Further development of VECTO

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Final report

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Abbreviations

AAUX	……..	VECTO Advanced Auxiliary Model
ACEA	……..	Association des Constructeurs Européens d'Automobiles
ADAS	……..	Advanced Driver Assistance Systems
AMT	……..	Automated Manual Transmission
AT	……..	Automatic transmission with hydraulic torque converter
BEV	……..	Battery Electric vehicle
CFD	……..	Computational Fluid Dynamics
CIF	……..	Customer Information File
CLCCR	……..	International Association of the Body and Trailer Building Industry
CONCAWE	……..	The oil companies' European association for environment, health and safety in refining and distribution
CoP	……..	Conformity of Production
CST	……..	Constant Speed Test (procedure to determine the air drag of HDV)
EffShift	……..	"Efficiency Shift" algorithm developed for VECTO gear shift models
FTE	……..	Full Time Equivalent
HDE	……..	Heavy Duty Engine with type approval according to Regulation (EC) 595/2009
HDV	……..	Heavy Duty Vehicle
HEV	……..	Hybrid Electric Vehicle
LDV	……..	Light Duty Vehicle; here vehicles with type approval according to Regulation (EC) 715/2007. These are officially called "Light Passenger and Commercial vehicles"
MRF	……..	Manufacturers Records File
OEM	……..	Original Equipment Manufacturer
PCC	……..	Predictive Cruise Control
PHEV	……..	Plug-In Hybrid Electric Vehicle (battery recharged from the grid also)
PIF	……..	Primary vehicle information file
PP	……..	Pilot Phase
SIL	……..	Software in the Loop
TPMLM	……..	Technical Permissible Maximum Laden Mass
UITP	……..	International Association of Public Transport
VECTO	……..	Vehicle Energy Consumption calculation TOol
VTP	……..	Verification Testing Procedure
WLTC	……..	Worldwide harmonized Light duty driving Test Cycle
WLTP	……..	Worldwide harmonized Light vehicle emissions Test Procedure

Executive Summary

The current approach on the certification of CO_2 emissions from HDV as laid down in Commission Regulation (EU) 2017/2400 and as implemented in the current official version of the VECTO tool does not cover several fuel efficiency technologies, which will play a relevant role in future HDV. Furthermore a few existing elements in VECTO had to be improved in order to reflect real world CO_2 emissions of HDV as representative as possible. The related specific issues which had to be addressed in this project were:

1. Update of generic gear shift algorithms for AMT and AT transmissions
2. Incorporation of Predictive Cruise Control (PCC) systems
3. Incorporation of Waste / Exhaust Heat Recovery (W/EHR) Systems
4. Incorporation of Gas and dual-fuelled engines
5. VECTO software update according to the methods elaborated in 1. to 4.

The option to consider OEM specific control strategies in the long-term future of VECTO appears worthwhile for several vehicle systems (e.g. gear shift strategies, ADAS or HEV controllers). Possible pathways to elaborate the related methods have also been analysed in this study.

Update of generic gear shift algorithms for AMT and AT transmissions

Starting point of the update was a review of the shortcomings of the current "Classic" gear shifts strategies for AMTs and ATs in VECTO. The main shortcomings were identified to not reflect aligned engine and transmission control systems, to not work properly for various kinds of drivetrain layouts (e.g. overdrive transmissions) and vehicle categories (e.g. AMT in bus applications) and to not properly rank AT design types AT-S (design type "serial", manufacturer ZF) and AT-P (design type "parallel", manufacturer "VOITH") in urban bus applications.

Based on those requirements the new gear shift models "EffShift AMT" and "Eff Shift AT" have been elaborated, implemented into the software and discussed with industry. Main principle of the EffShift approach is to trigger a gear shift if the combined fuel efficiency of engine and transmission in a candidate gear exceeds the corresponding value in the current gear by a certain threshold. Additionally certain criteria e.g. regarding driveability and to avoid gear oscillations apply. For torque converter shifts in AT transmissions additional rules in EffShift AT apply. In order to depict systematic differences in gear selection between AMT and AT technology the operation points used for rating of fuel efficiency and for checking the power requirements in a candidate gear are calculated differently in EffShift AMT and Eff Shift AT.

The features of the EffShift gear shift algorithm are assessed to be:

- Simple and robust approach to model gear shifts for all configurations of conventional powertrains (direct drive and overdrive transmissions, long and shorts axles) and all HD vehicle configurations (long haul, delivery, buses).
- The algorithm reflects a straight forward gear selection strategy of an aligned engine and transmission control system.
- Sophisticated gear shift features as stated by industry for recent vehicle generations (i.e. predictive shifting in combination with ADAS functions) are not reflected in EffShift. For

vehicles where engine and transmission controls are not aligned, EffShift might overestimate overall fuel efficiency.

- The algorithm is future-proof to be extended to model also gear shifts for Hybrid electric vehicles (HEV). In this case the EffShift rating algorithm needs to evaluate the combined energy/fuel consumption of internal combustion engine and electric machines (electric energy converted to fuel consumption by a cost factor). Merging of hybrid controller and EffShift is currently performed as part of the on-going "VECTO – Extensions to hybrids" contract.
- Compared to the current "Classic" VECTO approach the EffShift algorithm:
  - results in a slightly more dynamic driving behaviour
  - results in a small increase of simulation time (some 10 to 20%)

The new gearshift strategies have been validated to the extend possible based on the available data provided by industry and available at TU Graz from earlier projects. Also the general feedback from industry, that the EffShift approach is a significant improvement against the current "Classic" model, can be taken as a confirmation of the method. More scientific approaches for a validation would require a set of dedicated vehicle tests (or at least SIL simulations) where all relevant input data for VECTO could be made available.

Special sensitive applications fields are the comparison of AMT and AT in certain market segments and especially the competition of AT-P and AT-S in the urban bus market. From the small amount of data available at TUG it can be concluded that the rankings predicted by VECTO Effshift are closer to real world conditions than with Classic. However, especially for the AT-P vs. AT-S issue there is lack of comprehensive information at TUG to propose a final parametrisation of the VECTO EffShift model. It is suggested that ACEA-TF5, where several OEMs offer both transmission systems in their portfolio, comes up with a final proposal of parameters for a discussion in a VECTO board. In this regards the contractor will organise and perform a final feedback loop, make bug-fixes in the new models if necessary and implement the final parameters (if decided to be changed compared to the ones already implemented).

Advanced Driver Assistance Systems (ADAS) including Predictive Cruise Control (PCC)

In this contract the most relevant ADAS functions have been incorporated into the VECTO software and the necessary boundary conditions for a robust handling in the CO_2 certification have been elaborated. The implementation of this work was significantly influenced by the fact, that a first version of the methods needed to be ready before the end of 2018 in order to have the most relevant systems accounted for in the CO_2 standards baseline period starting in 2019. As a consequence, a two step implementation approach had to be executed:

- Implementation of a "Quick fix" approach based on a simple approach where fixed CO_2 credits are applied ("Phase 1" implementation)
- Implementation of an "In-the-loop" simulation approach using more sophisticated methods until the end of the project ("Phase 2" implementation).

In the work an overview on all known ADAS systems with impact on vehicles' fuel consumption was elaborated. Based on the overview a list of systems most relevant for the HDV CO_2 certification was compiled. Those are:

- Engine stop-start

- Eco-roll (with and without engine stop-start)
- Predictive Cruise Control (with three sub-functions)

For each identified relevant system, a concrete definition based on verifiable system characteristics was elaborated. In total 17 possible combinations are differentiated. For the phase 1 implementation only ADAS systems in AMT vehicles were considered. The related definitions are already part of Regulation (EU) 2019/318. For the implementation phase 2 additionally ADAS functions for vehicles with AT transmissions were introduced. Draft definitions for those systems to be incorporated in a future regulatory text have been elaborated.

The fixed CO_2 credits which are applied by VECTO in the phase 1 implementation have been elaborated based on a post-processing approach analysing modal simulation results for a set of reference vehicles of the lorry groups 4, 5, 9 and 10. Only those vehicle groups are currently covered by Regulation (EU) 2019/318. The raw CO_2 credits from the post-processing analysis have been applied with a "factor of conservatism" of 0.5 in order to not overestimate real world effects and to account for the less accurate method compared to in-the-loop simulation. Below the resulting CO_2 credits for a typical group 5 vehicle are summarised:

- Engine stop-start (ESS) during vehicle stops: credits are in the range of -1.5% in urban delivery, -0.3% in regional delivery and no impact in long-haul mission
- Eco-roll: credits are in the range from 0% to -0.3% (the "pure" Eco-roll function without combination with PCC is considered to be non-predictive thus the effect on overall fuel consumption is low)
- Predictive cruise control: credits are in the range from -0.1% to -0.7% in long haul and from -0.2% to 0.9% in regional delivery. For urban driving PCC is considered as not relevant.
- Combination of systems: the highest credits have been determined for the combination of all three basic ADAS systems. The maximum credits are -0.8% for the long haul cycle (with reference payload) and -1.4% in regional delivery cycle (reference payload). In the urban delivery cycle, only Engine stop-start is relevant, thus the combination of ADAS does not result in higher credits than with ESS alone.

The Phase 2 implementation is based on individual in-the loop simulation in VETO based on generic control algorithms for each ADAS function. This approach offers benefits compared to phase 1 implementation as:

- it is more accurate as it considers particular characteristics of the vehicle (e.g. curb mass, driving resistances),
- it is future-proof to cover interactions with other systems which aim to recuperate kinetic energy (e.g. HEV, smart auxiliaries)
- it can be applied to all vehicle groups (other lorry groups than 4, 5, 9, and 10, buses).

The control functions implemented into the VECTO code are based on proposals from industry and further testing and bug fixing during the project. In general, the VECTO results based on phase 2 methods confirm the "raw" reduction potentials as determined by the work in phase 1 by predicting approximately twice the rates from the current numbers in the official tool for the same set of reference vehicles.

The methods for phase 2 implementation could be taken over for official VECTO either in 07/2020 or in 07/2021 (however triggering a requirement to apply an adjustment procedure for the 2019 baseline) except for Eco-roll for AT transmissions. The latter AT system is not yet covered by

Regulation (EU) 2019/318, hence this function can not be considered in VECTO before the next amendment of Regulation (EU) 2017/2400 comes into force.

Regarding the model settings used in the phase 2 methods it is recommended to further collect feedback from industry in a second feedback loop and agree on final parameter sets e.g. in a VECTO board meeting before the method is applied in the official version of the tool. In this regards the contractor will organise and perform a final feedback loop, make bug-fixes in the new models if necessary and implement the final parameters (if decided to be changed compared to the ones already implemented).

As in all aspects of the HDV CO_2 legislation, the goal for VECTO shall be to reflect fuel consumption benefits from ADAS systems in real world conditions as representative as possible. To verify the results from VECTO by a straight forward test procedure based on fuel consumption measurements on a certain route driven w/ and w/o PCC engaged was judged to be a not feasible option. Some of the reasons are that the test results on fuel consumption are additionally influenced by variation of ambient conditions and that any test route will have different gradient profiles and traffic conditions compared to the cycle defined in the HDV CO_2 mission profile in VECTO.

Instead based on a stepwise validation approach as described in the report it is concluded that the methods as elaborated for VECTO provide robust estimations for the real world benefit for the implemented ADAS functionalities. Items to be further investigated are mainly the representativeness of mission profiles (hilliness) and representative values for underspeed and overspeed used by the generic ADAS algorithm in VECTO.

Waste / Exhaust Heat Recovery (W/HER) Systems:

The method elaborated for the consideration of waste heat recovery systems was tested with measurements at MAN and at JRC. The MAN tests used a MAN engine and WHR system mechanically coupled to the drive train. The tests at JRC were performed in cooperation with MAHLE using a WHR system from MAHLE which produced electric power. The electric power was converted by a motor to mechanical power which was fed also to the drivetrain since the electric power consumption from auxiliaries was lower than the produced electric energy.

The method developed for VECTO foresees a certification of the WHR system together with the engine and measures beside the fuel map also the electric power output of the WHR system if applicable. The WHTC correction factor method is applied for the fuel consumption and for the electric power to adjust the results to the exhaust gas temperature levels in the WHTC. The method showed already a satisfying accuracy and is in line with the current VECTO method for engines. Some details for the test set up need to be defined during the pilot phase for the amendment of the technical annexes of the regulation. This mainly concerns the definition of allowed cooling capacity and temperatures, since these have high influence on the WHR efficiency. Also a more detailed correction method was elaborated, which may be used as add on after the basic WHTC correction. This extended correction adjusts the results corrected to WHTC levels further to the temperature levels to be expected in the single VECTO mission profiles. The method would need additional steady state engine test points and did not lead to significant improvements in the accuracy when applied for the MAN system. The extended test method was not applied for the JRC tests. Thus, the extended method is recommended only, if it is tested in the pilot phase on more engines and proves there to have significant benefits compared to the basic method.

Gas and dual-fuelled engines

Gaseous fuels with lower carbon content than diesel fuel pose the opportunity to reduce CO_2 emissions of vehicles. Currently several different concepts of gas-fuelled engine technologies exist which are either based on liquefied petroleum gas (LPG) or natural gas (NG).

LPG and NG were already considered in the procedure for engine component certification, but for NG more detailed provisions were deemed necessary on the vehicle level. For NG two different systems for storage of the fuel in the vehicle exist which, either in compressed gaseous phase (CNG) or in liquid phase at very low temperatures (LNG). In the engine component certification for NG-fuelled engines there is no differentiation between these storage systems but a single specific reference fuel with a fixed composition is used. However, typical CNG and LNG available on the European market vary quite significantly in their carbon content which has an impact on the tailpipe CO_2 emissions of a specific vehicle. Therefore, commonly accepted standards for the fuel properties for CNG and LNG were elaborated and defined in the European CO_2 certification framework resulting in correct figures for CO_2 emissions and fuel consumption for such vehicles. Since the fuel properties cannot be defined on engine component level but need to be set on vehicle level, once the type of tank system is known, the fuel mass flow values from the engine component test derived for the reference fuel need to be converted to the respective values for either CNG or LNG later on in the vehicle simulation. Thus, a standardization method for the fuel mass flow based on the specific energy content was developed in order to guarantee consistency of the ratio CO_2 to fuel energy burnt from engine testing throughout vehicle simulation. All these amendments mentioned above were already introduced with Regulation (EU) 2019/318.

