by researchers with particular modelling expertise.

For the purpose of this work this analiysis is particularly important to evaluate the changes in energy demand, resulting climate change and air pollutant emissions from the electrification of passenger cars fleet.

The criteria used to select a benchmarkable set of energy scenarios:

- Type of scenarios considered: outlooks by organizations or reports
- Minimum time horizon: no earlier than 2030
- Release data: recent outlooks and reports published no earlier than 2010
- Scope: representing the whole energy system but focusing on passenger road transport

Different scenarios are described in the the energy outlooks taken in consideration for this work:

- IEA Global EV Outlook [9] and World Energy Outlook [4];
- McKinsey & Company portfolio of power-trains for Europe [19];
- ExxonMobil Outlook for Energy [20];
- EIA International Energy Outlook [21];
- BP Energy Outlook [22];
- Bloomberg EV Outlook [23];
- OPEC World Oil Outlook [24];
- ITF Transport Outlook [25];
- WEC Transport scenarios 2050 [26].

From these outlooks, twenty-one scenarios have been identified and analyised in order to capture:

- different approaches employed for scenario-building;
- the coverage;
- the level of segmentation of transport sector;
- the assumptions which are fundamental to understand the scope and the structure of the scenario.

Also a comparison of scenario projections is given.

2.2 Models

Long-term scenarios require the use of long-term modelling tools. For this reason the second step was to focus on models.

As already highlighted in section 1.2, abatement in transport sector will be multifaceted, and may include emissions reductions through increased efficiency of vehicle fleet, lower carbon intensity (CI) of fuels, and changes in transport demand. Therefore evaluations have to be based on results of whole-systems and integrated assessment models (IAMs). In recent years, these models have started to pay more attention to representing key energy demand sectors in greater detail, including the transport sector. Integrated mobility-energy systems modelling can elucidate the transition towards future, accounting for changes in mobility and travel demand, fuel and energy use, and for the impact of decisions and policies [27]. One of the advantage of IAMs is that the scenarios derived from them consider interactions of the transport system with other sectors.

For this reason, this work focuses on a plethora of major transportation models with a high degree of technological detail, and on the models with a specific interest in transport sector.

Thirteen models were identified from literature, analyising key parameters in model structures and boundaries of emissions and passenger transport representation.

A side by side comparison is described, focusing on the transport sector outcomes, inputs and assumptions.

This analysis also aims at identifying key uncertainties across the models, trying to understand how to possibly enhance these evaluations.

The considered models are:

- GCAM [28];
- MESSAGE [29];
- MoMo [30];
- Roadmap [31];

- REMIND [32];
- WITCH-T [33];
- TIMER [34];
- POLES [35];
- AIM-CGE [36];
- DNE21+ [37];
- GEM-E3 [38];
- IMACLIM [39];
- TIAM-UCL [40].

Only few model comparison studies have been conducted focusing on the transport sector outcomes of integrated models ([41], [33], [42] and [43]).

2.3 Driving cycles

The analysis carried out in the previous sections suggest the necessity of supplementing other models and approaches to reach a higher level of detail in the representation of vehicle technology. For this scope great importance is given to driving cycles (DC). Driving cycles are considered as travel based models used to estimate fuel consumption and to develop emission inventories. A driving cycle can be defined as a series of data points representing speed versus time, in a specific region or a part of a road segment [44].

A wide literature review was developed to find which aspects related to DC could be useful for our purpose to suggest a possible pathway for increasing the level of technological detail in modelling the integration between passenger road transport and energy sector.

The selected approach started from the research of existing driving cycles worldwide followed by creating a taxonomy and identifying which possible advantages could be derived from it.

Driving cycles are already used in the validation stages of new vehicle models but they have never been used as a source of additional input data for energy-transport related models.

Important examples of driving cycles for passenger cars are:

- New European Driving Cycle (NEDC);
- Common Artemis driving cycles (CADC);
- Federal Test Procedure American driving cycles (FTP-75);
- 10-15 Japanese driving cycles (J10-15);
- Composite Urban Emissions drive cycles for Australia (CUEDC);
- Worldwide Harmonized Light Vehicle Test Cycle (WLTC).

DCs can be divided in type-approval procedures, used for the determination of vehicles fuel consumption and the related emissions, and local driving cycles used for providing a clear representation of local driving pattern.

Chapter 3
Results

The review gives a lot of papers for each step followed in this work. As described in the previous chapter, all the information taken by the different papers analysed have been reorganized and used to create appropriate classifications and tables for future users. These results are intended to help future modelers with a detailed and comprehensive guidemap of main aspects to consider when approaching the integrated energy-transport modeling.

In Table 3.1, the number of papers read is presented and divided into four main sections of the work.

Table 3.1. Number of papers read

Total	Background	Scenarios	Models	Driving cycles
112	29	22	31	31

In this chapter the results for each section are shown and described.

3.1 Scenario analysis

The review of scenarios analyisis is mainly based on energy outlooks ([4], [9] and [19]-[26]). Nevertheless, at the very begging, different references are considered to describe what scenarios are and why they are important for this work.

The first report [17] is by Karjalainen et al. and is entitled “Energy models and scenarios in the era of climate change”, 2014. In this report energy scenarios are defined as tools used to assess the impacts of different developments under assumptions of certain outcome. Furthermore, it specifies that scenarios are not policy recommendations or exact predictions of what is likely to happen.

Saisiriat and Chollacoop in [45], “A scenario analysis of road transport sector: the impacts of recent energy efficiency policies”, highlight the importance of scenario analysis to evaluate the impacts of energy efficiency policies in road transport sector, developing a case study in Thailand.

This concept is strengthened in [46] by McKinsey & Company outlook “Global Energy Perspective 2019: Reference Case”, 2019. Scenarios are described as a powerful tool in the strategist's harmony for understanding uncertainty and developing strategy accordingly. Model-based scenario studies form a key tool to explore different decarbonization strategies [47].

When well executed, scenarios can boast a wide range of advantages and all the main outlooks are based on scenario analysis.

3.1.1 Description of Scenarios

Taking into account different Energy outlooks, it is possible to collect several scenarios. A list of considered scenarios is provided in Table 3.2.

Table 3.2. List of scenarios considered with description

Name	Organization/report	General description	Timeframe
Reference case	McKinsey	Electricity consumption doubles until 2050 and renewable make up over 50% of generation by 2035	2050
Accelerated transition	McKinsey	Faster uptake of EVs, 100% of vehicle fleet in Europe, China and America and 50% in the rest of the world by 2050	2050
Non-zero emission	McKinsey	World skewed towards ICE (60% ICE in 2050)	2050
Zero emission-EV	McKinsey	World skewed towards electric powertrains (35% BEVs and 35% PHEVs)	2050
Zero emission-FCEV	McKinsey	World skewed towards FCEVs (50% FCEVs)	2050
RTS	IEA	Factors in todays commitments and recent trends	2100
2DS	IEA	CO_2 trajectory with 50% chance of limiting average global temperature to 2°C	2100
B2DS	IEA	Explores how far deployment of technologies already available could take us beyond 2DS	2100
NPS	IEA	Key policies in place as well as recent updates for EVs	2040
EV30@30	IEA	30% of EVs	2030
Baseline	ITF	Maintaining emissions at their 2015 level	2050

Low carbon	ITF	Combines most optimistic scenarios for CO_2 emissions	2050
NEF	Bloomberg	Forecast of how electrification and shared mobility will impact road transport	2040
BAU	OPEC	Evolution of todays trends	2040
Assessed 2° C	ExxonMobil	Based on the climate stabilization targets (450 ppm CO_2e)	2040
ET	BP	Evolution of todays trends	2040
RT	BP	Reduction of CO_2 emissions by 45% by 2040	2040
Reference case	EIA	Evolution of todays trends	2050
Side cases	EIA	Changing Economic growth and oil price with different level (High and Low cases)	2050
Freeway	WEC	Envisages a world where market forces prevail to create a climate for open global competition	2050
Tollway	WEC	Regulated world where governments decide to put common interests at the forefront and intervene in markets	2050

The five scenarios presented by McKinsey & Company ([19], [46] and [48]) are mainly based on projections for the electrification of vehicle fleet. In the Reference case, described in the "Global Energy Perspective 2019: Refernence Case", [46], electricity consumption doubles until 2050, and renewables are projected to make up 50% of generation by 2035. Carbon emissions are forecasted to decline, expecially due to decreasing coal demand, but yet a 2-degree pathway remains far away. For this reason great importance is given to hydrogen, which could play an important role in decarbonising some of the hardest-to-abate sectors like long-haul freight transport, aviation and navigation.

The Accelerated Transition scenario [19], "Global Energy Perspective 2018: Accelerated Transition", captures eight shifts that lead to a more rapid energy transition. The first shift is related to road transport, today's biggest oil demand sector, and the goal is to accelerate the uptake of EVs of the vehicle fleet with high shares of 100% in China, Europe and North America and 50% in the rest of the world by the reference year 2050.

Assuming various power-train penetration in 2050, three European "worlds" (number of passenger cars set to rise to 273 million in Europe and to 2.5 billion worldwide) are defined in [48], "A portfolio of power-trains for Europe: a fact based analysis".

1. A world skewed towards conventional vehicles (5% FCEVs, 10% BEVs, 25% PHEVs, 60% ICEs);
2. A world skewed towards electric power-trains (25% FCEVs, 35% BEVs, 35% PHEVs, 5% ICEs);
3. Aworld skewed towards FCEVs (50% FCEVs, 25% BEVs, 20% PHEVs, 5% ICEs).

The study then focuses on the second world described, considered as a balanced scenario for the penetration of electric vehicles in Europe.

The Reference Technology Scenario (RTS) [49], by International Energy Agency (IEA), takes in account today's commitments by countries to limit emissions and improve energy efficiency. This represents already a major shift from an historical "business as usual" approach with no meaningful climate policy response. What emerges from this scenario is that the targets adopted till 2015 are insufficient to bring transport sector in line with 2° scenario (2DS).

2DS lays out an energy system pathway and a CO_2 emission trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100 [49]. This continues to be the central climate mitigation scenario, given that it represents a highly ambitious and challenging transformation of the global energy sector.

To explore how far deployment of technologies already available could take us beyond the 2DS, a Beyond 2°C Scenario (B2DS) [49] is also given.

The New Policies Scenario (NPS) is the central scenario of the IEAs "World Energy Outlook", 2018 [4]. The scenario incorporates the policies and measures that governments around the world have already put in place, as well as the likely effects of announced policies that are expressed in official targets or plans. In particular for this work is interesting to highlight that it includes key policies in place as well as recent updates on vehicles and electric vehicles for road transport segment.

Electrification of transport sector is central in the ambitious EV30@30 Scenario [4], which is in line with the EV30@30 Campaign Declaration. In this scenario, the EV30@30 target-the 30% market share of EVs for LDVs, buses and trucks collectively is met at the global level. If accompanied by a reduction of the carbon intensity of power generation exceeding 50% by 2030, this goal is in line with the Paris Agreement, to hold the increase in the global average temperature to well below 2°C above pre-industrial-level, as the growth in the market uptake of EVs continues after 2030.

International Transport Forum (ITF), in [25], "Transport Outlook 2017", assembles scenarios for future transport demand and related CO_2 emissions from all sectors and modes of transport. In particular, it gives a low-carbon scenario, which results from the combination of the most optimistic scenario from all modes and points to a lower bound of CO_2 emissions for 2050 with currently foreseen technology and mode choice trajectories. This scenario is opposed to the Baseline scenario [25] which only consider the current policies.

Bloombergs outlook [23] “Electric Vehicle Outlook 2019”, forecast their view of EV adoption on passenger cars, commercial vans and trucks, and buses globally, and the associated impacts on electricity, oil and battery material markets.

Organization of the Petroleum Exporting Countries (OPEC) “World Oil Outlook 2040” [24], examines the medium and long-term prospects to 2040 for the global oil industry, and analyzes various sensitivities that can impact the petroleum industry in the years ahead, and it focuses on the importance of reductions of road transport demand.