Dual-fuel engines concepts are close to market introduction that burn both diesel and gas fuels simultaneously in different relative shares depending on the operating conditions of the engine system. For those concepts new methods needed to be developed for the European CO2 determination framework. Therefore, a holistic method for considering dual-fuel engines in the engine test procedure as well as in the vehicle simulation was developed. This method is closely linked to the procedures for European pollutant emission type approval of engines. After the first draft of the method was available it was further discussed and detailed in a dedicated working group with experts on gas engines from different OEMs. One OEM also tested the method and also generated results for different VECTO mission profiles as a basis for analysing the accuracy to be expected by the newly introduced method for dual-fuel engines. In parallel, TUG performed a similar measurement campaign on a regular EURO VI Diesel engine to provide a reference value for the achievable accuracy for a conventional engine technology. As a result, the testing campaign showed that the accuracy of the chosen approach for dual-fuel engines is comparable to the one for a regular Diesel engine. As a final outcome, a list of necessary amendments to the existing technical annex to include dual-fuel engines was drafted as basis for future work. In addition an update of both VECTO and the VECTO Engine pre-processing tool in order to handle the new technology was performed.

VECTO Software update

For the implementation of the above described additional functionalities the same methods and processes already established during the implementation of VECTO 3 in the LOT4/SR7 project were applied. The lean software processes and workflows roughly follow the SPICE quality framework (ISO 15504, software lifecycle processes: ISO 12207). CITnet/JIRA has been used as issue tracker for all new features or adaptations of existing features. All implementations were done in separate branches and then merged into the main development tree. The development of the new VECTO functionality was done in a dedicated fork so that it does not interfere with the official VECTO version used for certification. Once the new features become effective, this fork can be merged into the official development repository.

The implementation of new functionality has been done in both, the engineering and declaration mode in parallel. Engineering mode allows for easily adjusting and exploring the effect of certain model parameters while in declaration mode generic values are used for most parameters.

Adding new functionality to VECTO required on the one hand to implement new component models (e.g., W/EHR system, gearshift strategy), to adapt existing models (e.g., driver model for in-the-loop ADAS functionality), and to extend the architecture itself. Extension of the architecture include the following items: (i) adding a generic method for pre-processors, (ii) post-processing the fuel consumption to consider energy savings or additional energy demands that cannot be included in the in-the-loop simulation (e.g., energy demand for engine start, power generated by W/EHR system), and (iii) allowing components to use a meta-model (i.e., a simplified copy of the powertrain).

Pre-processors are required for the in-the-loop implementation of the predictive cruise control functionality to analyse the driving cycle for potential PCC situations. The powertrain meta-model is used by the efficiency based shift strategy to assess the fuel consumption and gear rating for candidate gears.

The XML schema was adapted to allow for new model data. A new XML schema was developed for engines with dual-fuel or W/EHR systems.

The new functionality added to VECTO is also covered in unit tests, in total more than 1800 test cases.

Elaboration of possible pathways for long-term consideration of OEM specific gear shift strategies in VECTO

Several component controllers have influences on the fuel efficiency of a vehicle: gear shifting, Advanced Driver Assistance Systems (ADAS) including Predictive Cruise Control (PCC), smart auxiliaries, hybrids, heating strategies for exhaust gas aftertreatment and all combinations of these functions. These controllers are currently represented by generic control algorithms in VECTO or are implicitly covered in certified input data (e.g. exhaust heating strategies in the engine fuel consumption map). If vehicle specific control algorithms could be considered in VECTO, more incentives to optimise the controllers can be created. Thus not only vehicle specific gear shift strategies but all relevant controllers were included in the desktop analysis in this contract.

Three options to consider vehicle specific controllers were identified: a) Coupling the vehicle specific controller via software-in-the-loop (SIL) to the VECTO software; b) Designing a test procedure, where effects of controllers are considered implicitly and c) the application of artificial intelligence (AI) tools to set up the controller's behaviour in a software based on standardised vehicle tests. Option a) will be examined in a Horizon 2020 project from 2020 on; option b) uses a fuel map with wheel power and wheel speed as x- and y-axis in a VECTO simulation. The maps can be produced from real world tests similar to the VTP method and thus include the controllers behaviour relevant for the drive train and auxiliaries. Method b) seems also to be a simple default method to cover complex new technologies in the CO_2 certification. Option c) was not tested in detail due to a lack of test data available. The lack of access to complete test data sets for HDVs is general a problem in model development and validation. Thus it is suggested to set up complete data sets with VECTO input and VTP test results for some HDVs where the Commission and consultants have access to.

1 Introduction

The current approach on the certification of CO_2 emissions from HDV as laid down in Commission Regulation (EU) 2017/2400 and as implemented in the current official version of the VECTO tool does not cover several fuel efficiency technologies, which will play a relevant role in future HDV. Furthermore a few existing elements in VECTO had to be improved in order to reflect real world CO_2 emissions of HDV as representative as possible. The related specific issues which had to be addressed in this project were:

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2. Incorporation of Predictive Cruise Control (PCC) systems
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4. Incorporation of Gas and dual-fuelled engines
5. VECTO software update according to the methods elaborated in 1. to 4.

The report is structured as follows:

Chapter 2 gives a documentation per (sub-)task of the project as structured in the tender. For each task the descriptions contain:

- the findings from the analysis of the current situation and the identified requirements for an implementation into VECTO and into the Commission Regulation (EU) 2017/2400,
- descriptions of the methods elaborated, i.e. the test procedures for component certification and simulation approaches for VECTO,
- recommendations for future activities.

Chapter 3 lists the meetings held during the project.

Chapter 4 contains the list of references.

The Annexes contain detailed descriptions of methods developed and analysis performed related to VECTO gear shift models (Annex A.1) and related to Advanced Driver Assistance Systems (ADAS) and PCC (Annex A.2).

2 Work description per task

2.1 Task 1: Review and update different types of Automatic Transmission (AT) and Automated Manual Transmission (AMT) and their operation logic

Gear selection is one of the key parameters influencing fuel consumption and CO_2 emissions of HDVs. For VECTO a proper reflection of realistic gear-shift behaviour is essential both to meet real world CO_2 emission levels in absolute terms and - as an even more sensitive issue - to correctly predict the real world CO_2 ranking of different transmission technologies.

While the modelling of the hardware in the transmission seems to be already very robust, the gear shift strategies, i.e. the functionality describing at which rpm gears are changed, was identified not to work fully satisfactory for all transmission technologies, vehicle groups and mission profiles.

In its current approach VECTO uses generic gear shift algorithms specific for different transmission types (synchronised manual transmission (SMT); automated manual transmission (AMT); automatic transmission serial arrangement (AT-S); automatic transmission parallel arrangement (AT-P)) and for different vehicle types (trucks, city buses and coaches). These methods have been elaborated by TUG in cooperation with ACEA and transmission manufacturers.

The main topics identified to require further efforts in the development of VECTO and/or the procedures in Regulation (EU) 2017/2400 were:

1) Improvement of current or if necessary definition of new generic VECTO gear shift strategies (subtasks 1.1 and 1.2)
2) Elaboration of approaches to verify and if necessary adjust the generic VECTO gear shift strategies based on available test data (subtask 1.3)
3) Consideration of OEM specific gear shift strategies in VECTO (subtask 1.4)

2.1.1 WP 1.1: Review existing implementation of different transmission types in VECTO and collect feedback for their further update

2.1.1.1 Description of task

The existing implementation of gear shift models in VECTO had to be reviewed for any shortcomings and requirements for improvements had to be elaborated.

2.1.1.2 Work performed and findings

The sources of information used in the review were:

- Feedback from stakeholders collected from earlier projects (e.g. LOT4 SR7), dedicated meetings during the project (audio web and the VECTO board) and emails.

- Issues raised via the CITnet JIRA platform.
- Own analysis performed by the VECTO development team based on data provided by industry.
- Experience with the operation of VECTO in the context of the official certification as in place since 1st of January 2019 gained by the VECTO development team.

The result of the analysis is divided into two parts: a first list with general requirements for suitable generic gear shift algorithms in VECTO and a second list with specific shortcomings of the algorithms currently implemented into VECTO.

General requirements for suitable generic gear shift algorithms in VECTO:

1. Shall meet typical fuel efficiency of current systems
    a. To be able to provide representative average CO_2 levels for the European HDV fleet
    b. To enable any future and more complex approaches in Regulation (EU) 2017/2400 to consider OEM specific strategies to proof better performance than the generic strategy
2. Shall be able to provide correct rankings between different transmission technologies, i.e. between AT and AMT in some lorry and bus segments and between AT-P and AT-S for city buses
3. Shall be as complex as required to fulfil item 1. and 2. but as simple and robust as possible
    a. as the model needs to work for various kinds of vehicle configurations in a fully automatized way without any further possibility for "manual" adaptations
    b. to minimise notifications according to Article 10(2)[1] and related maintenance work on the software.

Specific shortcomings of the algorithms as currently implemented into VECTO:

1. The current definition of gearshift lines does not consider the specific shape of the engine fuel consumption map and the transmission efficiencies. As a consequence, in certain cases the engine map area with the highest fuel efficiency is outside of the VECTO shift lines. In the VECTO simulations the vehicle can not be operated in this area. An example is given in Figure 1. This shortcoming is valid for both for the current AMT and the current AT gear shift model.
2. The current definition of gearshift lines does not work properly for all combinations of drivetrain layouts and engine full-load curves. As a consequence, unrealistic operation patterns might occur in the simulations. An example is given in Figure 1. This shortcoming is valid for the current AMT gear shift model.

[1] A "notification according to Article 10(2)" of Regulation (EU) 2017/2400 is a dedicated process, where an OEM reports a malfunction of the simulation tool when calculating CO_2 emissions for a vehicle in the official application of the VECTO tool. Such a notification is logged in the CITnet JIRA system and triggers the maintenance of the tool related to bug fixes and related releases.

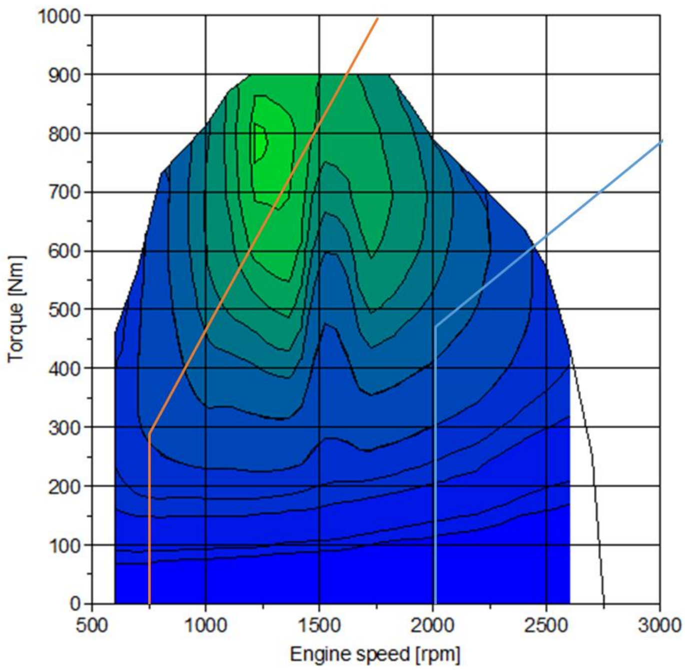

Figure 1: Example for gear shift lines for an 9 gear AMT vehicle with i_axle=4.3

3. The current definition of gear shift lines is based on engine speed at 85 km/h in the last gear. This definition does not work reasonably for vehicles with short axles (i.e. high axle ratios) and not for high floor buses (which are optimised for cruising speeds of 100 km/h). This shortcoming is valid for the current AMT gear shift model.
4. Based on the current VECTO gear shift models the gear selection in low speed cycles is less fuel efficient than gear selection in real vehicles. This issue was already discussed in the final report of the LOT4 / SR7 report [1]. This shortcoming is valid for the current AMT gear shift model.
5. Vehicles with overdrive transmissions are not covered reasonably as VECTO mostly uses the highest gear at cruising speeds 80 km/h and higher. Actual overdrive transmissions might use also a lower gear (generally with a direct gear) depending on the overall powertrain efficiency. This shortcoming is in general valid for both for the current AMT and the current AT gear shift model.
6. In the urban bus segment there is a competition between two different AT design types: AT-S (design type "serial", manufacturer ZF) and AT-P (design type "parallel", manufacturer "VOITH"). Feedback from ACEA and from VOITH received since the LOT3 and LO4 project indicated that VECTO gives a fuel penalty for AT-P transmissions to an amount which is not seen in real world data. This bias of the current VECTO models is estimated to be in the range of some 2% to 5% consumption.

2.1.1.3 **Status quo and further recommendations**

The findings on shortcoming of the current gearshift models have been the basis of the improvement of the gear shift algorithms as performed in WP1.2.

2.1.2 WP 1.2: Improvement of current or if necessary definition of new generic VECTO gear shift strategies

2.1.2.1 Description of task

Based on the findings from WP 1.1 the generic VECTO gear shift strategies were replaced by more suitable algorithms.

2.1.2.2 Work performed and findings

Gear shift model for AMTs:

For gearshifts of AMTs ACEA provided a proposal for an algorithm implemented in a MATLAB Simulink environment. The proposed algorithm, called "ACEA-TCU" (TCU … Transmission Control Unit), is based on the general principle to select a gear based on an optimisation of the combined efficiency of engine and gearbox in each particular time step in the simulation. This basic algorithm is superposed by several additional calculation and decision layers, which were introduced due to several reasons, e.g. to handle certain special cases of interaction of driver model and gear shift model, to mimic some "backward" calculation elements of VECTO in the SIMULINK environment and also caused by the background of origin algorithm, which was developed as an OEM in-house tool. The main principles of the ACEA-TCU were documented in the Interim report of the current project.[2]

The SIMULINK code was provided to TUG together with a documentation and a test data set. TUG analysed the code, converted the algorithms into a VECTO compatible structure and implemented the ACEA-TCU into the VECTO code. The resulting VECTO model behaviour was extensively tested by TUG and the results were discussed with stakeholders in several WebEx meetings and during the VECTO Board in January 2019. Main identified drawbacks for usage of the ACEA-TCU in the official application of VECTO were:

- The algorithm is very complex and "organic". Thus, the application to the variety of vehicles to be calculated by VECTO in the official CO_2 determination is expected to result in a much less stable VECTO operation and higher rates of VECTO aborts resulting in notifications according to Article 10(2) as currently the case.
- The demand on VECTO support is expected to increase significantly due to notifications according to Article 10(2) as mentioned above and expected support requests to explain certain gearshift behaviour.
- The ACEA-TCU approach results in a significantly increased VECTO simulation time. The original ACEA algorithm had a simulation time increase by a factor of 10 compared to the current VECTO gear shift model. The structure was optimised by the VECTO development team but due to the general principle the simulation time increase can not be reduced to a factor below a range of 2.5 to 3.