ExxonMobil, “Outlook for energy: A perspective to 2040” [20], provides a projection of energy deman through 2040 using the IEA and other credible third-part sources as a foundation. Projection is based on likely trends in technology, policy, consumer preference, geopolitics and economic development. To understand some of the characteristics of future transition pathway, this outlook analyize energy and emission data from a range of EMF27 (by Energy Modeling Forum) stabilization, policy and technology targets. So the scenario presented in this outlook is the result of 13 different scenarios, given as results by different EMF27 models that ran 450 full technologies (FT) cases [50]. These scenarios are considered as a whole and called Assessed 2°C scenario.

The British Petroleum (BP) 2019 edition of the “BP Energy Outlook” [22] considers a number of different scenarios, which consider only a tiny sub-set of the uncertainty surrounding energy markets out to 2040. Much of the outlook is described with reference to the Evolving Transition (ET) scenario, which assumes that government policies, technology and social preferences continue to evolve in a manner and speed seen over recent past. The outlook also considers the dual challenge facing the energy system: the need for more energy and less carbon and it considers the contribution reducing carbon emissions in different sectors of energy system, like transport, can make to achieving the Paris climate goals.

Specifically for transport sector a Low carbon transport scenario (LCT) is described by increasing efficiency, alternative fuels and shared mobility.

In the “International Energy Outlook 2019” [21] by the US Energy Information Administration (EIA), a Reference case provides a baseline to measure the impact of alternative assumptions. The so called side cases are addressed to see the impact of economic growth, taking the annual growth rates of global gross domestic product (GDP) as reference, and price uncertainty on energy consumption.

The six scenarios obtained are described with respect to the reference case:

1. 3.7% per year, High Economic Growth case;
2. 3%, Reference case;
3. 2.4% per year, Low Economic Growth case;
4. $ 185/barrel, High Oil Price case;
5. $100/barrel, Refernce case;
6. $45/barrel, Low Price case.

The impact of these factors are analysied specifically within the transport sector.
Finally, in the “Global Transport Scenarios 2050” [26] by World Energy Council (WEC), two scenarios are presented. The Freeway scenario envisages a world where market forces prevail to create a climate for open global competition, higher level of privatization, deregulation, and liberalization. The Tollway is best described as a regulated world where governments and promitent politicians decide to put common interests at the forefront and intervene in markets. So this two scenarios describe two divergent global transportation future looking out to 2050.

3.1.2 Classification

After the identification of scenarios described in the energy outlooks, the purpose was to organize all the scenarios under a classification depending on key parameters.
From [17] emerges the importance of considering the approach used for the scenario definition. Different types of energy scenarios can be constructed, using the techniques of forecasting and backcasting. Energy outlooks that are based on forecasting can include a calculation of most probable future to present policy-makers a business-as-usual case as well as the display alternative scenarios. In energy backcasting the starting point is a view of a possible and desired future, which is expressed as a goal or a target. So as opposite to forecasting scenarios, computation is conducted backwards, from future to present days, in order to reveal what different activities and steps are needed to reach the goal.
For the backcasting scenarios the target is reported in the classification.
All the scenarios considered in this work have a detailed representation of transport sector, giving insights for the main purpose of the work, passenger road transport segment.
The coverage can vary between scenarios giving global or country level scale. (Table 3.3).

Table 3.3. Classification of scenarios

Scenario	**Reference**	**Forecasting (F) or Backcasting (B)**	**Target**	**Coverage**
Reference case (Mckinsey)	[46]	F	/	Global
Accelerated transition	[19]	F	/	Global
Non zero emission-conventional	[48]	F and B	The forecasted data is then backcasted from the envisioned penetration of power-trains in 2050	EU
Zero emission-	[48]	F and B	Read previous	EU

electric vehicle dominated				
Zero emission-FCEV dominated	[48]	F and B	Read previous	EU
RTS	[49]	F	/	Global
2DS	[49]	B	Limit global temperature increase to 2°C and concentration of GHG in the atmosphere to 450 parts per million	Global
B2DS	[49]	B	Net-zero emissions by 2060	Global
NPS	[4]	F	/	Global
EV30@30	[4]	B	Reach 30% sales share for EVs by 2030	Global
Baseline	[25]	F	/	Global
Low carbon	[25]	B	Emissions of CO_2 and local pollutants are contained at their 2015 level until 2050	Global
NEF	[23]	F	/	Global
OPEC	[24]	F	/	Global
Assessed 2°C	[20]	B	Climate stabilization targets (e.g. 450 ppm CO_2 equivalent)	Global
ET	[22]	F	/	Global
RT	[22]	B	Reducing CO_2 emissions by 45% by 2040 meeting the Paris climate goals	Global
Reference case (EIA)	[21]	F	/	Global
Side cases	[21]	F	/	Global
Freeway	[26]	F	/	Global
Tollway	[26]	F	/	Global

Most of the scenarios taken into account are based on the methodology of energy forecasting. These energy outlooks are generally the ones describing a business as usual case or a reference case. The only exception is given by the scenarios proposed by EIA in which the forecast is based on some economic and price growth assumptions made for the projection.

From this classification it emerges how forecasting scenarios feature in numerous influential policy publications such as IEA or BP Energy Outlooks.

The drawback of forecasting scenarios is that they can be affected by numerous biases.

Actual technological development may occur (and has occurred) differently to the predictions of the forecasted scenarios.

Another considerable problem underlined by [17] is the dominance of forecasting outlooks by large energy policy actors that yield considerable power.

Backcasting approach explore different pathways to sustainability, and today, the formulation of low-carbon scenarios using backcasting methodology is increasingly common.

A particular case is the one described in [48]. This study provides a factual comparison of four different power-trains (BEVs, FCEVs, PHEVs and ICEs), on economics, sustainability and performance across the entire value chain between now and 2050. In order to ensure conclusions were as accurate as possible, both a forecasting and backcasting approach was then used. From 2010 to 2020, all cost and performance projections are based on proprietary industry data, after 2020, on projected learning and annual improvement rates. These forecasted data were then backcasted from the envisioned penetration of power-trains in the EU in 2050 as described in the previous section 3.1.1.

The percentage of forecasting and backcasting scenarios of the total range can be seen in Figure 3.1.

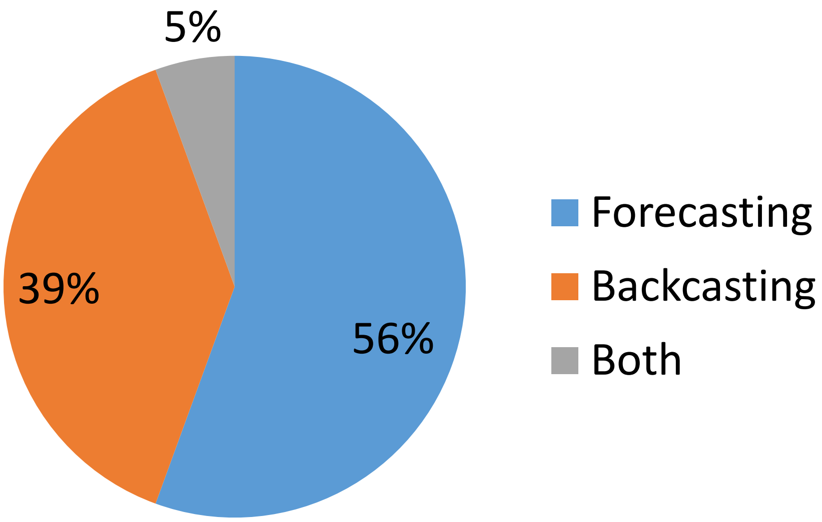


Figure 3.1. Classification of scenarios depending on approach

All the scenarios, except from the ones described in [48] which focus on the EU, are global sets of scenarios with no specific regional focus.

3.1.3 Comparison

All reviewed scenarios see an increasing role of renewable in the future. However, taking in consideration the energy mix by 2040, the overall fossil fuel share tends not to get lower than 70% (from todays 80%). Renewable gains are mainly at the expense of coal.

Most of the outlooks predicts a steep growth of natural gas, that compensate the decrease in oil usage for electricity production.

From this comparison, pathway towards the 2°C still need even stronger deployment of non-fossil energy. (Figure 3.2).

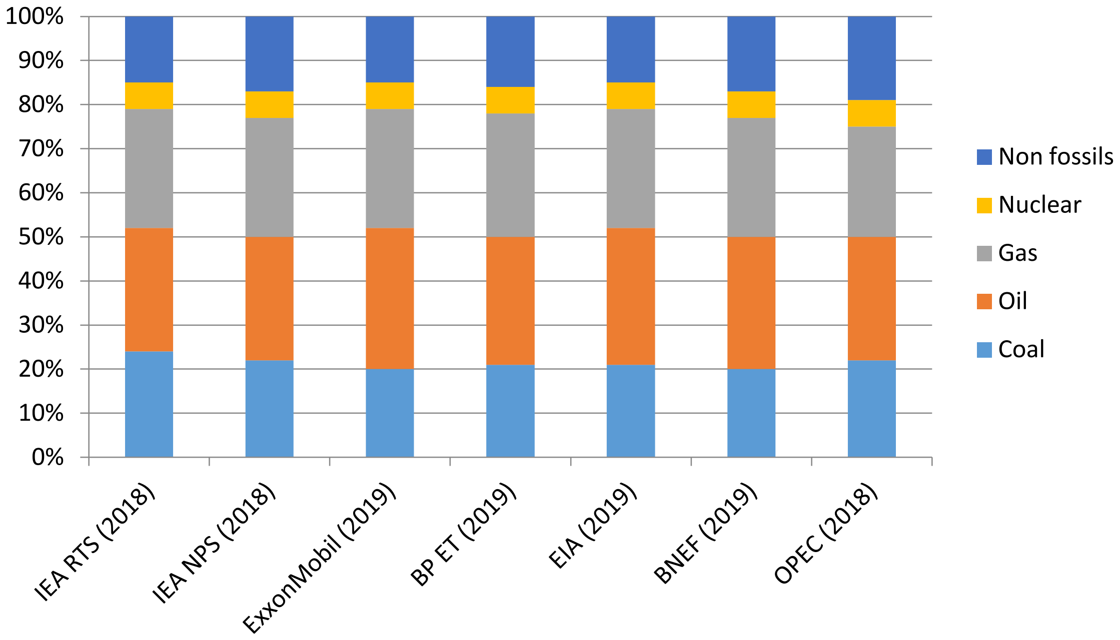


Figure 3.2. Energy mix by 2040 (%)

Taking in consideration the global number of EVs on the road by 2040 different considerations can be made. Not all the outlooks have a detaild projection for this type of consideration so for this comparison only few outlooks were considered.

Bloomberg outlook expect there to be 508 million passenger EVs on the road globally by 2040 (550 million including commercial EVs).

Compared to other major organizations, Bloomberg NEF hold the most aggressive view on EV adoption.

Among oil majors, BP and OPEC hold the most aggressive EV adoption forecast. Both expect there to be 300 million passenger EVs on the road in 2040.

ExxonMobil has a more conservative outlook, but the company has consistently increased its EV forecast in recent years and now expects a 2040 EV fleet size of over 150 million.

For the IEA scenario EV30@30 the projection accounts as reference year the 2030. Despite this it can be noticed how this projection is ambitious following the BNEF trend, reaching around 125 million EVs on road by 2030. (Figure 3.3).