[2] As the ACEA-TCU algorithm was decided not to be used in the official application of VECTO, the documentation is not part of the final report. The documentation of the ACEA-TCU can also be found on the CITnet JIRA platform.

After the discussions held in the VECTO board and further coordinated feedback from all involved stakeholders (ACEA and gearbox OEMs) stated that they do not further recommend to directly use the ACEA-TCU algorithm in VECTO. Instead ACEA stated that they "want the principles of the proposed TCU included in VECTO, but encourage TUG to modify or rework the algorithm to achieve the main functionality without so large increase in simulation time. Gearbox OEMs (ZF, Allison and VOITH) agreed to support TUG in their further work.

From this starting point TUG developed a new gearshift algorithm, called "Efficiency shift" (EffShift). EffShift was designed to consider the main principle of the ACEA-TCU, fulfil all the requirements as stated in section 2.1.1.2 and to be as simple and robust as possible under the given boundary conditions. The ACEA-TCU algorithm was kept in the VECTO code to provide as a reference in further testing of the EffShift model or any other kind of gearshift approach.[3] The EffShift model was discussed extensively with industry and two feedback loops of testing, improving and bug fixing were performed.

The main principles of the EffShift model as implemented for AMTs are described below. A full description of the EffShift algorithm is given in section A.1.2 of this report and the VECTO User Manual.

The EffShift strategy is on a first level based on engine speed and engine torque dependent gearshift lines for upshift and downshift (similar to the classic VECTO gearshift strategy). The location of the shift lines was defined based on the following considerations:

- A **downshift** is triggered:
  - If the engine speed drops below 1.1 times engine idling speed
  - If the driver model request for more than 98% of maximum engine torque at engine speeds lower than the lowest engine speed where 99% of maximum torque is available
- The **upshift** line is defined as a vertical line at the highest engine speed where 98% of the maximum power is available. In the EffShift model the upshift line is not relevant for upshifts in most cases but just limits the engine map area where the "Efficiency shifts" can take place.

Such "Efficiency shifts" are triggered between the shift lines if the combined specific fuel consumption of engine and gearbox (g fuel per kWh work at the cardan shaft) in a candidate gear is lower than a certain threshold compared with the current gear. Additionally, for an "Efficiency shift" to take place certain boundary conditions regarding available engine power in a candidate gear have to be met. Figure 2 gives a schematic picture of the EffShift model.

[3] In the VECTO "Engineering Mode" the gearshift model can be selected by the user. In the VECTO Declaration Model, as to be used in the official determination of CO2 values, the selection of the gear shift model is fixed.

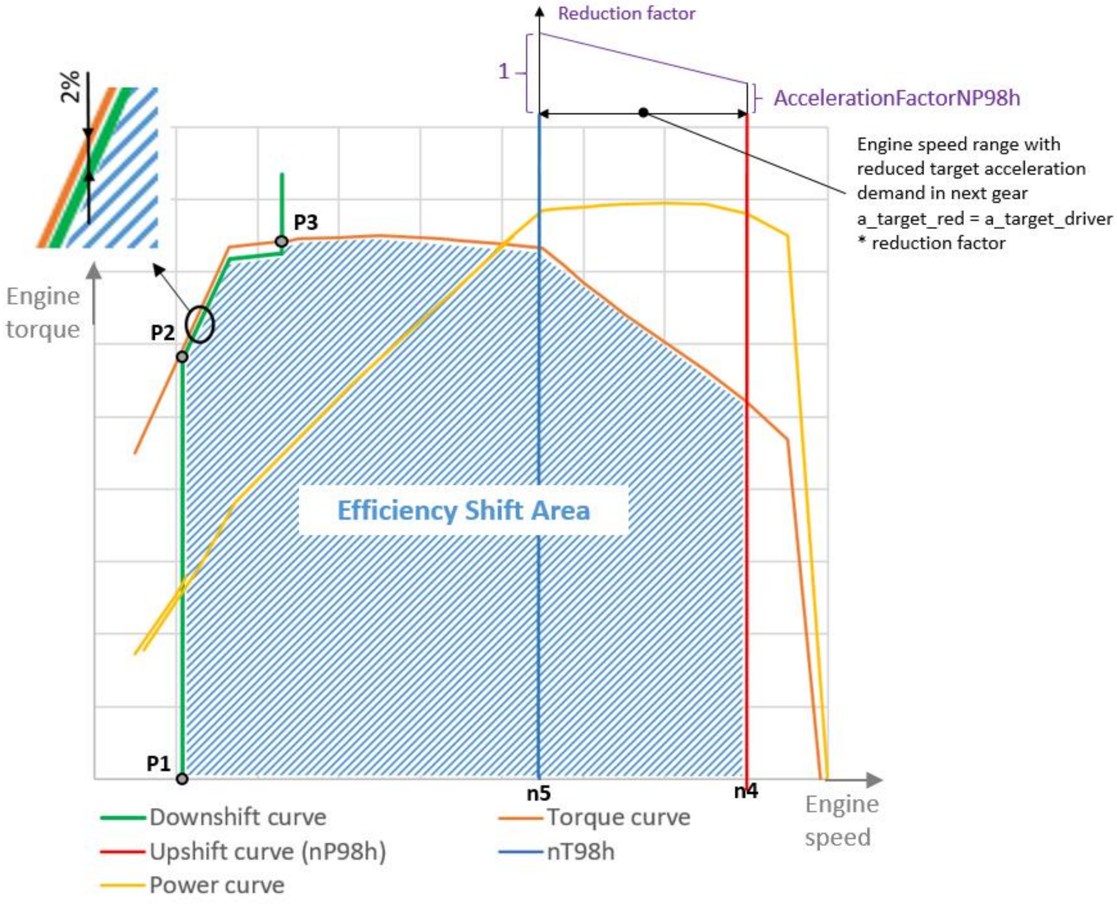

Figure 2: Schematic picture VECTO "EffShift" model

The shift lines are calculated according to Figure 2

Table 1: Definition of shift lines in EffShift AMT [4]

Point / curve	Engine speed (n)	Engine torque /T)
P1 (downshift line)	$n_1 = n_{idle} * 1.1$	T_1 =0
P2 (downshift line)	$n_2 = n_{idle} * 1.1$	$T_2 = T_{98\,@\,n2}$
P3 (downshift line)	$n_3 = n_{T99\,low}$	$T_3 = T_{99\,low}$
n4 (upshift line)	$n_4 = n_{P98\,high}$	(vertical)
n5 (left boundary for engine speed range with reduced target acceleration demand in next gear)	$n_5 = n_{T98\,high}$	(vertical)

[4] The nomenclature is explained in detail in the Annex A.1.1 on page 93.

Due to its very general approach the EffShift AMT model can be configured by only a small set of model parameters as show in Table 2.

Table 2: Model parameters used by EffShift model for AMT transmissions

Parameter name	Value	Explanations
Rating_current_gear	0.97	Defines the minimum fuel efficiency advantage in a candidate gear to trigger a gear shift (i.e. 3% for a value of 0.97)
RatioEarlyUpshiftFC	24	In gears with a higher total drivetrain ratio (axle plus gearbox) than this parameter, "Efficiency shifts" are disabled, i.e. the shifts are only triggered by the shift lines. Rationale: Gear shift in this gears are primarily triggered by power demand.
RatioEarlyDownshiftFC	24	
AllowedGearRangeFC	2	Defines the gear range for candidate gears for "Efficiency Shifts"(+/-)
AccelerationFactorNP98h	0.5	Defines the reduction of driver target acceleration in the engine speed range between nT98h and nP98h (see Figure 2)

Below simulation results based on the three shift models

- Classic", the shift-line based algorithm as currently implemented in the official VECTO version
- "TCU", the algorithm as elaborated by ACEA and transferred into the VECTO code
- "EffShift", the model elaborated in this contract and as described above.

are analysed. The comparison covers average speed, number of gearshifts, fuel consumption in g/km and combined fuel efficiency of the total powertrain (g fuel per kWh work at wheels). The latter figure allows for a straight forward comparison of fuel efficiency of different gear shift algorithms as differences in driving behaviour are normalised.

Table 3 shows the analysis for a typical group 5 long haul vehicle with a direct gear AMT 12 transmission. The VECTO Classic model was optimised for such vehicle configurations in long haul (LH) and regional delivery (RD) operation. As to be expected for those cycles the results do not differ significantly between the three gear shift models. For the urban delivery cycle (UD) the EffShift model results in some 2% lower fuel consumption at 2% higher average speeds than the Classic model. This is achieved in connection with about 20% less gear shifts compared to Classic. The TCU algorithm also slightly shifts more fuel efficient than Classic in connection with a slightly lower dynamic driving.

Table 3: Comparison VECTO results for a typical group 5 long haul vehicle ("Classic" = current VECTO, TCU = model as proposed by ACEA, EffShift = model as elaborated in this contract)

Cycle / payload	Gear shift model	average speed [km/h]	# gearshifts	FC abs [l/100km]	FC [g/kWh] wheel
LH / low	AMT-Classic	79.6	47	26.4	235.4
LH / rep	AMT-Classic	78.6	55	34.7	223.2
RD / low	AMT-Classic	60.6	207	28.0	240.1
RD / rep	AMT-Classic	60.2	214	34.8	229.7
UD / low	AMT-Classic	25.7	2047	45.1	270.1
UD / rep	AMT-Classic	25.5	2014	60.8	251.4
	values = changes compared to AMT-Classic				
LH / low	AMT-TCU	0.0%	-4.3%	0.0%	0.1%
LH / rep	AMT-TCU	-0.6%	36.4%	0.0%	0.3%
RD / low	AMT-TCU	-0.3%	-9.2%	-0.3%	0.1%
RD / rep	AMT-TCU	-0.9%	1.4%	-0.4%	0.2%
UD / low	AMT-TCU	0.5%	-19.0%	-1.9%	-0.6%
UD / rep	AMT-TCU	-1.2%	-16.6%	-4.6%	-0.4%
LH / low	AMT-EffShift	0.2%	-12.8%	-0.1%	-0.1%
LH / rep	AMT-EffShift	-0.1%	-12.7%	0.0%	0.0%
RD / low	AMT-EffShift	0.3%	-25.6%	-0.5%	-0.2%
RD / rep	AMT-EffShift	0.3%	-23.4%	-0.1%	-0.2%
UD / low	AMT-EffShift	1.9%	-22.3%	-2.1%	-2.4%
UD / rep	AMT-EffShift	1.4%	-23.9%	-1.7%	-1.5%

Table 4 shows the comparison for a group 2 delivery truck with a 6 gear overdrive AMT transmission. Again for the cycles LH and RD all three gear shift models give nearly similar results both for fuel consumption and average speed. In the UD cycle both the EffShift model and the TCU results in some 3% less fuel consumption compared to Classic. Again the EffShift model results in a slightly higher average speed in the UD cycle.

Table 4: Comparison VECTO results for •a group 2 delivery truck with a 6 gear overdrive AMT transmission (“Classic”= current VECTO, TCU = model as proposed by ACEA, EffShift = model as elaborated in this contract)

Cycle / payload	Gear shift model	average speed [km/h]	# gearshifts	FC abs [l/100km]	FC [g/kWh] wheel
LH / low	AMT-Classic	79.6	33	26.4	248.8
LH / rep	AMT-Classic	78.1	37	30.6	240.3
RD / low	AMT-Classic	60.7	163	20.0	279.4
RD / rep	AMT-Classic	60.7	157	21.6	269.2
UD / low	AMT-Classic	25.9	1513	25.1	325.9
UD / rep	AMT-Classic	26.0	1509	29.0	301.8
	values = changes compared to AMT-Classic				
LH / low	AMT-TCU	-0.2%	15.2%	-0.2%	0.0%
LH / rep	AMT-TCU	-0.9%	89.2%	0.0%	0.1%
RD / low	AMT-TCU	0.1%	-17.8%	-0.4%	-0.3%
RD / rep	AMT-TCU	-0.1%	-13.4%	-0.5%	-0.2%
UD / low	AMT-TCU	0.7%	-13.7%	-2.9%	-2.2%
UD / rep	AMT-TCU	-0.1%	-15.0%	-2.9%	-2.0%
LH / low	AMT-EffShift	0.0%	-18.2%	-0.2%	-0.1%
LH / rep	AMT-EffShift	-0.3%	-2.7%	-0.3%	-0.2%
RD / low	AMT-EffShift	0.3%	-9.2%	-0.4%	-0.4%
RD / rep	AMT-EffShift	0.2%	-9.6%	-0.4%	-0.4%
UD / low	AMT-EffShift	1.5%	-13.4%	-2.8%	-2.6%
UD / rep	AMT-EffShift	0.9%	-12.7%	-2.4%	-2.1%

Table 5 compares the simulation results for a group 2 delivery truck with a 9 gear AMT transmission and a high axle ratio (i_{axle} = 4.3). For this vehicle configuration the Classic model was identified to have obvious shortcomings, see Figure 1 on page 14). For the UD cycle both the EffShift and the TCU model predict a 6% lower fuel consumption by requiring some 20% less gear shifts. For the LH and RD cycles the fuel consumption is only slightly lower than with Classic.

Table 5: Comparison VECTO results for a group 2 delivery truck with a 9 gear AMT transmission and a high axle ratio ("Classic" = current VECTO, TCU = model as proposed by ACEA, EffShift = model as elaborated in this contract)

Cycle / payload	Gear shift model	average speed [km/h]	# gearshifts	FC abs [l/100km]	FC [g/kWh] wheel
LH / low	AMT-Classic	79.5	28	30.7	236.0
LH / rep	AMT-Classic	78.2	32	34.5	230.5
RD / low	AMT-Classic	60.7	121	23.6	257.8
RD / rep	AMT-Classic	60.7	123	24.9	252.8
UD / low	AMT-Classic	25.8	1466	23.8	301.0
UD / rep	AMT-Classic	25.8	1536	26.8	283.3
		values = changes compared to AMT-Classic			
LH / low	AMT-TCU	0.0%	-14.3%	-0.2%	-0.1%
LH / rep	AMT-TCU	-0.8%	-3.1%	-0.5%	-0.3%
RD / low	AMT-TCU	0.2%	-14.0%	-0.4%	-0.4%
RD / rep	AMT-TCU	0.0%	-16.3%	-0.6%	-0.5%
UD / low	AMT-TCU	0.8%	-11.6%	-5.2%	-5.1%
UD / rep	AMT-TCU	0.4%	-15.1%	-5.9%	-5.1%
LH / low	AMT-EffShift	0.1%	-14.3%	-0.1%	-0.1%
LH / rep	AMT-EffShift	-0.3%	0.0%	-0.3%	-0.2%
RD / low	AMT-EffShift	0.4%	-26.4%	-0.6%	-0.6%
RD / rep	AMT-EffShift	0.3%	-26.8%	-0.7%	-0.7%
UD / low	AMT-EffShift	1.7%	-23.0%	-6.2%	-6.4%
UD / rep	AMT-EffShift	1.7%	-27.1%	-6.2%	-6.1%

Gear shift model for ATs:

The main objective in revising the VECTO gear shift model for AT transmissions was to apply the general principle as for AMT gear shifts but take into account the relevant differences between AT and AMT technology. This should be the best basis to provide fair rankings between the two transmission concepts. Market segments, where AMT and AT transmissions compete are for example refuse lorries or interurban buses. A further special demand on the VECTO gearshift model for ATs is to provide a reasonable ranking in the urban bus segment between the AT technologies AT-S (design type "serial", manufacturer ZF) and AT-P (design type "parallel", manufacturer "VOITH").