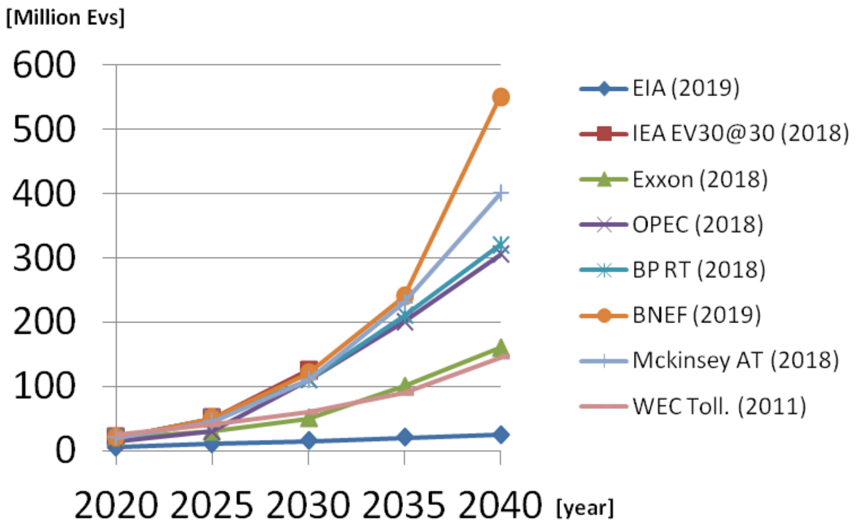


Figure 3.3. EV Outlooks perspectives

Most of the outlooks projects growing or at best plateauing CO_2 emissions. Few outlooks show a significant decrease in CO_2 emissions from LDV after reaching a peak. This is due to several factors like carbon pricing schemes, cost effective removal of carbon dioxide in steam methane reforming processes and significant improvements in energy efficiency. Comparing these outlooks some considerations are made.

The two scenarios by IEA which provide a considerable decreasing trend of emissions are the 2DS and the EV30@30. From [9] these reductions can be accounted to electric vehicles increasing share and stock. Elecctric vehicles reduce CO_2 emissions by half from an equivalent ICE fleet in 2030, offsetting 220 Mt CO_2-eq in the 2DS and 540 Mt CO_2-eq in the EV30@30.

Tollway scenario by WEC shows that CO_2 emissions from cars in 2050 are likely to drop by around 46% below 2010 levels [51]. This decrease starts after the peak of 2020 and in 2030 is at a low level of 2.6 $GtCO_2$.

Again, this is due to three main factors, including a drop in demand in 2050 by 13% below 2010 levels, a changing fuel consumption mix, and increases in engine efficiencies [51].

The less dramatic trend given by ITF low-carbon scenario, is due to the fact that this scenario considers solutions for maintaining emissions at their 2015 levels combining the most optimistic projections for CO_2 emissions for all modes and sectors. (Figure 3.4).

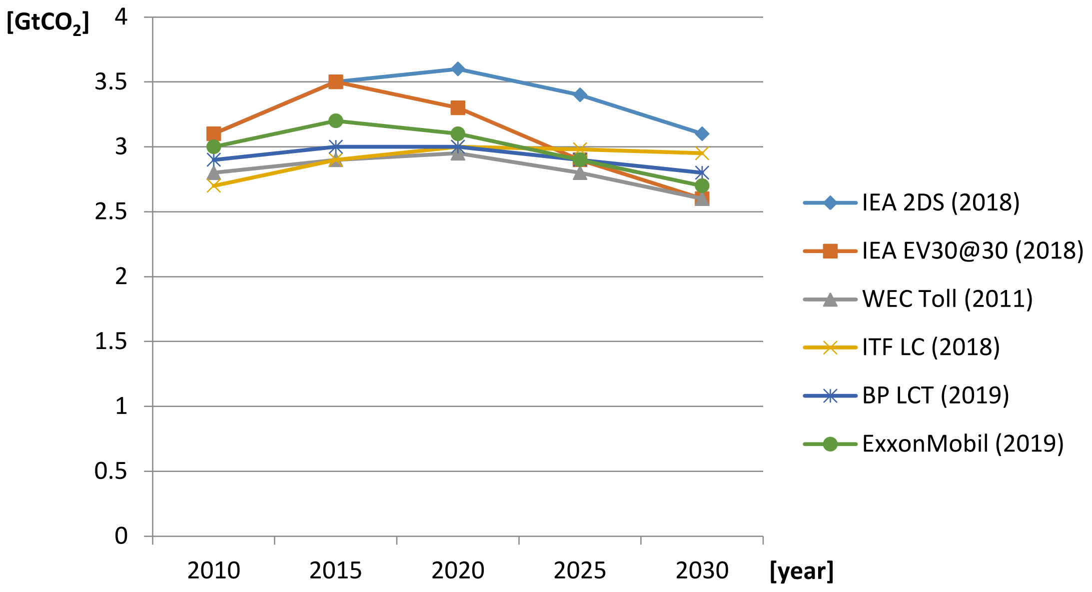


Figure 3.4. CO_2 emissions from road transport trends

When making comparisons between different outlooks, methodology variance have to be considered. Also assumptions are crucial but these are more related to models on which the scenarios are based.

3.2 Models

Many papers underline the importance of modeling transport sector in an integrated way with energy sector. Developments in the transport sector are very important for future climate change as it is a significant contributor to global CO_2 emissions.

Integrated assessment models (IAMs) have been developed to explore the interactions across the different sectors in a systems analyitical manner [52].

As underlined by [47], in the recent years, these models have started to pay more attention to representing key energy demand sectors in greater detail, in particular the transport sector. This means that IAMs are now able to provide insights into the possible long-term development of the global transport sector in the absence of stringent climate policies, but also possible pathways for country-wide transport systems to meet the ambitious emission reduction targets of the Paris Climate Agreement.

The main advantage of these type of models, is that the scenarios derived from them consider interactions of the transport sector system with other sectors [53]. The drawback of IAMs os their breadth and complexity [17] so this work focuses on comparing the frameworks and projections from thirteen global transportation models with considerable technology details, to identify the sources of divergence or consistency, as well as key knowledge gap.

3.2.1 Overview of models

The thirteen models compared in this work include:

- The Asia-Pacific Integrated Model (AIM) is a system of inter-related component models developed by an interdisciplinary team of researchers at NIES and Kyoto University [54]. The model framework consists of four models and the core of the model is AIM-CGE which represents the whole economic activity including energy and transport sectors.

- DNE21+ by Research Institute of Innovative Technology for the Earth (RITE), an integrated assessment model. It consists of 3 modules. One module is specific for energy-related CO_2 emissions [37].

- The General Equilibrium Model for Economy-Energy-Environment (GEM-E3) by Institute of Communication and Computer Systems (ICCS) is a multi-regional, multi-sectoral, recursive dynamic computable general equilibrium model which provides details on the macro-economy and its interactions with the environment and the energy system [38].

- Global Change Assessment Model (GCAM) is a long-term, global, technologically detailed, partial-equilibrium model developed and maintained by Pacific Northwest National Laboratory (PNNL) with modification for the transportation sector by the Institute of Transportation Studies (ITS), University of California, Davis [28]. It is an integrated assessment model with a specific transportation module.

- IMACLIM-R, which is part of the IMACLIM suite of modules, by CIRED (Centre International de Recherche sur l'Environnement et le Développement) [39]. This is a hybrid dynamic general equilibrium model of the world economy that covers the period 2001-2100 in yearly steps through the recursive iteration of annual static equilibria and dynamic modules.

- MESSAGE-Transport (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) by the International Institute for Applied Systems Analysis (IIASA). It's a specific module of the energy model MESSAGE which has other four modules.

- The POLES World energy model, developed by Joint Research Centre-European Commission (EC-JRC), is a recursive simulation model of the World energy system that includes full equilibrium of the energy markets. This model allows detailed assessment of greenhouse gas mitigation policies [35].

- Regional Model of Investments and Development (REMIND) by PIK (Potsdam Institut fur Klimafolgenforschung) in its latest version. The model was originally introduced by Leimbach et al. (2010), [55]. It is a global energy-economy-climate model spanning the years 2005-2100.

- TIMES integrated assessment model in University College London (TIAM-UCL) is a global energy systems model that is usually run along with climate module and an aggregated economic module in order to assess long-term energy decarbonisation scenarios and pathways [40]. It is a technology rich bottom-up cost optimization model with a specific module for transport sector.

- World Induced Technical Change Hybrid-Transport (WITCH-T) by CMCC (Centro Euro-Mediterraneo sui Cambiamenti Climatici) is a modification of the WITCH model with a transport module added from FEEM (Fondazione Eni Enrico Mattei) [33]. It is a global model which runs until 2100, with a linear-least cost optimization for transport sector.

- Mobility Model (MoMo) by the International Energy Agency (IEA) is a technical-economic database spreadsheet and simulation model that enables detailed projections of transport activity, vehicle activity, energy demand, and well-to-wheel greenhouse gas and pollutant emissions. MoMo is a transportation model which covers all transport modes and includes modules on local air pollutants and on the cost of fuels, vehicles and infrastructure, as well as analysis of the material needs for new vehicles [30].

- Roadmap by the International Council on Clean Transportation (ICCT) is a transportation “stand-alone” model. It gives detailed outputs for energy and oil consumption, GHG emissions and local pollutants for a vast range of different transport modes and regions [31].

- TIMER is a specific transport model part of the IMAGE integrated assessment model (Integrated Model to Assess the Global Environment) by the Netherlands Environmental Assessment Agency (PBL) and Utrecht University (UU). There is also a specific sub-model for passenger transport, called TRAVEL [34]. Sometimes, like in this work, it can be used as a stand-alone model.

These models include some IAMs and some “stand-alone” transportation models. (Table 3.4).

Table 3.4. Models information

Name	Institution	Ref.	Concept	# of regions	Solution method
AIM-CGE	NIES, Japan	[36]	IAM	17	General equilibrium
DNE21+	RITE, Japan	[37]	IAM	77	Partial equilibrium
GEM-E3	ICCS, Greece	[38]	IAM	38	General equilibrium
GCAM	PNNL, USA	[28]	IAM	32	Partial equilibrium
IMACLIM-R	CIRED, France	[39]	IAM	12	General equilibrium
MESSAGE	IIASA, Austria	[29]	IAM	11	Hybrid model
POLES	EC-JRC, France	[35]	IAM	57	Dynamic equilibrium
REMIND	PIK, Germany	[32]	IAM	11	Hybrid model
TIAM-UCL	UCL, UK	[40]	IAM	16	Partial equilibrium
WITCH-T	CMCC and FEEM, Italy	[33]	IAM	14	Hybrid model
MoMo	IEA, France	[30]	Transport	33	“What-if” style
Roadmap	ICCT, USA	[31]	Transport	16	“What-if” style
TIMER	PBL, Netherlands	[34]	Transport	26	Long-term system dynamics

These models differ in terms of scope and model structure. The integrated assessment models such as AIM-CGE, DNE21+, GEM-E3, GCAM, IMACLIM-R, MESSAGE, POLES, REMIND, TIAM-UCL and WITCH-T, cover all sectors of the energy system, including linkages with global land use, energy/economic, and climate systems, whereas MoMo, Roadmap and TIMER cover the global transportation sector only.

From [42] IAMs differ in the way they represent the transport sector. The ones with greater transport detail compared to the ones described herein, use a hybrid approach to model the transport demand and use of energy in the transport sector. The hybrid approach consists of a top-down demand formulation, relating demand to population and economic growth, and combining it with the explicit modelling of modes and technology options per mode.

Clearly, as underlined by [43], the degree of detail determines how well models are able to represent the key dynamics of the various transport sub-sectors and the different ways to mitigate emissions. The models which are based on this approach are MESSAGE, REMIND and WITCH-T.

General equilibrium models (or usually referred to as computable general equilibrium-CGE), such as AIM-CGE, GEM-E3 and IMACLIM-R, have a more detailed representation of economy with multiple sectors and often include higher resolution of energy technologies and regional detail [56].

DNE21+, GCAM and TIAM-UCL are partial equilibrium models. These type of models provide a detailed analysis of the interaction between environmental impacts and a particular sector of the economy [56]. Energy system models are usually considered as a subcategory of partial equilibrium models that provide a detailed account of the energy sector [57].

The transportation "stand-alone" models considered are MoMo, Roadmap and TIMER. These models don't have endogenous feedback from sectors outside the transportation system to changes in transportation sector assumptions or projections (e.g. energy use impact on energy prices). On the other hand these three models have more detailed representations of the transportation sector, such as vehicle characteristics, near-term policy goals and implementation, and detailed tracking of vehicle pollutant emissions as a function of vehicle emission control levels and utilization [58]. The transportation models allow the user to create "what-if" scenarios to explore the impacts of various technological, economic, demographic and policy trends [59].

In the following section a comparison of the models system boundary, resolution and structure is given.

3.2.2 Comparison

The thirteen models vary in structure, scope and variables included in calculations and projections.

These models have different system boundaries for CO_2 emission accounting, with implications for how these emissions are accounted for in policy analyses, and how they are reported to communicate the impacts of policies. Some models include greenhouse gas emissions from the production and use (well-to-wheel emissions) of a range of energy sources, others include only the use (tank-to-wheel).

The system boundaries of energy use and CO_2 emissions by each model characterized in this study are compared in Table 3.5.

Table 3.5. CO_2 accounting in selected models

Model	**System boundaries**
AIM-CGE	Indirect energy use is treated in energy transformation sector
DNE21+	Indirect energy use is not included
GEM-E3	All GHG-emitting and energy producing/consuming sectors are included
GCAM	Full fuel cycle of each fuel is represented
IMACLIM-R	All GHG-emitting and energy producing/consuming sectors are included
MESSAGE	Indirect energy use and emissions from fuel production and vehicle manufacture are included
POLES	Not specified
REMIND	Material needs and ambodied energy not considered
TIAM-UCL	Indirect fuel use from manufacturing, upstream energy and emissions are calculated but not tied to transport
WITCH-T	Indirect energy use and emissions from fuel production are included
MoMo	Tank-to-wheel and upstream energy/emissions using simplified fuel cycle assumptions
Roadmap	Well-to-tank emissions for fuels are included, but excludes lifecycle impacts of manufacture and end-of-life
TIMER	Not specified

Models that consider the full fuel cycle represent the whole lifecycle, from primary energy production and transformation to delivery to the transportation sector.

Most of the models, GEM-E3, GCAM, IMACLIM-R, MESSAGE, WITCH-T, MoMo and Roadmap, include upstream production and transportation CO_2 and non-CO_2 greenhouse gases emissions. Roadmap also includes indirect land-use change (ILUC) emissions based on literature reviews. Roadmap reflects the US biofuel policies and ILUC emissions are included in these policies. MoMo tracks tank-to-wheel and upstream energy/emissions using simplified fuel cycle assumptions which can vary depending on the context of utilization.

AIM-CGE considers indirect (i.e. lifecycle) energy use but only related to the energy transformation sector.

Also DNE21+ doesn’t include indirect energy use in the transportation sector. For example, emissions from car manufacturing process are classified into the industrial sector. In REMIND material needs and embodied energy are not considered, so only the fuel use is represented corresponding to tank-to-wheel emissions.

For TIAM-UCL indirect fuel use from manufacturing, upstream energy and emissions are calculated but not tied to transport.

POLES and TIMER do not specify which is the level of detail used for enrgy use and emissions, so emissions can be related only on tailpipe CO_2 emissions.

This classification based on system boundaries shows how generally IAMs have a more detailed representation and consideration of energy use and emissions, taking in account both the full fuel and vehicle cycles.

Other key point for this work is to identify at which level of detail is the passenger transport sector represented in these thirteen models. (Table 3.6).

Table 3.6. Modes and technologies for passenger travel

	Modes						**Technologies**				
Model	Soft modes	Car	Bus	Rail	Air	Ship	ICE	HEV	BEV	PHEV	FCEV
AIM-CGE		X	X	X	X		X	X	X	X	X
DNE21+		X	X	X	X		X	X	X	X	X
GEM-E3		X	X	X	X	X	X	X	X	X	
GCAM	X	X	X	X	X		X	X	X	X	
IMACLIM-R		X	X	X	X		X	X	X		
MESSAGE	X	X	X	X	X		X	X	X		
POLES		X	X	X	X	X	X	X	X	X	
REMIND		X	X	X	X		X	X	X		
TIAM-UCL		X	X	X	X		X	X	X	X	X
WITCH-T		X	X				X	X	X	X	
MoMo	X	X	X	X	X	X	X	X	X	X	X
Roadmap	X	X	X	X	X	X	X	X	X	X	X
TIMER	X	X	X	X	X	X	X	X	X	X	X

Models differ in the way they represent the passenger transport sector. For this sector different classes are identified in order to analyise the level of representation. Six modes, including soft modes (which comprises walking and bicycle), cars (including 2-3 wheelers), buses, air (including both short and long-distance) and shipping, and five technologies, ICE, HEV, BEV, PHEV and FCEV, are considered. The three “stand-alone” transportation models, MoMo, Roadmap and TIMER, have a greater level of detail detail both for modes and technologie (they also have a further disaggregation within the identified modes and technologies depending on classes and regions) as they are specifically developed to assess transportation system.

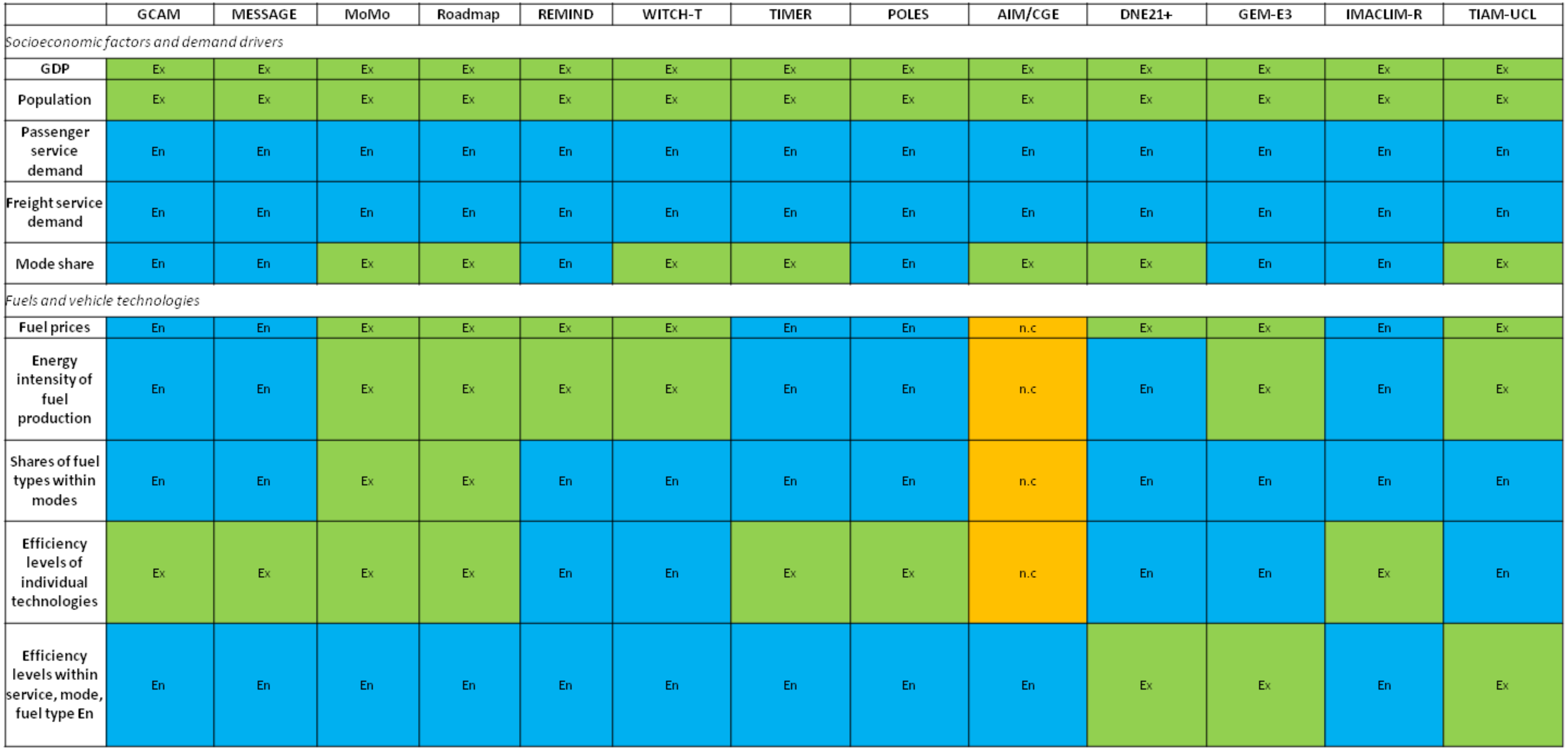
A high level comparison of endogeneity/exogeneity of key model drivers and parameters is given in Table 3.7.

Endogenous results are calculated by the models based on exogenous drivers. These exogenous values are taken directly from external sources. The key parameters are divided in two different categories of data: socioeconomic factors and demand drivers, and fuels and vehicles technologies.

First category is made by those factors that represent service demand (including passenger travel demand in passenger-kilometers travelled, PKT, passenger service demands by mode, and freight demand in tonne-kilometers travelled, TKT, across all modes of transportation) and economic growth (GDP and population).

The second category take in consideration aspects related to the fuels and vehicle technologies. In this category we have the representation of competition between vehicle technologies (expressed by factors related to efficiency of individual technologies) and modes. Also efficiency and fuel demands can be determined endogenously or exogenously by the models.

Table 3.7. Comparison of Exogenous drivers (Ex) and Endogenous calculations (En) for considered models



	GCAM	MESSAGE	MoMo	Roadmap	REMIND	WITCH-T	TIMER	POLES	AIM/CGE	DNE21+	GEM-E3	IMACLIM-R	TIAM-UCL
Socioeconomic factors and demand drivers													
GDP	Ex	Ex	Ex	Ex	Ex	Ex	Ex	Ex	Ex	Ex	Ex	Ex	Ex
Population	Ex	Ex	Ex	Ex	Ex	Ex	Ex	Ex	Ex	Ex	Ex	Ex	Ex
Passenger service demand	En	En	En	En	En	En	En	En	En	En	En	En	En
Freight service demand	En	En	En	En	En	En	En	En	En	En	En	En	En
Mode share	En	En	Ex	Ex	En	Ex	Ex	En	Ex	Ex	En	En	Ex
Fuels and vehicle technologies													
Fuel prices	En	En	Ex	Ex	Ex	Ex	En	En	n.c	Ex	Ex	En	Ex
Energy intensity of fuel production	En	En	Ex	Ex	Ex	Ex	En	En	n.c	En	Ex	En	Ex
Shares of fuel types within modes	En	En	Ex	Ex	En	En	En	En	n.c	En	En	En	En
Efficiency levels of individual technologies	Ex	Ex	Ex	Ex	En	En	Ex	Ex	n.c	En	En	Ex	En
Efficiency levels within service, mode, fuel type En	En	En	En	En	En	En	En	En	En	Ex	Ex	En	Ex

From this comparison of key drivers and calculations for the analysed models several considerations can be made. (Figure 3.5).

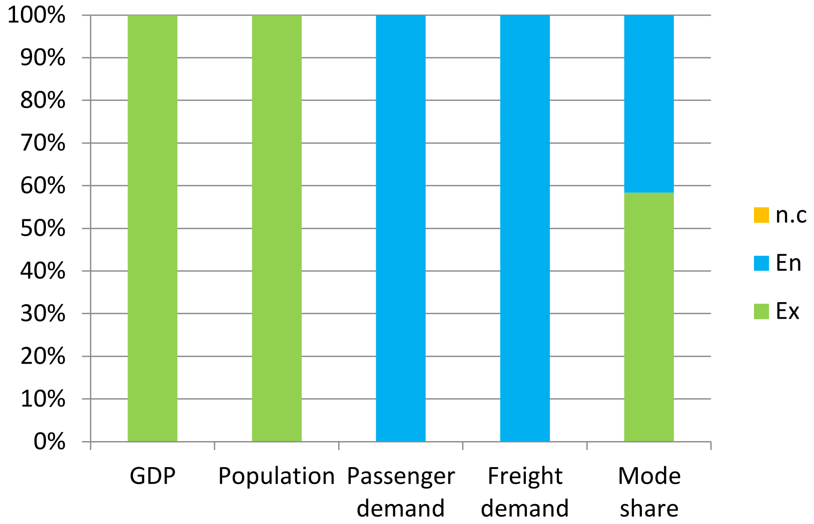


Figure 3.5. Socioeconomic factors and demand drivers results

Across all the thirteen models, population and income (GDP) are the exogenous drivers of passenger service demand in passenger kilometres travelled (PKT) and new vehicle demand. Passenger service demands by modes are estimated endogenously by all models, based on the total travel costs by mode, fuel, technology and time cost of travel. Also freight service demand is based on simple functions of population, GDP and fuel prices in these models.