The development of the new proposed approach to model AT gear shifts in VECTO was as follows:

- The EffShift model as developed for AMT transmissions was taken over in its main principles into the VECTO AT model.
- In parallel a gear shift model for AT transmissions was proposed by VOITH. In this algorithm gear shifts are triggered by target post-shift engine speeds defined as a function of engine load stage (ratio of actual engine torque and maximum engine torque at actual engine speed, correlating with acceleration pedal position in real vehicles) and currently available acceleration. This algorithm was reported as a simplified derivate of real gear shift

strategies as implemented in urban bus transmissions. The algorithm is further described below. The original material on the approach as provided by VOITH can be found in Annex A.1.3. This approach was implemented by TUG into VECTO as a separate option for AT gear selection.

- A prototype version of VECTO with both new options was distributed to industry (ACEA plus AT OEMs) and two feedback loops have been performed.
- The main drawbacks identified for the original VOITH model as implemented in VECTO are
  - the approach is much less general (i.e. gear shift rpms have to be parametrised as absolute values, sets like shown in Table 9 to be elaborated for all possible gear shift sequences in a transmission) and would also need to be parameterised separately for different vehicle types (lorries, urban buses, coaches). This is judged to be not practicable.
  - The ranking between AMT and AT vehicles in competing market segments might be biased due to the application of completely different generic approaches for gear selection in VECTO.
- Based on the received comments and test cases an improved version of the "EffShift AT" model considering parts of the VOITH model has been elaborated.

The elements where the final "EffShift AT" differs from "EffShift AMT" are described below:

- For ATs the upshift line is parameterised via the post-shift engine speed (for AMTs it's the pre-shift engine speed). In the model parameterisation this engine speed is calculated for each gear by multiplication of the engine speed "nP98h" by the ratio of $i_{nextgear}/i_{current\ gear}$.
- In order to depict differences in gear selection which result from the different shifting sequences (AT: powershift, AMT: traction interruption) the operation points used for rating of fuel efficiency and for checking the power requirements in a candidate gear are calculated differently.
- For up-shifts from a torque converter gear ("C") to a locked gear ("L") the relevant part of the VOITH gearshift model was taken over into the VECTO EffShift AT model. The used algorithm can be summarised as follows:
  1) Definitions:

Table 6: Definitions for C→L shifts

Parameter	Unit	Description
torque ratio	[%]	current engine torque / maximum engine torque at actual engine speed
a_min	[m/s²]	available acceleration at actual engine torque for maximum loaded vehicle
a_max	[m/s²]	available acceleration at actual engine torque for empty vehicle
a_curr	[m/s²]	available acceleration at actual engine torque for current vehicle mass

2) In each time-step a target post-shift engine speed from the shift strategy is calculated in a three step approach a. to c.:
   a. The current engine load stage is determined based on current torque ratio and a set of hysteresis thresholds (example see Table 8)
   b. For the current engine load stage and the current slope each a rpm value is interpolated from a parameter table (example see Table 9 for a_min and for a_max)
   c. The final value for target post-shift engine speed is interpolated for the current value of a_curr from the results of step b.
3) If the estimated engine speed after a C→L shift is calculated to be equal or higher than the target engine speed as calculated above, the gear shift is initiated. This approach in combination with the proposed parameters as shown in Table 9 reflects that the shifts from C→L are performed with absolute priority in order to minimise driveline losses from torque converter operation.

- For triggering gear shifts between gears “1C” and “2C” (if applicable for a certain transmission) the same function as in the VECTO Classic model is applied.

Table 7 to Table 9 summarise the set of generic parameters as used by the EffShift AT model. General model parameters as listed in Table 7 cover the same functionality than in the EffShift AMT model, except for the parameter “ATLookAheadTime” which is only relevant for ATs. Values could in principle be set differently for AMTs and AT and also differently for lorries and buses if there is technical or empirical evidence. All shown parameters are recommended to undergo a further feedback loop at industry to come to a final decision in the VECTO board which values should be used in a later official CO_2 determination. This recommendation applies also to the model parameters as shown in Table 8 and Table 9 relevant for C→L shifts.

Table 7: General model parameters used by EffShift model for AT transmissions

Parameter name	Value	Explanations
Rating_current_gear	0.97	Defines the minimum fuel efficiency advantage in a candidate gear to trigger a gear shift (i.e. 3% of a value of 0.97)
RatioEarlyUpshiftFC	24	In gears with a higher total drivetrain ratio (axle plus gearbox) than this parameter, “Efficiency shifts” are disabled, i.e. the shifts are only triggered by the shift lines. Rationale: Gear shift in this gears are primarily triggered by power demand.
RatioEarlyDownshiftFC	24	

Parameter name	Value	Explanations
AllowedGearRangeFC	1 for ATs with ≤ 6 gears 2 for ATs with more than 6 gears	Defines the gear range for candidate gears for “Efficiency Shifts”(+/-)
AccelerationFactorNP98h	0.5	Defines the reduction of driver target acceleration in the engine speed range between nT98h and nP98h (see Figure 2)
ATLookAheadTime	0.8	Defines look ahead time for rating of fuel consumption for AT transmissions.

Table 8: Boundary values between engine load stages (values for torque ratio in [%]) (relevant for C→L shifts)

	1<->2	2<->3	3<->4	4<->5	5<->6
Hysteresis upper	19.70	36.34	53.01	69.68	86.35
Hysteresis lower	13.70	30.34	47.01	63.68	80.35

Table 9: Matrix with target post-shift engine speed defined as delta to engine idling speed (values in rpm, relevant for C→L shifts)

engine load stage	a_max			a_min		
	slope ≤ -5%	slope 0%	slope ≥ 5%	slope ≤ -5%	slope 0%	slope ≥ 5%
1	90	120	165	90	120	165
2	90	120	165	90	120	165
3	90	120	165	90	120	165
4	90	120	165	110	140	185
5	100	130	175	120	150	195
6	110	140	185	130	160	205

Table 10 gives a comparison of simulation results for a group 9 refuse truck with a 6 gear AT transmission based on the VECTO Classic AT shift model and the EffShift AT model.[5] As seen for EffShift AMT calculation results for the LH and RD cycle do not change significantly between Classic and EffShift. For the municipal cycle Effshift reduces fuel consumption by some 2%.

Table 10: Comparison VECTO results for a group 9 refuse truck with a 6 gear AT transmission ("Classic" = current VECTO, EffShift = model as elaborated in this contract)

Cycle / payload	Gear shift model	average speed [km/h]	# gearshifts	FC abs [l/100km]	FC [g/kWh] wheel
LH / low	AT-Classic	79.7	32	Confidential	
LH / rep	AT-Classic	77.4	40		
RD / low	AT-Classic	61.1	124		
RD / rep	AT-Classic	60.8	126		
MU / low	AT-Classic	9.3	260		
MU / rep	AT-Classic	9.3	262		
		values = changes compared to AMT-Classic			
LH / low	AT-EffShift	0.0%	6.3%	0.0%	0.0%
LH / rep	AT-EffShift	0.7%	0.0%	0.4%	0.3%
RD / low	AT-EffShift	0.0%	0.0%	0.1%	0.0%
RD / rep	AT-EffShift	-0.1%	3.2%	0.1%	0.1%
MU / low	AT-EffShift	0.1%	28.5%	-1.9%	-2.1%
MU / rep	AT-EffShift	0.1%	26.0%	-1.7%	-2.8%

Table 11 and Table 12 give a comparison of results based on different gear shift models for each an urban bus with a 6 gear AT-S transmission and a bus with a 4 gear AT-P transmission. For the AT-S bus the VOITH model predicts higher fuel consumption than Classic, whereas gear shifting by EffShift model results in approximately similar fuel consumption in l/100 km. For the AT-P vehicle both the VOITH model and the EffShift models predict slightly lower fuel consumption (0 to -2%).

Due to confidentiality reasons the ranking between AT-P and AT-S cannot be shown for this vehicle in detail. Both the Classic and the EffShift model predict a higher fuel consumption for the AT-P vehicle with a smaller disadvantage for the AT-P based on EffShift. The results from the VOITH model inverts the ranking, i.e. a slightly lower fuel consumption for the AT-P is predicted. For this dataset no reference data from measurements is available. The issue on ranking between AT-P and AT-S is further discussed in the validation section.

[5] The VOITH model is not able to simulate this vehicle as it applies the torque converter in the first two gears (VOITH covers only torque converter in the first gear). ACEA did not provide a proposal for AT gearshifts, so no figures for "TCU" can be shown.

Table 11: Comparison VECTO results for an urban bus with a 6 gear AT-S transmission ("Classic"= current VECTO, Voith = model as provided by VOITH , "EffShift" = model as elaborated in this contract)

Cycle / payload	Gear shift model	average speed [km/h]	# gearshifts	FC abs [l/100km]	FC [g/kWh] wheel
UrbanDelivery	AT-Classic	30.2	201.0	confidential	
HeavyUrban	AT-Classic	11.7	1017.0		
Suburban	AT-Classic	25.7	435.0		
Urban	AT-Classic	16.7	963.0		
Interurban	AT-Classic	33.2	979.0		
	values = changes compared to AMT-Classic				
UrbanDelivery	Voith	0.8%	-5.0%	4.0%	2.9%
HeavyUrban	Voith	-0.1%	-24.6%	2.9%	2.3%
Suburban	Voith	0.7%	-19.8%	6.8%	4.8%
Urban	Voith	0.0%	-26.4%	5.5%	4.8%
Interurban	Voith	1.5%	-13.1%	3.1%	1.6%
UrbanDelivery	AT-Effshift	0.0%	4.0%	-0.7%	-1.0%
HeavyUrban	AT-Effshift	-0.2%	16.9%	-1.3%	-1.7%
Suburban	AT-Effshift	0.3%	3.7%	1.1%	-0.2%
Urban	AT-Effshift	0.0%	22.4%	-0.4%	-0.9%
Interurban	AT-Effshift	0.9%	-0.6%	0.1%	-0.9%

Table 12: Comparison VECTO results for an urban bus with a 4 gear AT-P transmission ("Classic"= current VECTO, Voith = model as provided by VOITH , "EffShift" = model as elaborated in this contract)

Cycle / payload	Gear shift model	average speed [km/h]	# gearshifts	FC abs [l/100km]	FC [g/kWh] wheel
UrbanDelivery	AT-Classic	30.2	77.0	confidential	
HeavyUrban	AT-Classic	11.7	373.0		
Suburban	AT-Classic	25.6	181.0		
Urban	AT-Classic	16.6	387.0		
Interurban	AT-Classic	33.1	415.0		
	values = changes compared to AMT-Classic				
UrbanDelivery	Voith	0.0%	15.6%	-0.4%	-0.6%
HeavyUrban	Voith	-0.3%	18.2%	-2.1%	-2.0%
Suburban	Voith	-0.2%	25.4%	-0.7%	-1.2%
Urban	Voith	-0.3%	19.6%	-1.7%	-1.7%
Interurban	Voith	-1.0%	25.5%	-0.8%	-0.8%
UrbanDelivery	AT-Effshift	0.0%	7.8%	-0.5%	-0.7%
HeavyUrban	AT-Effshift	-0.1%	37.5%	-1.8%	-2.4%
Suburban	AT-Effshift	0.4%	7.7%	0.1%	-0.6%
Urban	AT-Effshift	0.0%	33.6%	-1.4%	-1.8%
Interurban	AT-Effshift	0.5%	7.7%	-0.5%	-1.2%

2.1.2.3 **Status quo and further recommendations**

Based on the requirements as identified in WP1.1 the new gear shift models "EffShift AMT" and "Eff Shift AT" have been elaborated, implemented into the software and discussed with industry.

The features of the EffShift gear shift algorithm are assessed to be:

- Simple and robust approach to model gear shifts for all configurations of conventional powertrains (direct drive and overdrive transmissions, long and shorts axles) and all HD vehicle configurations (long haul, delivery, buses).
- The algorithm reflects a straight forward gear selection strategy of an aligned engine and transmission control system. From common sense it can be concluded that the EffShift approach reflects real world operation of the variety of vehicles in the fleet much better than the VECTO "Classic" model based on fixed gear shift lines defined by rules derived from long haul lorries.
- Sophisticated gear shift features as stated by industry for recent vehicle generations (i.e. predictive shifting in combination with ADAS functions) are not reflected in EffShift. For vehicles where engine and transmission controls are not aligned, EffShift might overestimate overall fuel efficiency.
- The algorithm is future-proof to be extended to model also gear shifts for Hybrid electric vehicles (HEV). In this case the EffShift rating algorithm needs to evaluate the combined energy/fuel consumption of internal combustion engine and electric machines (electric energy converted to fuel consumption by a cost factor). Merging of hybrid controller and EffShift is currently performed as part of the on-going "VECTO – Extensions to hybrids" contract.
- Compared to the current "Classic" VECTO approach the EffShift algorithm:
  - results in a slightly more dynamic driving behaviour
  - results in a small increase of simulation time (some 10 to 20%)
- The model parameters of EffShift AMT and EffShift AT as provided with the final software release from this contract are recommended to undergo a further review loop at industry to come to a final decision in the VECTO board which values should be used in a later official CO_2 determination. This especially applies to the sensitive areas: competition of AT-P and AT-S transmissions in urban buses and the comparison of AMT and ATs. This issue is further elaborated in the recommendation paragraph of the section (2.1.3.3 on page 34).
- Once in the official VECTO version EffShift algorithm replaces the "Classic" model, this has implications on the calculated CO_2 emissions on a fleet level. Thus it is assumed that an adjustment procedure for the 2019 baseline might need to be performed. In the related analysis it needs to be taken care of the fact, that the changes in CO_2 compared to current Classic are significantly influenced by the drivetrain configuration. It is recommended to analyse the implications of the change of gear shifts models by a set of vehicles representing the real distribution of transmission and axle ratios. This is of special importance for the vehicle sub-group 4-UD, as for this cycle significant changes in fuel consumption when switching from Classic to EffShift mode can be expected.