The mode share is generally given exogenously, but in certain models like GCAM or MESSAGE the modelling transportation energy use is done by estimating what mode of transport they choose. These models are called “service demand” models, and can be more intuitive and appropriate when one wants to model societal shifts in modes of transportation, either in emerging economies as they develop or in developed economies as they decarbonize [28].

Taking in consideration the fuels and vehicles technologies factors the percentage of input assumptions and outputs are given in Figure 3.6.

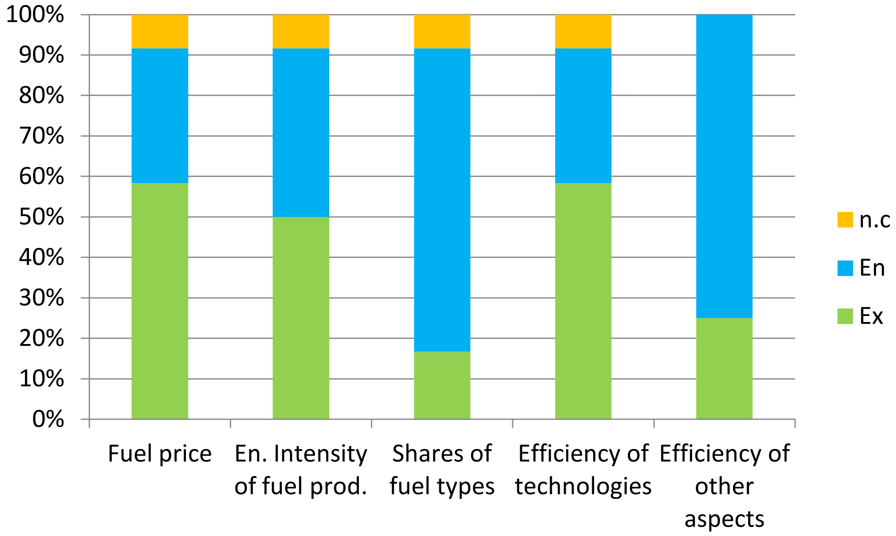


Figure 3.6. Fuel and vehicle technologies factors

From this figure, divergence and consistency between considered models can be related expecially to these type of factors. All the identified parameters have a quite equally divided share between endogenous and exogenous factors.

Fuel price is calculated endogenously by five models out of the selected sample. GCAM, MESSAGE, POLES and IMACLIM-R, determine fuel costs endogenously by the supply sector part of the model. TIMER is connected to a larger energy system model and determine fuel prices endogenously. All the other models of the sample consider fuel price as an exogenous assumption.

Nearly the same share can be attributed to energy intensity of fuel production. The same models which considered fuel price as endogenous calculation also consider energy intensity as endogenous. Only exeption is given by DNE21+ which have the fuel price as an exogenous assumption but calculates internally the energy intensity of its production.

Shares of fuel types is driven mostly by fuel prices and vehicle costs. 77% of models calculate these shares endogenously. For example in TIMER within the transport modes vehicles with different energy efficiency, costs and fuel type characteristics compete [60].

Efficiency is connected to the competition between different modes, technologies and fuels. For GCAM, MESSAGE, MoMo, Roadmap, TIMER, POLES and IMACLIM-R, efficiency of new technology vehicles decline over time exogenously.

All models assume improvements in energy efficiency of vehicle technologies and show a gradual penetration of alternative fuel vehicles across all transportation technology and modes.

AIM-CGE has a very particular structure calculating only fuel efficiency improvements. The other factors considered in this work are not explicitly determined by this model.

A consistent comparison of fuel carbon intensity trends across models is not possible as models differ in terms of their accounting of carbon emissions as shown in Table 3.5.

3.2.3 Criticisms and limits

Model comparisons allow to get to a better understanding of future transport system behaviour but at the same time shows that further model developments are needed. Taking into account also the other model comparison papers ([41]-[43]), different criticisms and limits can be highlighted. It should be noted that all of the criticisms presented here stem from the existing critical literature.

1. Lack of trasparency around model structures and input assumptions: the main drawback of IAMs as underlined by [17] is their breadth and complexity. Model structure and input assumptions are not always explicitly explained and detailed. Also qualities of the energy sub-systems are not always provided. Some important aspects such as fuel price and non-economic factors. Yeh et al, [43], conclude that future model improvements should focus on reducing data gaps by improving access to data and coordinating efforts to align historical data and compare imput assumptions.

2. Need to increase vehicle technology level of detail: McCollum et al, in [29] describes the importance of improving the representation of different LDV size classes (e.g. sports car, small/midsize/large car, small/large SUV) for capturing consumer preferences. This technological improvement in representation is also underlined by [61].

3. Over-reliance on particular technologies: many models still over rely on traditional technologies without taking in appropriate consideration technology efficiency aspects. Salvucci et al, [61], identifies the breakthrough technologies as a possible challenge and solution for models. The inclusion of new technologies could provide additional solutions for those transport modes whose emissions are harder to reduce (e.g. aviation). Also the impact of the rate of technology change should be deepened [62]. Muratori et al. in [27] states that the transportation system is typically analyzed piecemeal compartmentalized into specific analysis categories such as single-sector technology adoption.

4. Inadeguate representation of real-world policies, mode choice and consumer preferences: Muratori et al, in [27], undelines that a major challenge for transport and energy models is to properly capture the heterogeneity of people, markets, and places and its influence on decisions and technology adoption. Consumer preferences are now affected by policy limitations, potential changes induced by automation, and mode/vehicle choice that considers new technologies. [43] seek to understand how to translate findings from the study of IAMs into relevant policy implications such as additional policy targets needed and feasibility of policy goals.

> Also the paper by McCollum et al, [29] look specific at the role of heterogeneous consumer behaviour in light-duty vehicle purchasing decisions, highlighting the importance of representing this consumer heterogeneity for modelling future transport transition. [47] states that future research would do well to focus on further representing the influence of consumer choice and heterogeneity.

These criticisms are identified in all the models considered in this work. (Table 3.8).

Table 3.8. Criticisms identified in works model sample

	GCAM	MESSAGE	MoMo	Roadmap	REMIND	WITCH-T	TIMER	POLES	AIM/CGE	DNE21+	GEM-E3	IMACLIM-R	TIAM-UCL
1					X	X			X	X	X	X	X
2	X	X	X	X	X	X	X	X	X	X	X	X	X
3					X	X	X		X	X		X	
4	X	X	X	X	X	X	X	X	X	X	X	X	X

A solution suggested by Gambhir et al, [63], is to supplement IAMs with other models and approaches and that this has considerable merit. In this way it obviates the need of adding huge additional complexity to the already-complex IAMs.

3.3 Driving cycles

A driving cycle, or driving schedule, can be defined as a series of data points representing vehicle speed versus time and is supposed to represent typical driving patterns [64]. Driving cycles are key to understand how a vehicle is used. For this reason driving cycles are important components for evaluating vehicles and play a fundamental role in vehicle design since it affects the cost, fuel consumption and the emissions of the vehicle.

Although there exist a vast number of driving cycles for different purposes and usage scenarios, not all of them are equally important. USA, Europe, Australia and Asia can be identified as the four main regions where many countries have been developing driving cycles during last thirty to forty years. Examples of existing driving cycles include US FTP-72/75 and Highway Fuel Economy Test cycle (HWFET), Common ARTEMIS driving cycle (CADC) and New European Driving Cycle (NEDC) for the European region, the Japanese 10-15 mode cycle and new JC08 cycle, the Composite Urban Emissions Drive Cycle (CUEDC) for Australia and the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) developed by the UN ECE GRPE (Working Party on Pollution and Energy) and already adopted in Europe and Japan.

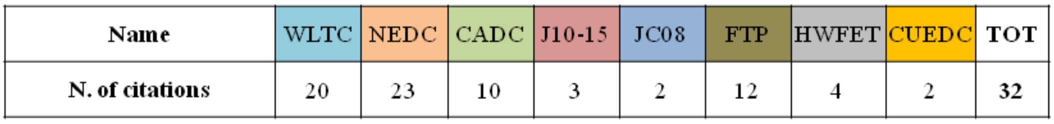
In order to describe each cycle and it’s specific utilization, information about them is taken from the references of papers that mention them. In Table 3.9, the main papers talking about driving cycles are shown.

Table 3.9. List of references referred to driving cycles

References	NEDC	WLTC	CADC	J10-15	JC08	FTP	HWFET	CUEDC
[65]	X		X					
[66]						X		
[44]			X			X		X
[67]	X	X						
[68]			X					
[69]	X	X						
[64]	X	X	X					
[70]			X					
[71]	X	X	X					
[72]	X	X	X					
[73]	X	X						
[74]	X	X		X	X			
[75]	X	X						
[76]	X	X						
[77]		X						
[78]	X	X						
[79]	X	X	X					
[80]	X	X				X		
[81]	X	X						
[59]								X
[82]	X	X						
[83]	X		X					
[84]	X			X		X		
[85]	X	X						
[86]	X					X	X	
[87]						X	X	
[88]						X		
[89]	X	X				X	X	
[90]	X	X	X			X		
[91]	X	X				X	X	
[92]		X				X		
[93]	X			X	X	X		

Among these 32 papers the most citated driving cycle is the New European Driving Cycle (NEDC) used for legislation in the EU, with 23 citations, followed by the new World Harmonized Light Vehilcles Driving Cycle (WLTC) and the US Federal Test Procedure (FTP) with 20 and 12 citations respectively. (Table 3.10).

Table 3.10. Number of driving cycles citations



Name	WLTC	NEDC	CADC	J10-15	JC08	FTP	HWFET	CUEDC	TOT
N. of citations	20	23	10	3	2	12	4	2	32

3.3.1 Description

The considered sample of driving cycles for this work has different characteristics depending on weather these cycles are legislative certification driving cycles like the NEDC or the FTP, or if they are appositely designed for emission estimations. It stands to reason that cycles used for legislation have a bigger influence than purely academic cycles, or cycles that only aplly to a very specific type of vehicle [90].

Literature then generally distinguish transitory and modal cycles [69]. Both type of cycles are static and limited in length. Transitory cycles consist of many changes in speed, whereas modal cycles include longer periods of cruising at constant speed. An example of modal driving cycle is the NEDC, which is currently the most common reference for passenger cars in Europe. WLTC is a transitory cycle, and these cycles are generally considered to be more realistic [93]. A specific description of the considered driving cycles is provided.

- New European Driving Cycle (NEDC): This is the cycle employed for the type approval tests for emissions certification of light-duty vehicles. The test is performed on a chassis dynamometer. This test was established in the 70s in order to measure at the time regulated pollutant emissions but not CO_2 or fuel consumption. The testing of the latter was introduced in the 80s. The NEDC has received a lot of criticism and is currently considered outdated [67]. NEDC consists of smooth accelerations and decelerations which fail to reflect modern driving patterns [81]. The NEDC consists of two separate driving cycles, the urban driving cycle (UDC also known as ECE-15) and the extra-urban (EUDC with higher average velocity). The duration of yhe whole cycle is 1180 s, the UDC is 780 s and the EUDC is 400 s. The full test starts with four repetitions of the urban driving cycle (to represent city driving conditions) followed by the extra urban driving cycle to account for more aggressive and high speeds driving modes. The overall length of about 20 min is short compared to other cycles. Emissions are sampled during the cycle according to the constant volume sampling (CVS) technique, analyzed and expressed in g/km for each of the pollutants. The speed profile is shown in Figure 3.7.

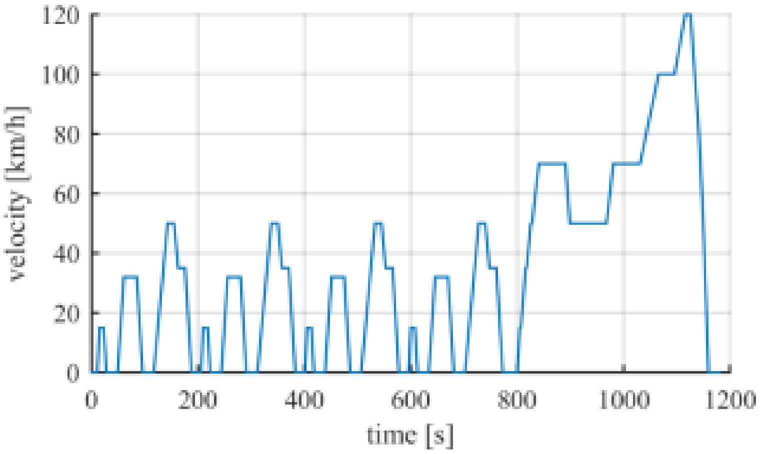


Figure 3.7. Speed profile of the NEDC [69]

- Worldwide Harmonized Light Vehicles Test Cycle (WLTC): WLTC are chassis dynamometer tests for the determination of emissions and fuel consumption from light-duty vehicles. These test cycles are part of the Worldwide harmonized light vehicles test procedure (WLTP). The development of the WLTC has been carried out under a program launched by the World Forum for the Harmonization of Vehicle Regulations of the United Nations Economic Commission for Europe (UNECE) through the working party on pollution and energy transport program (GRPE). The aim of this project was to develop a harmonized light duty test cycle, that represents the average characteristics around the world and to have a legislative world-wide-harmonized TA procedure put in place from 2017 onwards [78]. This test procedure is characterized by new and more realistic speed profile and gear-shifting logic, developed from approximately one million kilometers of in-use vehicle activity data and by a number of additional provisions in the vehicle characterization to run the test [77]. As a result vehicles type-approved under the WLTP show significantly more realistic fuel and energy consumption figures than what was available before in Europe (e.g. [73] and [76]). The WLTP is divided into three slightly different cycles depending on the power-to-mass (PMR) ratio of the vehicle. The PMR parameter is defined as the ratio of rated power (W)/curb mass (kg). Class 3 vehicles are divided into 2 subclasses according to their maximum speed: Class 3a with a maximum speed lower than 120 km/h and Class 3b with a higher vehicle speed. Class 3 is the relevant cycle for most of todays passenger cars. This cycle combines four different phases of driving: low, medium, high and extra high. (Figure 3.8).

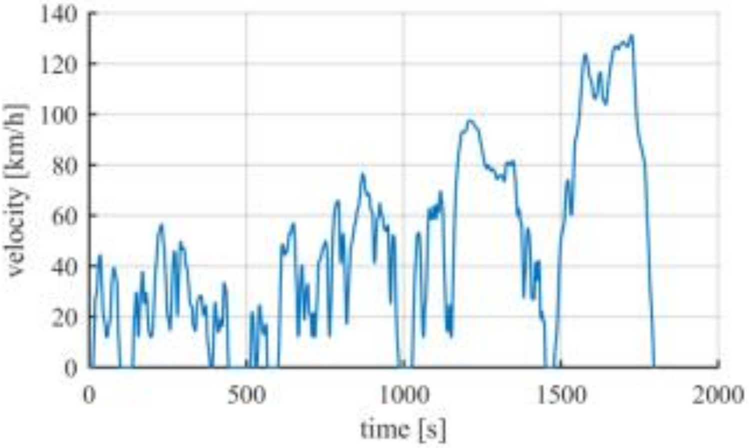


Figure 3.8. Speed profile of WLTC Class 3 [90]

- Common Artemis driving cycle (CADC): chassis dynamometer procedures developed within the European ARTEMIS project. Derived from a large database of 60 representative European private cars selected in France, the UK and Germany. These cycles are not used for type-approval, but it was specifically designed for emission modeling purposes [65]. The CADC is part of a set of reference driving cycles. Such driving cycles present a real advantage as they are derived from a large database [68]. The cycle is 52 minute long and includes three diving schedules: urban, rural road and motorway. The three parts can be used independently, and therefore all start and end wuth zero speed [94]. This is a transient driving cycle with many changes in speed. (Figure 3.9).

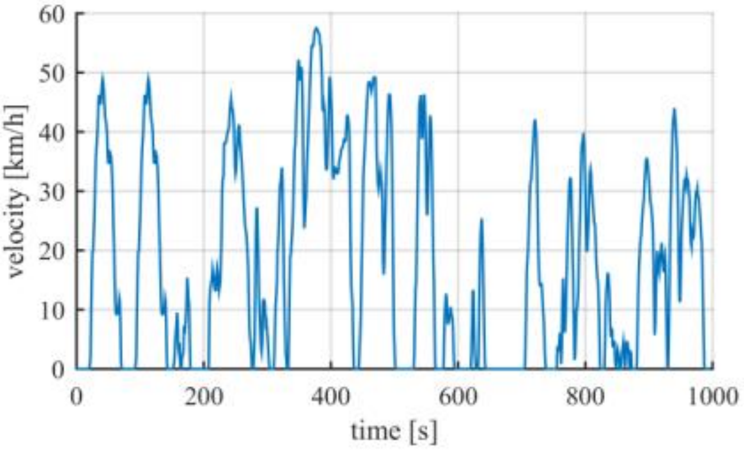


Figure 3.9. CADC speed profile [95]

- Japanese 10-15 mode (J10-15) and JC08 cycle: the 10-15 mode cycle had been used in Japan for emissions and fuel economy testing for light duty vehicles. This test was gradually replaced by the newer JC08 cycle over the period 2008-2011 [74]. Emissions are measured over the last four segments. The new procedure , JC08, had been fully phased-in by October 2011 and represents driving in congested city traffic, including idling periods and frequently alternating acceleration and deceleration. Measurement is made twice, with a cold start and with a warm start. The JC08 has a total duration of 1204 s. (Figure 3.10).

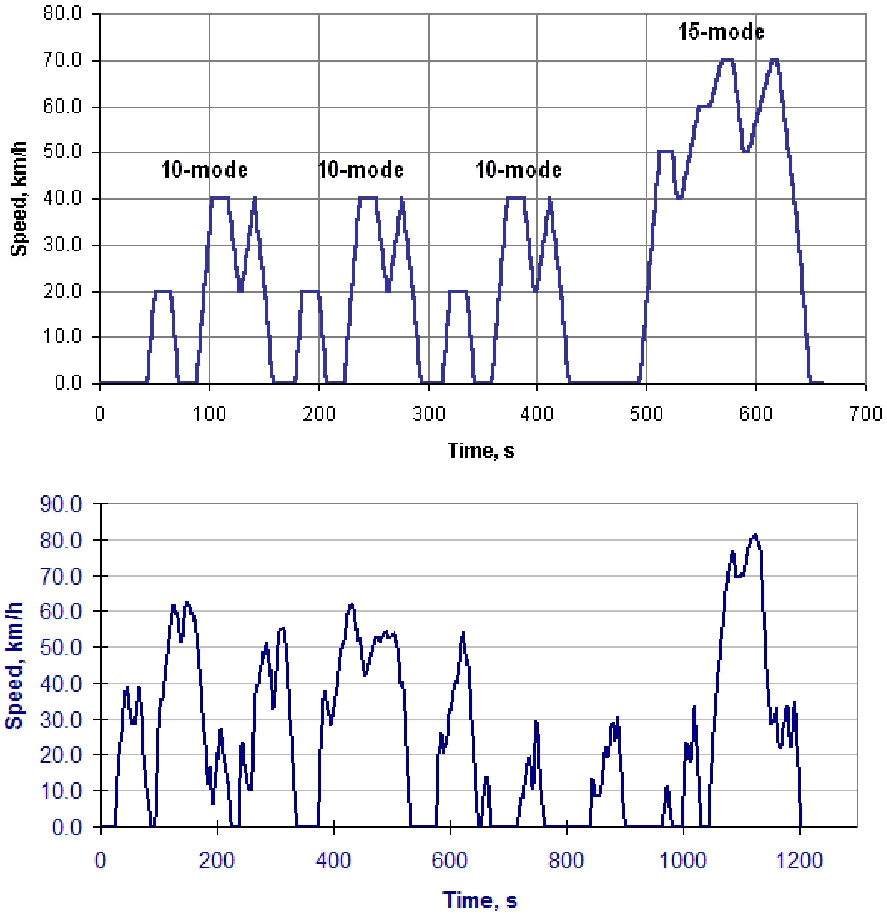


Figure 3.10. Japanese 10-15 Mode cycle and JC08 [74]

- US Federal Test Procedure (FTP) and Highway Fuel Economy Test Cycle (HWFET): The FTP-75 (often referred to as simply FTP) has been used for emission certification and fuel economy testing of light-duty vehicles in the United States. FTP 72 and FTP 75 cab be considered as first two driving cycles that were developed in the world [44]. There are two variants of FTP cycles. The FTP-75 is derived from the FTP-72 by adding a third phase of 505s, identical to the first phase of the FTP-72 but with a hot start [80]. The entire FTP-75 cycle consists of four segments; Cold start transient phase, stabilized phase, hot soak and hot start transient phase [86]. Compared to the NEDC there is no specific distinction between urban, rural or motorway, so the cycle is viewed as a whole [90].

  The HWFET cycle is a chassis dynamometer driving schedule developed specifically for the determination of highway fuel economy of light duth vehicles

[87]. The test is run twice with a maximum braek between runs of 17s. (Figure 3.11).

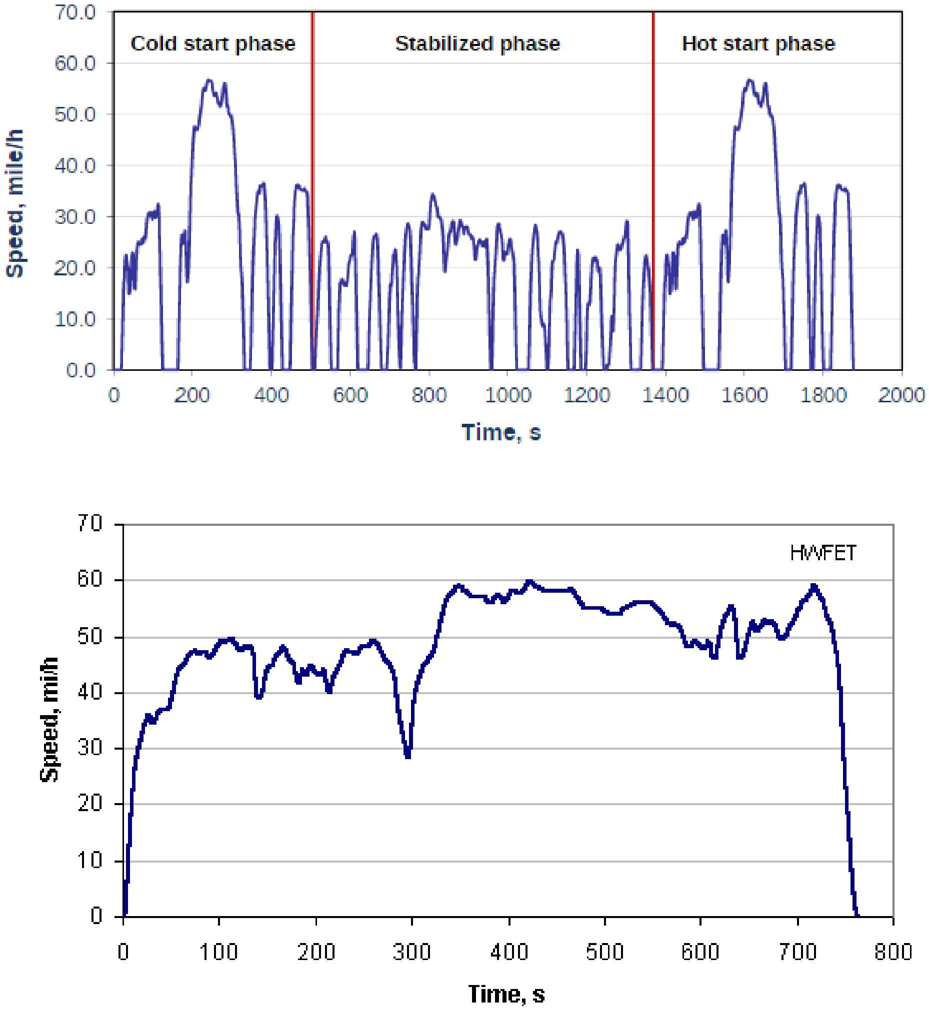


Figure 3.11. American driving cycles FTP-75 and HWFET [89]

- The Composite Urban Emissions Driving Cycles (CUEDC): Commissioned by the Australian National Environmental Protection Commission in 1998 as part of the Diesel National Environment Protection Measure. These cycles were created with the intention to closely replicate actual Australian on-road urban driving. Differently from other cycles considered in this work, CUEDCs are used for chassis based dynamometer testing of both heavy and light vehicles. They are composed of four distinct drive cycle segment; congested, minor roads, arterial and highway [59]. This is a transient driving cycle with many changes in speed. Different cycles were developed for each of the major diesel powered vehicles categories ranging from off-road passenger vehicles and light goods vehicles to heavy combination vehicles. (Figure 3.12).