- Further recommendations related to gear shift models for SMT[6] transmissions: In the current VECTO version for gearshifts of SMT transmissions a simplified version of the AMT "Classic" algorithm is applied. Thus, the gearshifts might be affected by several of the issues as listed for AMTs. Gear shifts of SMTs have not been analysed so far as the market penetration in the heavy lorry groups as currently covered by Regulation (EU) 2017/2400 is very low (below 2%, data for 2013 from [4]). Thus, in the entire development of VECTO so far no measurement data has been available. With the foreseen extension of VECTO to the medium segment (vehicles in the range from 5 to 7.5 tons TPMLM) the share of SMT vehicles is assumed to increase significantly. It is hence recommended to verify and if necessary modify the current VECTO gear shift model for SMTs based on data to be collected from industry (e.g. from the pilot phases). Work on SMTs and medium vehicles was not part of the current contract.

2.1.3 WP 1.3: Elaboration of approaches to verify and if necessary adjust the generic VECTO gear shift strategies based on available test data

2.1.3.1 Description of task

Test data, recorded either in real world or under specific test conditions, can in principle be used either to validate or even to calibrate simulation algorithms for gear selection. In WP 1.3 available measurement data has been analysed in these regards. Options for a potential use in VECTO are:

i. Verification and further calibration of generic VECTO strategies.
ii. Calibration of VECTO strategies to be used in the simulation of specific vehicles.

2.1.3.2 Work performed and findings

Ad i. Verification and further calibration of generic VECTO strategies

In a first step, the basic requirements on suitable datasets (i.e. reference data for gear selection) to verify and/or further calibrate any gearshift algorithm in VECTO have been analysed. In order to be able to compare test data and model results in direct manner (i.e. analysis of gear shifts or engines speeds on a second by second basis or via statistics), several boundary conditions have to be met. The available data needs to cover the full set of VECTO input data including measured engine fuel map and transmission loss maps, as those data are also explicitly considered in the EffShift strategy. For the trip precise gradient data needs to be available and other ambient influences need to be low (e.g. ambient wind) as any source of drag potentially also influences gear shift behaviour.

[6] Synchronised manual transmissions

Furthermore the trips need to be driven in a manner that the generic driver model in VECTO is able to reproduce the actual vehicle speed pattern in its "target speed mode"[7]. Those high demands on any reference data set results from the finding, that driver/driving behaviour and gear selection deeply interact: e.g. gear selection is triggered by driver behaviour (throttle pedal actuation incl. kick-down behaviour), acceleration capability of the vehicle is determined by selected gear.[8]

Based on those findings the validation of the VECTO gear shift models was done in a two step approach:

1) Validation of the VECTO driver model regarding typical acceleration and deceleration behaviour
2) Validation of the gear shift algorithms by comparison with operation data with similar driving behaviour as the VECTO driver

For part 1) ISC trips available in the TU Graz database from national projects on pollutant emissions have been analysed. Only trips which were driven by professional drivers have been analysed. The tests have been performed according to the ISC provisions of Regulation (EU) 582/2011 consisting of parts with urban, rural and motorway driving and with representative payloads.

Figure 3 gives a comparison of the acceleration and deceleration behaviour from the ISC trips and VECTO as function of vehicle speed. For the data shown for VECTO, results for a group 5 vehicle simulated in the mission profiles long haul, regional delivery and urban delivery with reference payload have been used. This vehicle configuration approximately corresponds to the average specifications of vehicles measured in the ISC tests. In the analysis all data with accelerations between -0.3 m/s² and +0.3 m/s² have been removed as these vehicle operation states are part of the cruising and coasting behaviour which are not subject of analysis in this context.

For the comparison of the acceleration behaviour the 95% and the 90% percentiles of data with accelerations above 0.3 m/s² are analysed. This upper range of acceleration events refers to the VECTO model element "driver target acceleration". A very good agreement of ISC data and VECTO driver model behaviour can be observed for those percentiles. Lower percentiles for accelerations can not be reasonably compared here as those vehicle operation states predominately are determined by the full-load acceleration capabilities. As the ISC trips were not available as VECTO input data, the specific conditions for road slope and specific motorisation of the vehicle (kW rated power per ton vehicle mass) do not match between the analysed ISC and VECTO data.

For deceleration events Figure 3 compares the 5% to 50% percentile curves for events below -0.3 m/s². As expected real world data show a much wider spread of deceleration rates which is not reflected by the driver model. On average the VECTO model decelerates slightly more aggressive than observed in the ISC. This issue is not seen critical for simulation of conventional vehicles but will be subject of further validation in the ongoing project on extension of VECTO to hybrids. Due

[7] The VECTO "target speed mode" is the simulation mode as to be used in the official CO_2 determination. Aside this official use VECTO can also be operated in the "measured speed mode" which allows in principle for reproduction of any measured real world driving cycle. However, any gear shift algorithm will perform differently in "target speed mode" and "measured speed mode" due to the fact that accelerations and decelerations are triggered differently with the VECTO driver model is used in the "measured speed mode". Hence for a validation of the VECTO gear shift models applied in the official CO_2 determination, reference data which can be reproduced in the VECTO "target speed mode" are required.

[8] This finding refers to any kind of "automatized" transmission technologies, i.e. AMT and AT transmissions. For manual transmissions the driver determines gear selection in a direct manner.

to the capability to regenerate kinetic energy for those vehicles the deceleration behaviour is of much higher importance than for conventional HDVs.

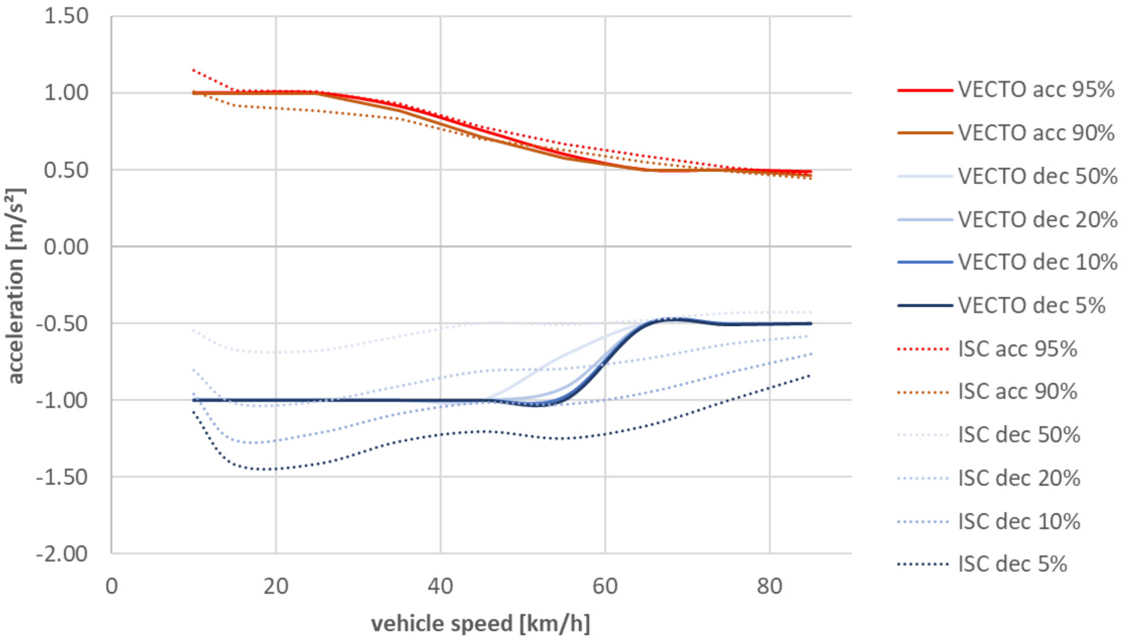

Figure 3: Comparison acceleration and deceleration behaviour from VECTO and ISC measurements (group 5 vehicle, mix of urban, rural and motorway)

This analysis is a good indication that the current VECTO driver model does reflect typical real world driving behaviour. Regarding future activities it is recommended that upcoming provisions on real-world monitoring of vehicles shall also cover collection of vehicle speed and acceleration data. Together with data on the power-to-mass ratio, this data could be used to check the representativeness of VECTO (mission profiles, driver model) on a much broader basis.

For the actual validation of the gear shift models industry was asked for suitable data. The performance of measurements was not part of the current contract. The requirements on the data to be able to perform a direct comparison between reference data and model predictions have been communicated and several OEMs provided data. Table 13 gives an overview of the provided datasets for lorries and AMT transmissions. All data sets have at least one peculiarity that prevents suitability for direct comparison. In principle reference data generated by SIL - with the real OEM controller "in-the-loop" of a vehicle simulation tool - would provide the highest potential for comparison. In the provided SIL datasets however either the driver model was not compatible with VECTO (#1, #5) or additional vehicle control functions (Eco-roll and special PCC functions for #2) did prevent that similar vehicle speed traces could be simulated by VECTO in the target speed mode. As a more general approach to compare the most promising datasets (#2 and #5) with VECTO, the cycle averaged result for overall specific powertrain efficiency (g fuel /kWh wheel work) and fuel consumption (l/100 km) have been analysed. The specific powertrain efficiency, which is significantly determined by gear selection, was predicted by EffShift very well (maximum deviation 2.5%). Deviations for simulated fuel consumption were found to be somewhat higher (maximum deviation 4%) which can be attributed to the fact that the total cycle work between VECTO and SIL does not match completely. The value for fuel consumption is much more sensitive to differences in vehicle speed than the specific powertrain efficiency.[9]

Table 13: Overview validation datasets provided to TUG for lorries and AMT

OEM	Vehicle group	Complete VECTO input data available	Source of gear shift data	Cycles	VECTO compatible target speed available	Other issues
#1	5	yes	SIL	Custom	no	
#2	5	yes	SIL	VECTO (LH, UD, RD)	yes	Due to other controls applied in SIL environment (e.g. specific ADAS functions) vehicle speed could not be reproduced in VECTO.
#3	5	no	road test	Custom	no	
#4	10	yes	chassis dyno	Custom	no	
#5	4, 5	only for group 5	SIL	Custom cycles, VECTO (LH, RD)	yes	Driver model applied in SIL drives much more aggressive than VECTO driver

Further data measured in on-road test with the purpose to validate the VECTO gear shift models was available from the LOT 4 project (2015 – 2017). For the purpose to compare the performance of AMT and AT transmission a group 9 refuse truck (MB Econic) was measured on a test track in both transmission configurations. As test cycle an earlier version of the VECTO Municipal cycle was used.

Table 14 shows the deviation of simulated fuel consumption (l/100km)[10] based on three options for gear selections in VECTO with the measured value. In the “measured speed mode”, where also the gears as recorded during the measurement have been provided as input to VECTO, the measurement with the AMT vehicle is underestimated by 4% whereas the measurement with the AT vehicle was met very well. The reasons of this deviations are not exactly known, but are judged to be in the typical range of combined uncertainties from on-road measurement and simulation. For

[9] The results of the comparison between EffShift and SIL are:

- Dataset OEM #2 (Cycle LH): -1.4% g/kWh wheel work, +3.9% fuel consumption
- Dataset OEM #5 (Cycle RD): +2.4% g/kWh wheel work, -1.0% fuel consumption

[10] An analysis for specific powertrain efficiency, which would be more significant than the analysis for fuel consumption, can not be provided for the MB Econic data as no torque measurement rims were installed during the measurement.

simulations using the VECTO gear shift models the test data was then converted into a target speed cycle. As the case for the above mentioned datasets also in this case the simulated cycle does not fully match with the measured speed profiles. When compared to the measured fuel consumption the VECTO Classic model overestimates the measured value for the AMT by 2.6% and underestimates the AT by 3.3%. The VECTO Effshift selects gears for the AMT much more fuel efficient (-5.5% compared to measurement) and comes close to the simulation with the gears as input from the measurement. The AT vehicle is simulated by the Effshift algorithm with approximately the same deviation than using the Classic model (-3.9%).

Table 14: Deviation fuel consumption (l/100) from simulation with measurement (municipal cycle)

	VECTO measured speed + gears	VECTO Classic	VECTO EffShift
MB Econic AMT	-4.3%	2.6%	-5.3%
MB Econic AT	0.9%	-3.3%	-3.9%

Of special interest for this dataset is the ranking of transmission technologies. In the measurement the AT transmission was found to have 6% higher fuel consumption than the AMT. The VECTO Classic model predicts similar fuel consumption for AT and AMT whereas the latest EffShift model meets the ranking figure from the measurement quite well.

Table 15: Deviation of fuel consumption (AT/AMT-1) in the municipal cycle

	Measure-ment	VECTO measured speed + gears	VECTO Classic	VECTO EffShift
AT vs. AMT	6.0%	11.8%	-0.1%	7.6%

ZF announced to analyse data recorded at a delivery truck in both transmission configurations on a chassis dyno and compare with VECTO simulation results for a further validation of the ranking predicted by VECTO between AMT and AT. TUG will assist in this exercise. Results shall be discussed in a VECTO board to discuss the final parameterisation of the EffShift model.

Of special importance is the ranking predicted by VECTO for the two different AT design type AT-S (design type “serial”, manufacturer ZF) and AT-P (design type “parallel”, manufacturer “VOITH”) as in the urban bus segment there is a competition between the two technologies. Feedback from ACEA and from VOITH received since the LOT3 and LOT4 project indicated that VECTO Classic indicates a fuel penalty for AT-P transmissions to an amount which is not seen in real world data. This bias of the VECTO Classic was estimated to be in the range of some 2% to 6% fuel consumption.

To investigate the behaviour of the new available AT gear shift models measurement data for an 18 m articulated bus from the LOT4 project has been reanalysed. As suitable reference data only tests in SORT cycles were available. Table 16 gives the results for fuel consumption AT-P vs. AT-S from measurement and simulation. Results from measurement indicate the vehicle with the AT-P transmission to have 1.3% to 4.4% higher fuel consumption than the AT-S. The EffShift model in its current parameterisation predicts a 2% higher gap between AT-P and AT-S than seen in the measurement and thus reduces the bias from the Classic model by some 2%. The VOITH model with the parameterisation as proposed in October would invert the ranking of transmission technologies compared to the measured values. Regarding the measurement data it needs to be mentioned, that those were not executed in a fully comparable manner. Influences of systematic differences (e.g. different idling times for AT-P and AT-S) on fuel consumption were corrected in a post-post processing as far as possible, but a certain range of uncertainty regarding the significance of the data remains.