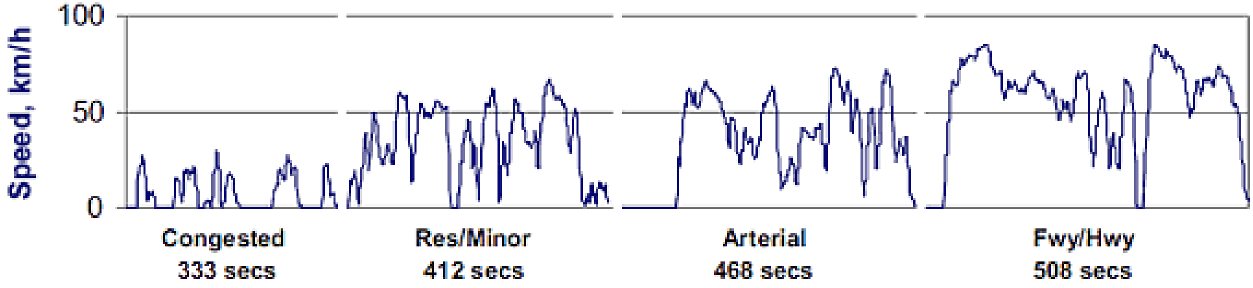


Figure 3.12. Diesel CUEDC cycle (Source: Environment Australia)

A description recap of the selected driving cycles is provided in Table 3.11. Most of the considered driving cycles for this work are transient driving cycles as they are considered to be more realistic.

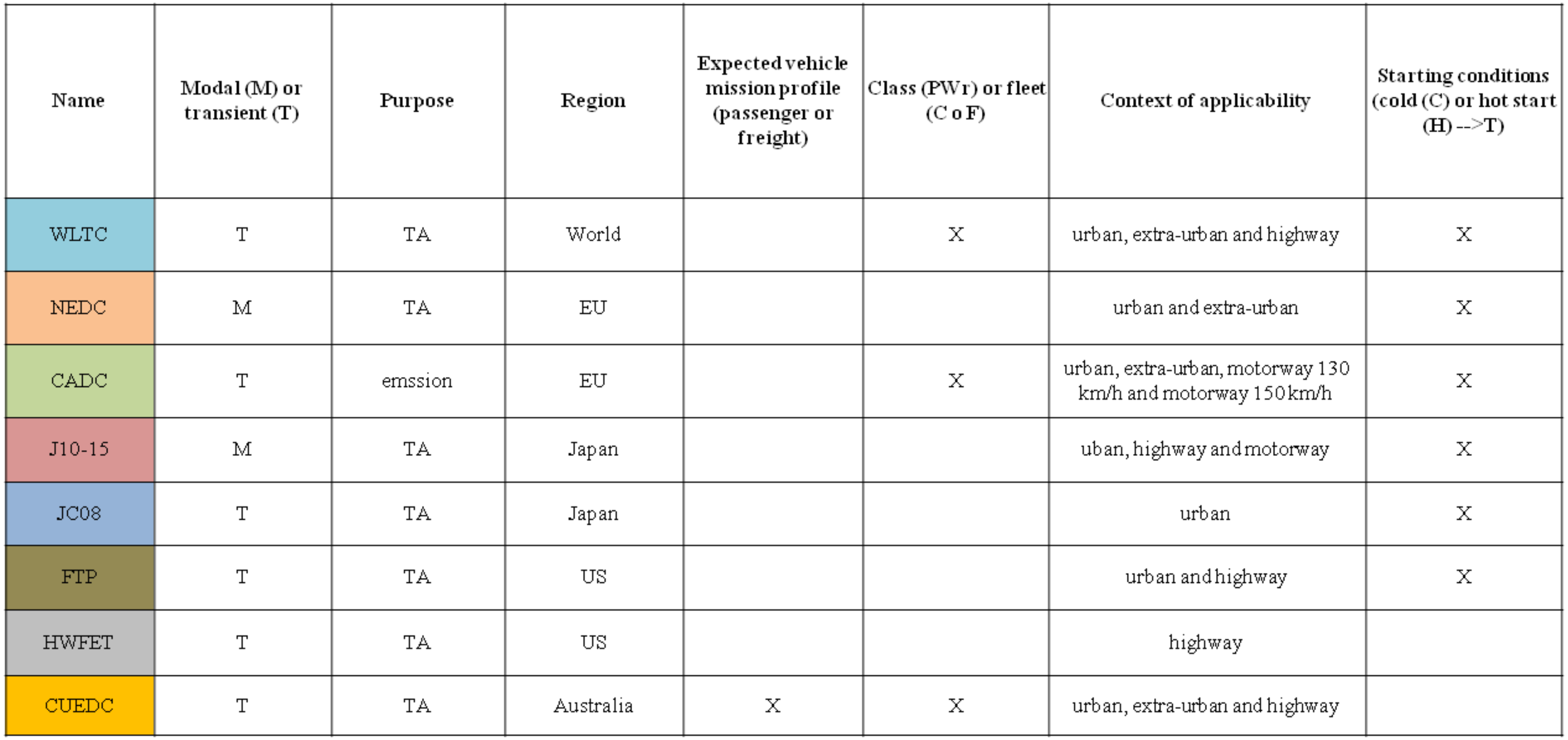
The CADC is the only sample real-world simulation driving cycle which was specifically designed for emission modeling purposes.

As stated by [44] USA, Europe, Australia and Asia can be identified as the four main regions for developing driving cycles.

The Australian CUEDC is the only cycle used both for testing light and heavy duty vehicles. The others are specifically designed for passenger cars testing whereas for these countries specific heavy duty vehicles testing cycles exist.

Temperature is considered in tests by introducing a cold or hot start, but not all the test cycles are provided of this element. Most of the cycles of this work have different versions with a specific hot or cold start run.

Table 3.11. Classification of selected driving cycles



Name	Modal (M) or transient (T)	Purpose	Region	Expected vehicle mission profile (passenger or freight)	Class (PWr) or fleet (C o F)	Context of applicability	Starting conditions (cold (C) or hot start (H) -->T)
WLTC	T	TA	World		X	urban, extra-urban and highway	X
NEDC	M	TA	EU			urban and extra-urban	X
CADC	T	emssion	EU		X	urban, extra-urban, motorway 130 km/h and motorway 150 km/h	X
J10-15	M	TA	Japan			uban, highway and motorway	X
JC08	T	TA	Japan			urban	X
FTP	T	TA	US			urban and highway	X
HWFET	T	TA	US			highway	
CUEDC	T	TA	Australia	X	X	urban, extra-urban and highway	

3.3.2 Taxonomy

DCs are built on the basis of real-world measurement procedures. They are used to estimate real world vehicle fuel consumption as well as real world emissions. DCs aim at cover the role of unified and world-wide recognized test procedures. However these cycles do not reflect the actual behavior of the driver or regional influences. Therefore, manufacturers have developed their own usage and test cycles and are able to extract data from the vehicle to analyse the individual driving behavior and vehicle usage. A large number of parameters can influence the vehicle energy consumption and the related emissions, including driver capabilities, driving context, traffic conditions, ambient temperature, etc. Such a variability causes the need for a taxonomy which identifies possible disaggregation of emission and fuel consumption cycle outputs. Evidence explained in literature is that local or regional conditions can differentiate driving patterns depending on which area is under examination ([96] and [97]).
Cycles can be defined depending on several elements:

- Gross vehicle weight (LDV or HDV);
- Expected vehicle mission profile (e.g. passenger road cars or freight);
- Class and categories of vehicles;
- Load (modal or transient);
- Coverage (specific region or city);
- Context of applicability (e.g. urban, extra-urban, etc);
- Temperature.

This taxonomy shows that driving cycles can give specific emission and fuel consumption values at this level of disaggregation.
Literature leads to consideration of various driving cycles for various vehicle weights. Specific test cycles can be designed depending on the gross vehicle weight. Driving behaviours are different between a LDV or a HDV so also testing cycles have to be more specific in order to have more representative values for emissions and consumption. Within this category a further disaggregation can be made depending on the expected vehicle mission profile as LDV can be light-passenger cars or light-commercial vehicles. These categories will surely have different driving patterns and consequently emissions and consumption values.
Always considering the vehicle detail, cycles can be specific depending on other types of classes or categories. An example is the WLTC which considers three classes of vehicles defined by PMR. Most common cars belong to class 3. Vans and buses can also belong to class 2 [81]. Also the CADC enables to consider vehicle characteristics. Two groups were considered in function of the power to mass ratio [68].

Emissions can also be disaggregated depending on parameters not related to vehicle technology.

Cycles can have continuous or transient speed phases and depending on this values will be more or less accurate and representative of real-life driving patterns.

A big variety of driving cycles can be run depending on region or specific city analysis. For example in [64], a set of DCs was obtained in the context of the city of Florence. Other examples are the Pune cycle [98], the Hong Kong cycle [99], Bangkok cycle [45], Beijing cycles [97] and driving cycles in eleven typical Chinese cities [100]. Within the same region, other considerations can be made on context of applicability, with specific urban, extra-urban or highway set of emission values.

Finally cycles can be derived for specific temperature conditions by including in tests, hot or cold start in order to simulate engine behavior in particular start phase.

The suggested disaggregation of emission and consumption given by driving cycles is summarized in Figure 3.13.

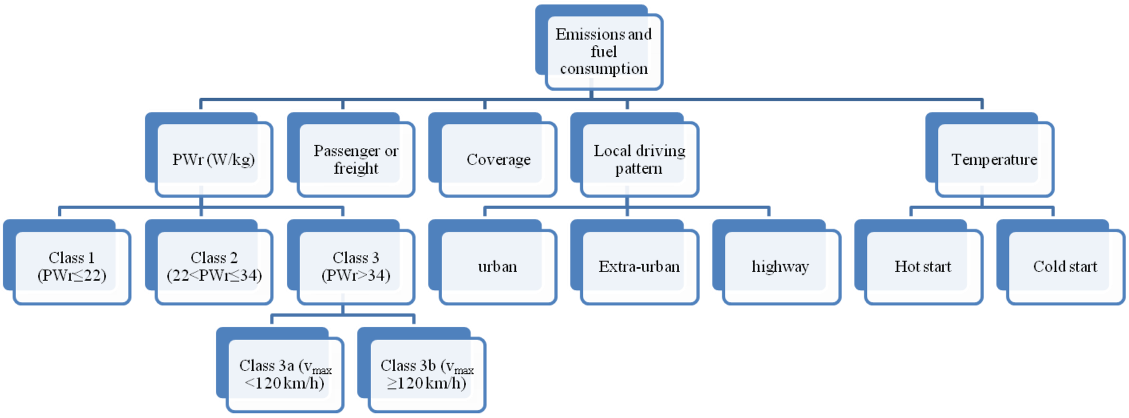


Figure 3.13. Disaggregation of emissions and fuel consumption from driving cycles

3.3.3 Driving cycles utilization

Type-approval driving cycles are mainly used for the determination of vehicles fuel consumption and the related emissions, for comparative and certification processes. These driving cycles are also used in the validation stages of transport models. An example is given by Rakha et al, in [88], where two fuel consumption transport models are generated and then validated by the use of driving cycles to demonstrate that estimates of vehicle fuel consumption and CO_2 emission rates are consistent with in-field measurements. Also in [89], by Fiori et al (2016), speed profiles of driving cycles are used to validate the developed model.