Table 16: Comparison ranking AT-P to AT-S from measurement and simulation in SORT cycles

Cycle	Fuel consumption (AT-P/AT-S - 1) Measure-ment	Gearshift model	VECTO	delta VECTO compared to measurement
Sort 1	3.8%	Classic	8.8%	5.0%
		Effshift	6.3%	2.5%
		VOITH	1.5%	-2.3%
Sort 2	4.4%	Classic	6.9%	2.6%
		Effshift	5.0%	0.7%
		VOITH	2.3%	-2.1%
Sort 3	1.3%	Classic	5.1%	3.8%
		Effshift	4.8%	3.5%
		VOITH	-4.6%	-5.9%

In parallel to the development of the VECTO EffShift model at TUG, ACEA-TF5 as well the transmission OEMs also performed extensive simulations and analysis based on their in-house datasets. Partial simulation data and indications from measurement have been shared with TUG. This information has been used to improve the EffShift AT model to its current status and to find the current set of model parameters. Based on the latest test results reported to TUG the gap between AT-P and AT-S was reduced also at simulations performed at OEMs. Results of testing of the final version of the EffShift model by industry could not be included into this report as the final software was released at the very end of the contract.

Besides the above mentioned datasets there is lack of comprehensive information at TUG to propose a final parametrisation of the VECTO EffShift model. For the urban bus AT-P and AT-S topic it is suggested that ACEA TF5, where several OEMs offer both transmission systems in their portfolio, comes up with a final proposal of parameters for a discussion in a VECTO board. ACEA-TF5 already indicated related activity.

Ad ii. Calibration of VECTO strategies to be used in the simulation of specific vehicles

Basically it would be conceivable to offer the possibility to calibrate a basic gear shift strategy in VECTO based on certified gear shift data. This model could then be applied in the official CO_2 determination for related specific vehicles. A comparable approach is implemented in CO2MPAS, where for passenger cars and light commercial vehicles with automatized transmission the measured data in the WLTP is used in a first step to calibrate two different gearshift models. In a second step it is then evaluated which of the models correlated better with the gear shifts as observed in the WLTP. This model is then used for the simulation of fuel consumption and CO_2 emissions in the NEDC.

However, an implementation of the of above mentioned approach, i.e. an individual calibration of any VECTO gearshift model based on specific OEM data - would require several accompanying elements in the HDV CO_2 regulation:

i. requirements to measure and certify gearshift data as input to calibrate VECTO
ii. family concepts to define vehicle configurations to which this specific parameterisation can be applied in the official CO_2 determination
iii. the availability of testing methods to verify real world system behaviour on certain number of vehicles against the system behaviour as simulated with the generic model and the specific parametrisation in VECTO.

Especially the development of methods related to item iii. is assumed to be a very difficult task as any validation measurement will not fully match with the VECTO generic model with the specific parameterisation.

A much more promising approach is seen to directly consider OEM specific gearshift algorithms using software-in-the-loop (SIL)[11] techniques in the determination of CO_2 emissions. Such an approach can be expected to much better reflect individual shifting behaviour. For any SIL approach also a good correlation of any validation measurement with model result could be demanded. Possible pathways including challenges in their implementations are drafted in section 2.1.4 below.

2.1.3.3 **Status quo and further recommendations**

The new gearshift strategies as recommended for future use in the official VECTO version (EffShift AMT and EffShift AT) have been validated to the extent possible based on the available data provided by industry and available at TU Graz from earlier projects. Also the general feedback from industry, that the EffShift approach is a significant improvement against the current "Classic" model, can be taken as a confirmation of the method. More scientific approaches for a validation would require a set of dedicated vehicle tests (or at least SIL simulations) where all relevant input data for VECTO could be made available.

Special sensitive applications fields are the comparison of AMT and AT in certain market segments and especially the competition of AT-P and AT-S in the urban bus market. From the small amount of data available at TUG it can be concluded that the rankings predicted by VECTO Effshift are closer to reality than with Classic. However, especially for the AT-P vs. AT-S issue there is lack of comprehensive information at TUG to propose a final parametrisation of the VECTO EffShift model. It is suggested that ACEA-TF5, where several OEMs offer both transmission systems in their portfolio, comes up with a final proposal of parameters for a discussion in a VECTO board.

It is not recommended to further investigate on options for an OEM specific parameterisation of generic gear shift algorithms (approach as implemented for AT vehicles in CO2MPAS). Instead it

[11] SIL (Software in the Loop): combination of an independent software element into a single simulation, e.g. longitudinal simulated model with interface to black box controller software

is recommended to directly investigate in approaches to directly consider OEM specific control algorithms via SIL in the context of VECTO.

2.1.4 WP 1.4: Elaboration of possible pathways for consideration of OEM specific gear shift strategies in VECTO

2.1.4.1 Description of task

The option to consider OEM specific control strategies into the VECTO CO_2 certification appears worthwhile for several vehicle systems (e.g. gear shift strategies, ADAS or HEV controllers). Often discussed options are either to use a SIL (Software in the Loop)[12] interface to VECTO or full vehicle testing methods which are used to calculate a "bonus factor" to cover the controller behaviour in an implicit manner. Pathways to elaborate the related methods have been analysed in WP 1.4 based on results of a stakeholder workshop in June 2019 by a desktop study.

2.1.4.2 Work performed and findings

Following relevant influences of component controllers on the VECTO results have been identified:

- Gear shifting
- ADAS including PCC
- Smart auxiliaries
- Hybrids
- Heating strategies for exhaust gas aftertreatment
- Combinations of these control functions

The updated VECTO version offers for each of these topics generic controllers and/or calculation methods. The results of the simulation using generic controllers certainly may overestimate the fuel efficiency for some OEMs and underestimate it for others. This is mainly depending, how well the vehicle specific control algorithms are optimised for a high energy efficiency[13].

If the CO_2 certification process could reflect the possible differences in the vehicle efficiencies due to specific control algorithms, the development of improved controllers would be more attractive for OEMs.

To consider vehicle specific control strategies, basically three options are attractive:

a) Coupling the vehicle specific controller via SIL to the VECTO software.
b) Designing a test procedure, where effects of controllers are considered implicitly.
c) Use artificial intelligence (AI) to set up the controller behaviour in a software based on standardised vehicle tests (e.g. by using neural networks).

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[12] SIL (Software in the Loop): combination of an independent software element into a single simulation, e.g. longitudinal simulated model with interface to black box controller software

[13] Limits for controller optimisation in real vehicle applications may also exist due to different hardware, e.g. design of the drivetrain for low vibration and noise at low engine speeds to allow early shifting.

Option a) SIL method

Several constraints exist for using SIL for the simulation of all individual HDVs in VECTO:

- The demand for a short computation time, since controllers usually need real time software operation. A real time simulation would need several hours per vehicle[14], depending on the number of mission profiles relevant for the vehicle group.
- The need to certify the controller behaviour in the SIL environment, since:
    - this would need a costly vehicle on-road test which has then to be repeated in the SIL system to check that the controller acts similar as on the road.
    - The proper connection of a controller software to a "VECTO-SIL version" can be time consuming and costly, since all signals needed by the specific controller have to be made available and to be connected to the VECTO system correctly.
    - Certified control algorithms must not be altered later in vehicles without new certification. Today it is e.g. common practice that gear boxes allow different strategies and the best version for the typical customer profile can be selected without need for certification (e.g. for hilly or flat routes of buses and/or fast versus fuel saving).
- The additional complexity of the VECTO software required to be compatible with OEMs specific controller models. The requirements are assessed to cover
    - Compatibility with standard software used by OEMs for controller development. The most common simulation system in this context is MATLAB Simulink.
    - Flexibility to provide additional signals in the simulation environment (e.g. CAN signals for temperatures or status of other vehicle systems not covered in the standard VECTO model) which are needed to replicate real world behaviour of the control systems.

  Any simple transformation of the "standard VECTO" as used in the official CO2 certification into a tool using forward modelling principles would not solve any of the requirements as listed above. Instead an alternative approach, using common VECTO compatible modules to be applied e.g. in an individual MATLAB environment (further explanations are given below) is seen as a much more reasonable option.
- The additional complexity of the entire certification system necessary to support such a SIL method.

All together a switch to a SIL solution in VECTO seems not to be attractive, at least in short and medium term. A viable alternative may be the use of a SIL version of VECTO only to calculate a "Smart controller bonus" for vehicle specific controllers compared to the generic VECTO controllers (option a in Figure 4). Such a "Smart controller bonus" may then be certified and applied to the basic VECTO results for all vehicles within a "controller family".

[14] If a group 5 long haul vehicle would be simulated in real-time, the simulation time would be at some 20 hours.

This would reduce the issue with long computation times and complex model set up, since only a few vehicles need to be simulated with the SIL-system. However, a robust family system is needed to use the method in the certification process. The family system has to group vehicles according to controller software and the affected vehicle hardware. The families have to be large enough, to make the option cost-efficient. This seems to be a challenging task, having all possible future vehicle designs and controller architectures in mind.

With less effort for the extension of VECTO to support SIL, also OEM specific software for vehicle simulation may be used to compute the "Smart controller bonus" (option b in Figure 4). Since vehicle development at OEMs is already frequently using vehicle simulation tools which are already SIL compatible, the effort to set up the models would be reduced. To be able to use those OEM specific SIL models for an official CO_2 determination fully compatible with the VECTO approach, common modules written in a MATLAB compatible code could be provided by the Commission.[15] Those models need to reflect all the physical models as part of VECTO e.g. calculation of driving resistance forces including cross-wind influence or engine model compatible with the input data according to Regulation (EU) 2017/2400. Those models then could be combined to a complete vehicle model where the OEM specific SIL code replaces the generic VECTO controllers.

Additional effort then needs to be put to the certification of the SIL system. As described before, the certification of a SIL system may be based on the simulation of real world driving and a comparison of measured and simulated energy flows and rotational speeds with defined tolerances for passing the certification. Such a certification process was developed for the certification of engines for hybrid HDVs in the Gtr No. 4 ("HILS method[16]"). In the test phase it showed a quite high effort needed for the validation of the HILS in the certification. The HILS has not been introduced in the European type approval system for HD engines.

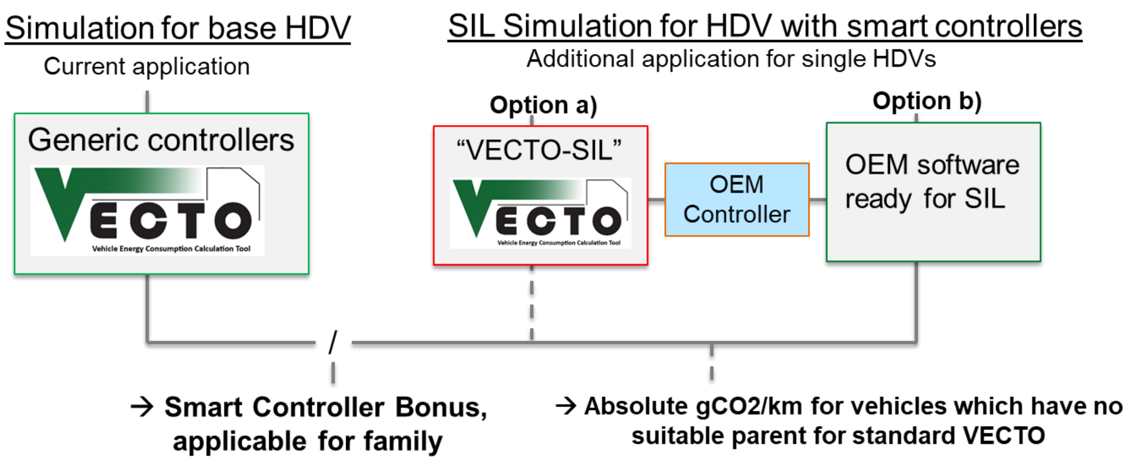


Figure 4: Schematic picture of the simulation system for the "Smart controller bonus" method

[15] E.g. the software Octave is reported to be compatible with Matlab and available as open source.

[16] HILS (Hardware In the Loop System) uses the Controller as hardware in the vehicle simulation tool. Since only the controller software is relevant for the vehicle simulation, SIL provides for this application the same results as HILS, as long as the same controller functions are applied.

The set-up of a VECTO SIL demonstrator and of an "OEM-like SIL" system is part of a work package of the LONGRUN project, which is funded by the Horizon 2020 action of the EU. The project starts January 2020. The VECTO related work is coordinated in this project by TU Graz. All results of the work package shall be communicated with the Commission's VECTO team and also reporting to the VECTO board is possible on demand.

Option b) VTP map method

As an alternative to SIL systems a VTP like test method seems to be a promising option to consider controller effects. This option may also be used for vehicles with drivetrain systems not yet covered by VECTO to allow a certification as long as the drivetrain system is not implemented in VECTO[17].

The VTP map method can use most parts of VECTO but replaces the detailed simulation of the drivetrain by a simple fuel map using vehicle speed and wheel power as x- and y coordinates (Figure 5).

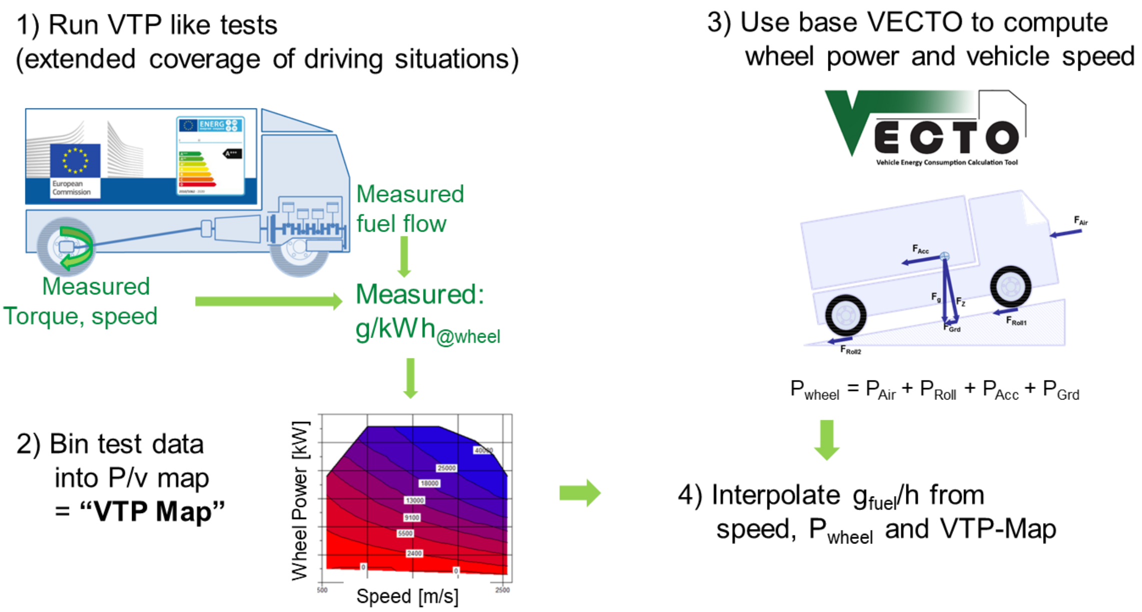


Figure 5: Schematic picture of the VTP map method

To calculate the vehicle speed and wheel power in a VECTO simulation for the VTP-map method, the vehicle mass, loading, air drag and rolling resistance from the vehicle have to be used as defined for the conventional method. In addition the full load curve of the drive train has to be provided. This may be defined simply as maximum power as function of wheel speed and can also be produced from a VTP-like test, as long as the test includes full load accelerations.

The accuracy of this VTP map method was tested based on an "ideal data set". Using a HDV model in VECTO, the urban delivery, regional delivery and long haul cycles were simulated. From the 1 Hz results for the regional delivery cycle the VTP map was produced (Figure 6). From the wheel power

[17] Including method and software development, test phases and amendments of the corresponding technical annexes the time to consider new technologies in VECTO in a detailed simulation may be more than 4 years.

and vehicle speed simulated with VECTO for the urban delivery and long haul cycle, the fuel consumption for these cycles was interpolated from the VTP map.

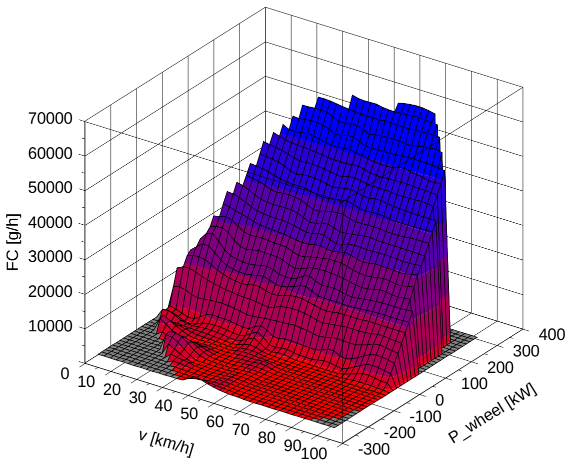
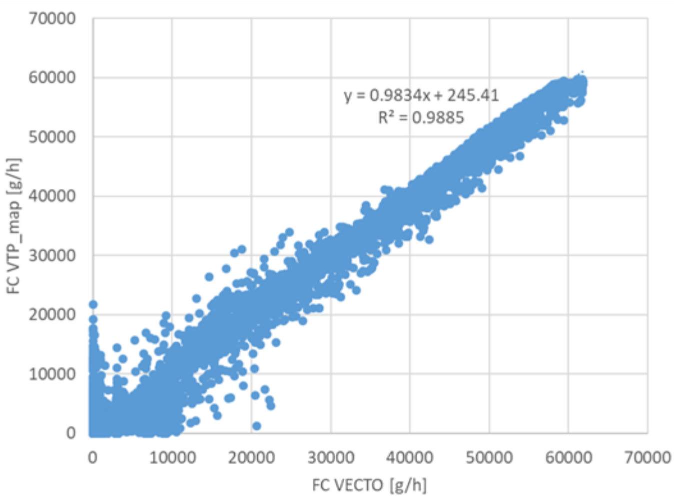


Figure 6: VTP map produced from the regional delivery cycle

The deviation between the interpolation from the VTP-map and the detailed simulation of the drivetrain by VECTO was 0.2% for the urban delivery and for the long haul cycle. The second per second deviations certainly are higher, since the VTP-map levels out several details, such as different gears at similar vehicle speed and torque interruptions at gear shifts. The latter effect explains the large differences around the zero fuel flow point (Figure 7). Thus, the VTP map would have to be produced from longer real world driving test.



Cycle	Deviation VTP-Map / VECTO
UD	-0.2%
LH	-0.2%

Figure 7: Deviation between VTP-map result and detailed VECTO simulation

The VTP-map seems to have several interesting advantages:

+ Any kind of drive train can be covered and a compatibility with the conventional VECTO results is given since wheel power and speed are results from the standard VECTO procedure.
+ The VTP-map can be produced easily from real world tests (torque and rotational speed at the driven wheels and fuel flow have to be measured as defined in the VTP test procedure in Annex Xa from Regulation (EU) 2017/2400 and its amendments).
+ All effects of vehicle specific controllers on gear changes, auxiliary power demand, exhaust heating strategies and even hybrid system control are included in the measured fuel flow in the VTP map.

Following disadvantages and open issues were identified:

- All possible drivetrain configurations (engine, gearbox, axle) need to be tested and/or a suitable family concept would need to be available
- Since auxiliary power demand is included implicitly in the measured fuel consumption, the setting of the auxiliaries, such as the HVAC system, in the test have to be defined quite exactly or have to be corrected in a post-processing step when the VTP map is produced to be in line with the generic auxiliary power consumption in the standard VECTO method.
- The test duration may have to be quite long for a representative map. E.g. complex hybrid systems with high energy storage capacity may have a rather high variability in the fuel flow at given speed and wheel power since the SOC of the battery is also a relevant parameter for the controller decision of the best hybrid strategy at each time step.
- The uncertainty of the resulting fuel consumption values may be too high for more complex systems (the 0.2% shown above are the theoretical optimum, not the expected average). This needs further testing and validation.

The VTP-map method may be used to directly calculate the fuel consumption and CO_2 values with VECTO, if the VTP map is designed as a certification procedure for drivetrain families. The method may also be used to calculate the “Smart controller bonus” explained already for option a). In this case VECTO would calculate the fuel consumption values once with the standard method based on the generic control algorithms and once with the VTP-map, which includes the vehicle specific controllers for the gear box, the auxiliaries and the hybrid system, if applicable.

For drive-train designs not covered by VECTO yet, such as complex power split hybrids, the method can be used to calculate the fuel consumption directly. The calculation of a “Smart controller bonus” needs always the definition of a reference drive train for the standard VECTO simulation, which can hardly be defined for such new technologies.

The effect of vehicle speed adjustments by vehicle specific predictive cruise control systems cannot be assessed with the VTP-map method, since the vehicle speed is one axis and the resulting wheel power the other axis of the map. Thus the speed and wheel power trajectories for the VECTO cycles always have to be simulated by VECTO.

Option c) Artificial intelligence (AI)

Neural networks available in the Matlab Simulink software show good results for the simulation of the engine speed after some tuning of the model parameters (number and type of neurons etc.) but were sensitive against extrapolation of the data used to set up the model.

Since no full test data set was available for testing the overall accuracy of option c) no results for the expected accuracy can be provided. However, the implementation of AI models developed from test data into VECTO seem to be a risky task. Existing AI methods may not be applicable due to IPR restrictions and the development of independent AI software routine for VECTO may need quite high efforts until it meets the demands in terms of reliability and applicability for vehicle certification.

2.1.4.3 **Status quo and further recommendations**

The set-up of a VECTO SIL demonstrator is part of a work package of the LONGRUN project, which is funded by the Horizon 2020 action of the EU. TUG is coordinator of the VECTO related work in LONGRUN. It is recommended to monitor the results achieved in the project before a decision on further activities for SIL extensions of VECTO are made by the Commission.

The VTP-map approach showed promising results in this desktop study and may be further developed in a follow up project since it may provide a simple solution for several possibly upcoming problems. These are the certification of complex drivetrain technologies in the short term while implementation of the necessary methods in VECTO and in the regulations may need years and the consideration of vehicle specific control algorithms which are more efficient than the generic controllers in VECTO.

Methods based on artificial Intelligence have yet not been tested in detail since access to suitable test data is missing. This is also the case for the VTP map and may also be the case for the SIL system later. Therefore it is strongly suggested to put effort in the setup of complete test data sets for some HDVs accessible for the Commission and the Consultants in a next project. The test data has to include:

- All input data needed to simulate a vehicle in VECTO (XML input data including engine map, WHTC correction factors, gear box and axle maps, air drag and tire RRC values etc.).
- A set of on road tests with the data described in the VTP (Annex Xa of 2017/2400) for the vehicle.
- As nice to have also a set of engine tests of the vehicles engine with transient engine loads (e.g. simulated VECTO cycles for urban, regional delivery and long haul).

Since the component tests can hardly be performed without support from the OEMs, it should be negotiated, if some of the EURO VI vehicle data used for former and current pilot studies can be provided by ACEA to be used in anonymised form. The more costly alternative is to run independent component tests.

Without such complete data sets, an independent assessment of the accuracy of new methods is not possible and also the development of new simulation methods is less efficient since improvements in the software performance in drive train simulation can hardly be assessed.

2.2 Task 2: Predictive Cruise Control (PCC)

Advanced Driver Assistance Systems (ADAS) can significantly contribute to fuel efficient driving behaviour. The most important system of this kind is "Predictive Cruise Control" (PCC). The main principle of PCC is to optimize the use of potential and kinetic energy during the driving cycle correlated with a more or less significant reduction of the vehicles' average speed. Such systems typically allow the driver to manually intervene into the control strategy and to shift between rather fuel efficient or rather time optimized vehicle operation.

Such systems were not considered in the CO_2 certification with VECTO before the current project was launched. ACEA already elaborated drafts for simulating the fuel consumption benefit of the systems "Engine Stop-Start" (ESS), "Eco-roll" and PCC and its possible combinations in their White Book since 2016 [2], [3].

Task 2 in this project covered the implementation of effects of the most relevant ADAS systems into the VECTO software and the elaboration of the necessary boundary conditions for a robust handling in the CO_2 certification. Basically, the following three approaches for implementation of effects of ADAS into VECTO could be followed up during this project:[18]

1. Simple statistical approach for calculation of fuel consumption benefit as a function of vehicle group, mission profile and main relevant vehicle characteristics
2. Post-processing of instantaneous VECTO simulation results
3. In-the-loop simulation in VECTO

Accuracy but also efforts for implementation into VECTO increase from option 1. to option 3. For a medium to long term solution, method 3. appeared to be the most promising method, as e.g. the interdependency with other vehicle systems (like smart auxiliaries or brake energy recuperation of hybrid vehicles) can be considered correctly.

The work in this project on the implementation of ADAS systems into VECTO was significantly influenced by the fact, that during the inception meeting the Commission asked for a quick introduction of ADAS into VECTO before the end of 2018 in order to have the most relevant systems accounted for in the CO_2 standards baseline period starting in 2019. As a consequence, a two step implementation approach had to be executed:

- Implementation of a "Quick fix" approach based on a comparably simple approach (corresponding to a combination of approaches 1. and 2. as listed above) which could be finalised until the end of 2018 (subsequently labelled as "Phase 1" implementation)
- Implementation of an "In-the-loop" approach using more sophisticated methods until the end of the project (subsequently labelled as "Phase 2" implementation).

[18] More advanced options would be:

4. VECTO in-the-loop using generic control strategies plus certified control parameters
5. VECTO in-the-loop plus SIL connection to OEM specific control strategies

Approach 5. and partly approach 4. would require the availability of methods as pointed out in section 2.1.4 and were hence considered not to be an option during this project.

2.2.1 WP 2.1: Definition of ADAS systems relevant for consideration in VECTO

2.2.1.1 Description of task

In WP 2.1 an overview on all known ADAS systems with impact on vehicles' fuel consumption was elaborated. Based on the overview a list of systems relevant for the HDV CO_2 certification was compiled. For each identified relevant system, a concrete definition based on verifiable system characteristics was elaborated.

2.2.1.2 Work performed and findings

For the phase 1 implementation the starting point was the list of relevant ADAS systems from the ACEA White Book Version 2016 [2]. This list has been reviewed by TUG and further discussed with stakeholders. In several audio web sessions definitions robust enough for an implementation into Regulation (EU) 2017/2400 have been elaborated. The list of systems and definitions is given below. This text is identical to the definitions as implemented to Annex III of Regulation (EU) 2017/2400 by the amending Regulation (EU) 2019/318.

8. Advanced driver assistance systems

8.1 The following types of advanced driver assistance systems, which are primarily aiming for reduction of fuel consumption and CO2 emissions, shall be declared in the input to the simulation tool:

8.1.1 **Engine stop-start during vehicle stops**: system which automatically shuts down and restarts the internal combustion engine during vehicle stops to reduce engine idling time. For automatic engine shut down the maximum time delay after the vehicle stop shall be not longer than 3 seconds.

8.1.2 **Eco-roll without engine stop-start**: system which automatically decouples the internal combustion engine from the drivetrain during specific downhill driving conditions with low negative gradients. During these phases the internal combustion engine is operated in engine idling. The system shall be active at least at all cruise control set speeds above 60 km/h.

8.1.3 **Eco-roll with engine stop-start**: system which automatically decouples the internal combustion engine from the drivetrain during specific downhill driving conditions with low negative slopes. During these phases the internal combustion engine is shut down after a short time delay and keeps shut down during the main share of the eco-roll phase. The system shall be active at least at all cruise control set speeds of above 60 km/h.

8.1.4 **Predictive cruise control (PCC)**: systems which optimise the usage of potential energy during a driving cycle based on an available preview of road gradient data and the use of a GPS system. A PCC system declared in the input to the simulation tool shall have a gradient preview distance longer than 1 000 meters and cover all following functionalities:

1) Crest coasting

Approaching a crest, the vehicle velocity is reduced before the point where the vehicle starts accelerating by gravity alone compared to the set speed of the cruise control so that the braking during the following downhill phase can be reduced.

2) Acceleration without engine power

During downhill driving with a low vehicle velocity and a high negative slope the vehicle acceleration is performed without any engine power usage so that the downhill braking can be reduced.

3) Dip coasting

During downhill driving when the vehicle is braking at the overspeed velocity, PCC increases the overspeed for a short period of time to end the downhill event with a higher vehicle velocity. Overspeed is a higher vehicle speed than the set speed of the cruise control system.

A PCC system can be declared as input to the simulation tool if either the functionalities set out in points 1) and 2) or points 1), 2) and 3) are covered.

For the further work related to the phase 2 implementation a questionnaire was send out to industry to collect further types of fuel efficiency relevant ADAS functions. Table 17 gives a compilation of the collected information including a judgement related to the relevance of the system for the phase 2 implementation as performed in this project.