Local driving cycles, considered as the time series of speeds, that when reproduced by a vehicle, the resulting fuel consumption (FC) and emissions are similar to the average FC and emissions of all vehicle of the same technology driven in that region, are used to give a clear representation of local driving pattern.

The idea suggested in this work, is to increase the level of technological detail in modeling energy system and transport sector in an integrated way, using driving cycles as input variables for models. In particular driving cycles could provide more input data to the model framework such as:

- Segmentation of vehicle fleet;
- Data for different countries and regions;
- Data for classes of vehicles depending on power to weight ratio;
- Emissions and consumption for different typologies of roads like urban or extra-urban;
- Temperature related behavior of vehicles.

In the models analysed in section 3.2 many of these further segmentations are not available as shown in Table 3.12.

Table 3.12. Added benefit by driving cycles in the considered models. Green stands for “already present” and red for “not present”

	Vehicle parameters			External factors		
Model	Weight	PWr	Other	Regions	Roads	Temperature
AIM-CGE	🟩	🟥	🟥	🟩	🟥	🟥
DNE21+	🟥	🟥	🟩	🟩	🟥	🟥
GEM-E3	🟩	🟥	🟩	🟩	🟥	🟥
GCAM	🟩	🟥	🟩	🟩	🟥	🟥
IMACLIM-R	🟥	🟥	🟩	🟩	🟥	🟥
MESSAGE	🟩	🟥	🟩	🟩	🟥	🟥
POLES	🟩	🟥	🟩	🟩	🟥	🟥

REMIND	🟩	🟥	🟥	🟩	🟥	🟥
TIAM-UCL	🟥	🟥	🟩	🟩	🟥	🟥
WITCH-T	🟩	🟥	🟩	🟩	🟥	🟥
MoMo	🟩	🟥	🟩	🟩	🟥	🟥
Roadmap	🟩	🟥	🟩	🟩	🟥	🟥
TIMER	🟩	🟥	🟩	🟩	🟥	🟥

Disaggregation of data with respect to PWr, roads and temperature conditions are not present in the models considered in this work. Data for specific regions are already provided in models and also data for different gross vehicle weights and other classifications can be already found in the analysed models, expecially in the transportation “stand alone” models which already have a greater level of representation of the road transport sector.

Driving cycles are simple models so they can be easily integrated into modeling frameworks like IAMs. In this way some main criticisms of IAMs, underlined in section 3.2.3 could be overcome.

Driving cycles could act firstly on the problem of increasing vehicle technology level of detail. Driving cycles are specifically related to vehicle technology and give the opportunity to capture emissions and fuel consumption for different sub-classes of vehicles. In this way specific rates could be obtained referring to specific utilization or specific sub-classes of vehicles, not limiting any more the possible considerations at usual transport modes.

The implementation of driving cycles in models could also have the potential to reduce the problem of representation of driving patterns. This term is used vaguely to describe the way drivers drive. Driving cycles are time series of speeds that could be able to represent driving patterns. So by supplementing these cycles to already available models a greater level of representativeness for consumer behaviours in IAMs could be reached.

In conclusion, driving cycles give the opportunity to reach very high degree of technological detail in representing passenger road transport sector, with specific DCs for each region but also city, for vehicle technologies and fleets.

Nevertheless, additional work is required to confirm the solution proposed in this manuscript, and to establish methodology to implement the resulting DC into model framework. While desiderable, it seems difficult to fully harmonize technological parameters across a broader range of models due to structural differences in the representation of technology.

Conclusions

The scope of this thesis work is to analyse different models, identifying limits of technological detail in representing road passenger transport in modelling the intertwined effects between transport and energy systems and providing a possible solution for increasing the degree of technological richness. The focus is on scenario analysis, transportation "stand-alone" models and IAMs with a high degree of technological detail in transport representation, and on driving cycles.

The whole work is driven by a deep and rigorous literature review of existing scenarios, models and driving cycles, identifying key parameters in order to organize classifications and comparisons between different tools.

The starting point of the work is a detailed analysis of the background, to describe the road passenger transport sector with respect to market shares, trends, CO_2 emissions and fuel consumption.

This analysis is then followed by the focus on energy scenarios described by major organization outlooks. This type of analysis is useful to evaluate the impacts of energy efficiency policies on road transport sector answering some crucial "what-if" questions. A classification was then created depending on the building-approach (forecasting or backcasting) and on the spatial coverage. The scenarios built using a forecasting approach amount to 56% of the set considered. The approach used has a crucial role when comparing different outlooks because forecasting scenarios are generated to exploring possible future developments stating a pool of assumptions and setting parameters values. Instead, backcasting scenarios are based on the selection and identification of specific target set in the future and the modelling frameworks at the basis compute optimal pathways according to pre-defined objective functions.

Main outputs were then compared. Taking into consideration the energy mix by 2040, for all scenarios, the overall fossil fuel share tends not to get lower than 70% from todays 80%, highlighting that pathway towards 2°C still need stronger deployment of non-fossil energy. Comparing the global number of EVs on the road by 2040, Bloomberg NEF hold the most aggressive view on EV adoption, expecting there to be 508 million passenger EVs on the road globally. Most of the outlooks projects growing CO_2 emissions, but IEA 2DS and EV30@30, WEC Tollway, ITF LC, BP LCT and ExxonMobil scenarios, show a significant decrease in CO_2 emissions from road cars after reaching a peak in 2020.

After highlighting the major outlooks a section is dedicated to a comparative analysis between 13 models. Models are first divided into transportation "stand-alone" models or integrated assessment models (IAMs) then compared with respect to how emissions are considered within their frameworks and to the level of technological representation for road transport sector. IAMs show a greater representation of emissions as they include upstream production and transportation CO_2 emissions. On the other hand, transportation “stand-alone” models have a greater level of detail both for modes and technologies, with a further disaggregation within the identified modes and technologies depending on classes and regions. This type of description was then followed by a comparison of endogenous calculations and exogenous drivers of model drivers and parameters. This comparison was based on two different categories of parameters: the socioeconomic factors and demand drivers such as GDP, population, passenger service demand, freight service demand and mode share, and the fuels and vehicle technologies focusing on fuel prices, energy intensity of fuel production, shares of fuel types within modes, efficiency level of individual technologies and efficiency levels within service, mode and fuel type. The second category of data show a greater percentage of exogenous drivers for each factor suggesting that this is the category to work on..

Four main criticisms and limits were identified and then related to the considered models.

The four limits are due to: lack of trasparency around model structures and input assumptions, need to increase vehicle technology level of detail, over-reliance on particular technologies and inadeguate representation of real-world policies, mode choice and consumer preferences.

To overcome some of these criticisms models could be supplemented with other models and approaches and this work proposes driving cycles as a possible solution.

Driving cycles (DCs), are a series of data points representing vehicle speed versus time supposed to represent typical driving patterns, and to understand how a vehicle is used.

The DCs for USA, Europe, Australia and Asia, which can be identified as the four main regions where many countries have been developing driving cycles during last thirty to forty years, were identified and described. A taxonomy was also created in order to evidence the possible greater characterization of fuel consumption and emissions supplied by these travel based models. Specific cycles can be defined depending on several elements such as gross vehicle weight, expected vehicle mission profile, class and categories of vehicles, load, coverage, context of applicability and temperature. All these specific elements have an impact on emissions and consumption of vehicles. Driving cycles are simple models so they can be integrated into modeling frameworks like IAMs. The models considered in this work evidence that disaggregation of data with respect to PWr, roads and temperature are not present. Driving cycles could increase the vehicle level of technology in models giving a further disaggregation of emissions and fuel consumption. Additional work is required to confirm this solution.

Since now DCs have been used only in the validation steps of new transport models by comparing emission outputs.

To conclude, it is possible to state that the technological detail in representing energy systems and passenger road transport sector can still be deepened but driving cycles could be a possible option towards this goal. It is also possible to state that there is not the best energy-transport model, but the most suitable one, depending on specific user purposes and needs. Selecting one rather than another gives extreamly different results depending on the wide range of differences into frameworks and assumptions.

All brings the research and the literature towards increasingly high degree of representation of road passenger transport within models with more flexible, transparent and accessible structures.

Acronyms

AIM	Asian pacific Integrated Model
ARTEMIS	Advanced Rational Transport Evaluation and Multi-modal Information System
AT	Accelerated Transition
BAU	Business At Usual
BEV	Battery Electric Vehicle
BNEF	Bloomberg New Energy Finance
BP	British Petroleum
B2DS	Beyond 2 Degree Scenario
CADC	Common ARTEMIS Driving Cycle
CI	Carbon Intensity
CIRED	Centre International de Recherche sur l’Environnement et le Développement
CMCC	Centro euro Meditteraneo sui Cambiamenti Climatici
CUEDC	Composite Urban Emission Driving Cycle
DC	Driving Cycle
EC-JRC	European Commission-Joint Research Centre
EIA	Energy Information Administration
ET	Evolving Transition
EU	European Union
EUDC	Extra-Urban Driving Cycle
EV	Electric Vehicle
FC	Fuel Consumption
FCEV	Fuel Cell Electric Vehicle
FEEM	Fondazione Eni Enrico Mattei

FTP	Federal Test Procedure
GCAM	General Change Assessment Model
GDP	Gross Domestic Product
GEM-E3	General Equilibrium Model for Economy-Energy-Environnement
GHG	GreenHouseGas
HEV	Hybrid Electric Vehicle
HDV	Heavy Duty Vehicle
HWFET	Highway Fuel Economy Test Cycle
IAM	Integrated Assessment Model
ICCS	Institute of Communication and Computer Systems
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
IEA	International Energy Agency
IIASA	International Institute for Applied System Analysis
ILUC	Indirect Land Use Change
IMAGE	Integrated Model to Assess the Global Environnement
ITF	International Transport Forum
ITS	Institute of Transportation Studies
LDV	Light Duty Vehicle
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental impact
MoMo	Mobility Model
NEDC	New European Driving Cycle
NPS	New Policy Scenario
OPEC	Organization of the Petroleum Exporting Countries
PHEV	Plug-in Hybrid Electric Vehicle
PIK	Potsdam Institut fur Klimafolgenforschung
PMR	Power Mass Ratio

PNNL	Pacific Northwest National Laboratory
PKT	Passenger-Kilometres Travelled
REMIND	Regional Model of Investments and Development
RITE	Research Institute of Innovative Technology for the Earth
RT	Rapid Transition
RTS	Reference Technology Scenario
SUV	Sport Utility Vehicle
TA	Type Approval
TFC	Total Final Consumption
TIAM-UCL	TIMES Integrated Assessment Model in University College London
TKT	Tonnes-Kilometres Travelled
UDC	Urban Driving Cycle
UNECE	United Nation Economic Commission for Europe
USA	United States of America
UU	Utrecht University
WEC	World Energy Council
WITCH-T	World Industry
WLTC	Worldwide harmonized Light-duty vehicles Test Cycle
WLTP	Worldwide harmonized Light-duty vehicles Test Procedure
2DS	2 Degree Scenario

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