Table 17: Overview fuel-efficiency related ADAS systems not considered in phase 1 implementation

Short description / name	**Falls into existing ADAS category in VECTO**	**System description**	**OEM estimation for fuel savings [%]**	**TUG judgement for relevance in phase 2 implementation and justification**
Eco-roll without engine stop-start for transmission type AT	Eco-roll + interaction with PCC (if applicable)	System which automatically decouples the internal combustion engine from the drivetrain (either by opening the torque converter lock-up clutch or by gear “neutral”) to reduce engine drag losses during specific downhill driving conditions.	n.a.	**Considered relevant for phase 2 implementation** (in phase 1 only Eco-roll for AMT transmissions was considered)
Pulse and Glide	PCC	Permission of small hysteresis around cruise control set speed to combine rolling and acceleration at efficient operating points instead of constant operating point with lower efficiency	n.a.	Not claimed to be of priority by industry for phase 2 implementation into VECTO. **Not considered for phase 2 implementation.**

Short description / name	Falls into existing ADAS category in VECTO	System description	OEM estimation for fuel savings [%]	TUG judgement for relevance in phase 2 implementation and justification
PCC local speed limits	PCC	The speed limits of a street are predicted and are integrated into the target speed for cruise control.	n.a.	For any future consideration VECTO cycles would need to be complemented with speed limit information. Not claimed to be of priority by industry for phase 2 implementation into VECTO. **Not considered for phase 2 implementation.**
PCC off-highway	PCC	The system reacts predictive on obstacles like roundabouts and intersections but also takes the curvature of turn into consideration and optimizes the fuel consumption based on these values also for interurban routes not only on long haulage	1-5% on VECTO regional delivery route	For any future consideration VECTO cycles would need to be complemented with additional information on curvature etc. Not claimed to be of priority by industry for phase 2 implementation into VECTO. **Not considered for phase 2 implementation.**
Enhanced methods to gather information on route and vehicle position	PCC	Enhanced sensor systems (e.g. GPS, gyrometer) and enhanced data collection and data processing methods provide more accurate or comprehensive input information to PCC control algorithms	2.5-5% (area dependent)	Definition and verification of technologies goes far beyond current level of implementation of ADAS in Regulation (EU) 2017/2400. Not claimed to be of priority by industry for phase 2 implementation into VECTO. **Not considered for phase 2 implementation.**
Predictive shifting strategy (AMT + AT transmissions)	PCC	Systems which predict the most fuel-economic gear ratio of future driving situations based on available information of road gradient data and GPS data. This is also to avoid gear hunting which leads normally to higher fuel consumption	n.a.	Options for consideration of enhanced OEM specific gear shift strategies is discussed in section 2.1.4. in this report. **Not considered for phase 2 implementation.**

Short description / name	Falls into existing ADAS category in VECTO	System description	OEM estimation for fuel savings [%]	TUG judgement for relevance in phase 2 implementation and justification
Predictive engine cooling	None	The engine cooling system is controlled by a predictive system to be as fuel-efficient as possible (e.g. reduced cooling in up-hill conditions if downhill sections are immediately ahead).	n.a.	Consideration of functionality would require a detailed simulation of engine cooling demand in VECTO and robust verification methods. Impact on overall fuel consumption assessed to be low. Not claimed to be of priority by industry for phase 2 implementation into VECTO. **Not considered for phase 2 implementation.**
Variable idling speed	Engine stop/start	Instead of engine start-stop with technical challenges a reduced idling speed in special situations can be set and thus save nearly the same amount of fuel	n.a.	Not claimed to be of priority by industry for phase 2 implementation into VECTO. **Not considered for phase 2 implementation.**
Platooning	None	Grouping of vehicles with shortened distance to reduce air drag	n.a.	Currently platooning requires an exceptional permission as driving with related short distances between vehicles is not allowed by Road Traffic Regulations. To be considered reasonably platooning would need to be well established on European motorways and data on typical usage need to be available. **Not considered for phase 2 implementation.**

As a conclusion from the analysis for the phase 2 implementation of ADAS only Eco-roll for AT transmission was identified to be of further relevance. This conclusion was presented to stakeholders in the VECTO Board meeting in January 2019. For the other systems listed in Table 17 it is recommended to wait for further decisions about a future implementation into VECTO until the long-term methods to consider OEM specific control strategies as drafted in section 2.1.4 become apparent.

Below the draft definitions for the Eco-roll function for AT transmission list listed. Please note that this definition has not yet been introduced into the working document for Annex III and the wording might be changed by the activity of the HDV CO_2 Editing board.

Eco-Roll without engine stop-start for AT transmissions.

"System which automatically decouples the internal combustion engine from the drivetrain during specific downhill driving conditions with low negative gradients. The system shall be active at least at all cruise control set speeds above 60 km/h. Any system to be declared in the input to VECTO has to cover either 1) or 2) or both functionalities:

1) Torque converter lock-up clutch open:

The torque converter lock-up clutch is open during Eco-roll mode. This allows the engine to operate in coast mode at lower engine speeds and reduces or even eliminates fuel injection.

2) Gearbox in Neutral, torque converter lock-up clutch closed:

By shifting the gearbox to Neutral, the combustion engine is de-coupled from the drivetrain, and engine operates at idle speed

The combination of Eco-roll with engine stop start is not a relevant system for vehicles with AT transmissions.

2.2.1.3 Status quo and further recommendations

Currently available fuel-efficiency relevant ADAS systems have been analysed and evaluated for relevance of implementation into the current approach of VECTO. For the relevant systems clear definitions of the functionality have been elaborated. From the current point of view, it is recommended to wait for decisions on implementation of further systems into VECTO until the long-term methods to consider OEM specific control strategies in VECTO become apparent.

2.2.2 WP 2.2: Elaboration of generic simulation approaches

2.2.2.1 Description of task

In WP 2.2 generic simulation approaches for the relevant systems identified in WP 2.1 have been elaborated.

2.2.2.2 Work performed and findings

As already mentioned in the introduction to this work chapter, the implementation had to be performed in two phases.

Phase 1 implementation:

Phase 1 implementation was triggered by the boundary condition that the entire approach needed to be elaborated and implemented into the software until the end of 2018. The selected approach is to apply generic CO_2 credits to values for fuel consumption and CO_2 emissions:

*CO_2 incl. ADAS = CO2 * (1 + CO_2 credit)*[19][20]

The CO_2 credits were determined separately for each combination of the following items:

- ADAS technology and all reasonable combinations of systems (in total 17 combinations, see Table 18 on page 50), based on the definition of single systems as listed in section 2.2.1.2
- Vehicle groups 4, 5, 9, and 10 (the lorry groups which are regulated in the CO_2 standards legislation)
- Mission profile
- Payload

The generic CO_2 credits have been determined based on the work steps listed below. A documentation of the applied methods is given in section A.2.2. The workflow was:

- Definition of ADAS functionalities were taken from the ACEA White Book version April 2016 [2] and further elaborated in discussions during expert group meetings.
- Post-processing of instantaneous VECTO results for „typical vehicles" to estimate potential fuel savings per ADAS technology. As "typical vehicles" the VECTO vehicle models as elaborated in [5] have been used.
- The CO_2 benefits for certain combinations of ADAS systems (especially for the interaction of Eco-roll and PCC) could not be directly calculated by a post-processing approach as precise definitions of interaction of systems and analysis of in-the-loop simulations would be required. For those combinations the CO_2 credits were estimated based on expert judgement using rather conservative assumptions (i.e. resulting in lower CO_2 credits)[21].

The resulting tables with CO_2 credits have been discussed with stakeholders and been confirmed based on an individual OEM level.[22] The complete set of final result is given in section A.2.2.2. In a final step the CO_2-credits have been multiplied with a "factor of conservatism" of 0.5 before final implementation in VECTO. This factor shall cover the following considerations:

- A lower accuracy of the methods used in phase 1 implementation compared to approaches applied in phase 2 and possible later implementations (generic in the loop model, OEM specific in the loop model),

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[19] CO_2 credits are defined to have negative values.

[20] In the real implementation in the VECTO software this calculation is performed for fuel consumption. The results for CO_2 emissions are then calculated based on fuel consumption and the carbon content of the fuel.

[21] The assumptions are:

- Only 80% of Eco-roll considered in package with PCC1&2
- Only 60% of Eco-roll considered in package with PCC1&2&3
- Combined effects of Eco-roll and PCC cannot be less than for Eco-roll and PCC alone

[22] ACEA did not provide consolidated feedback as the commenting of ADAS effects would fall into compliance issues. All individual OEMs which responded confirmed the order to magnitude of CO_2 credits.

- the current approach does not consider that systems might be set inactive by drivers for a certain percentage of driving time (fuel saving vs. time/performance),
- Further influences which reduce real world performance like quality of route data, interaction with vehicle safety systems,
- CO_2 credits for ADAS shall increase in future as systems further evolve over time and possibly efforts for OEMs to declare/certify such systems in VECTO expected to increase, which shall be rewarded.

The tables on the following pages give the complete set of CO_2 credits as implemented for phase 1 in VECTO. The credits are specified as reduction rates compared to a vehicle without any ADAS feature. Table 18 gives the explanations to allocate the "ADAS combination number" as used in current VECTO to the included ADAS functionalities. Please note that the results as shown in this chapter reflect credits as currently implemented in the official version and differ from the values as listed in section A.2.2.2 by the "factor of conservatism" 0.5 as described above.

The order of magnitude of CO_2 credits are exemplarily explained based on the values for the group 5 vehicle as given in Table 20:

- Engine stop-start (ESS) during vehicle stops: credits are in the range of -1.5% in urban delivery, -0.3% in regional delivery and no impact in long-haul mission
- Eco-roll: credits are in the range from 0% to -0.3% (the "pure" Eco-roll function without combination with PCC is considered to be non-predictive thus the effect on overall fuel consumption is low[23])
- Predictive cruise control: credits are in the range from -0.1% to -0.7% in long haul and from -0.2% to 0.9% in regional delivery. For urban driving PCC is considered as not relevant. Results for PCC were found to be very sensitive to payload conditions (lower credits for low payload). Further analysis also showed that the road slope as defined for the current long haul mission profile leads only to very few PCC events due to a very low level of hilliness. Thus, the credits for regional delivery are higher than for long haul.[24]
- Combination of systems: As to be expected the highest credits have been determined for the combination of all three basic ADAS systems. The maximum credits are -0.8% for the long haul cycle (with reference payload) and -1.4% in regional delivery cycle (reference payload). In the urban delivery cycle, only Engine stop-start is relevant, thus the combination of ADAS does not result in higher credits than with ESS alone. As mentioned above, the assessment of reduction rates for combination of systems from phase 1 was judged to be uncertain.[25]

[23] Activation of Eco-roll without predictive functionality, i.e. without taking into account the information of the course of slope ahead, can result in a certain share of activation events with negative impact on fuel consumption.

[24] Related to this finding ACEA has announced ongoing analysis of real world data on hilliness and the requirement to update the long haul cycle.

[25] A comparison of the CO2 credits from phase 1 implementation with the results of phase 2 implementation is given in Figure 8 on page 33.

Table 18: List of implemented ADAS technologies and combinations (phase 1 implementation)

Comb-ination nr.	Engine stop-start during vehicle stops	Eco-roll without engine stop-start	Eco-roll with engine stop-start	Predictive cruise control (1, 2)	Predictive cruise control (1, 2, 3)
1	yes	no	no	no	no
2	no	yes	no	no	no
3	no	no	yes	no	no
4/1	no	no	no	yes	no
4/2	no	no	no	no	yes
5	yes	yes	no	no	no
6	yes	no	yes	no	no
7/1	yes	no	no	yes	no
7/2	yes	no	no	no	yes
8/1	no	yes	no	yes	no
8/2	no	yes	no	no	yes
9/1	no	no	yes	yes	no
9/2	no	no	yes	no	yes
10/1	yes	yes	no	yes	no
10/2	yes	yes	no	no	yes
11/1	yes	no	yes	yes	no
11/2	yes	no	yes	no	yes

Table 19: ADAS - CO2 credits for Group 4 vehicles (phase 1 implementation)

Comb-ination nr.	Group 4					
	Long Haul		Regional Delivery		Urban Delivery	
	ref. payload	low payload	ref. payload	low payload	ref. payload	low payload
1	0.0%	-0.1%	-0.5%	-0.5%	-1.2%	-1.5%
2	0.0%	0.0%	-0.1%	-0.1%	0.0%	0.0%
3	-0.1%	0.0%	-0.2%	-0.1%	0.0%	0.0%
4/1	-0.4%	-0.1%	-0.1%	0.0%	0.0%	0.0%
4/2	-0.5%	-0.1%	-0.2%	-0.1%	0.0%	0.0%
5	-0.1%	-0.1%	-0.6%	-0.6%	-1.2%	-1.5%
6	-0.1%	-0.1%	-0.7%	-0.6%	-1.2%	-1.5%
7/1	-0.4%	-0.1%	-0.6%	-0.5%	-1.2%	-1.5%
7/2	-0.6%	-0.1%	-0.7%	-0.6%	-1.2%	-1.5%
8/1	-0.4%	-0.1%	-0.2%	-0.1%	0.0%	0.0%
8/2	-0.5%	-0.1%	-0.3%	-0.1%	0.0%	0.0%
9/1	-0.4%	-0.1%	-0.3%	-0.2%	0.0%	0.0%
9/2	-0.5%	-0.1%	-0.4%	-0.2%	0.0%	0.0%
10/1	-0.4%	-0.2%	-0.7%	-0.6%	-1.2%	-1.5%
10/2	-0.6%	-0.2%	-0.7%	-0.6%	-1.2%	-1.5%
11/1	-0.4%	-0.2%	-0.8%	-0.7%	-1.2%	-1.5%
11/2	-0.6%	-0.2%	-0.8%	-0.7%	-1.2%	-1.5%

Table 20: ADAS – CO2 credits for Group 5 vehicles (phase 1 implementation)

Comb-ination nr.	Group 5									
	Long Haul				Regional Delivery				Urban Delivery	
	ref. payload	low payload	EMS ref. payload	EMS low payload	ref. payload	low payload	EMS ref. payload	EMS low payload	ref. payload	low payload
1	0.0%	-0.1%	0.0%	0.0%	-0.3%	-0.4%	-0.2%	-0.3%	-1.3%	-1.8%
2	-0.1%	0.0%	-0.1%	0.0%	-0.1%	-0.1%	0.0%	-0.2%	0.0%	0.0%
3	-0.2%	-0.1%	-0.1%	0.0%	-0.2%	-0.2%	-0.1%	-0.3%	0.0%	0.0%
4/1	-0.5%	-0.2%	-0.1%	-0.2%	-0.6%	-0.2%	-0.5%	-0.3%	0.0%	0.0%
4/2	-0.7%	-0.2%	-0.3%	-0.3%	-0.9%	-0.4%	-0.8%	-0.5%	0.0%	0.0%
5	-0.1%	-0.1%	-0.1%	0.0%	-0.4%	-0.5%	-0.3%	-0.5%	-1.3%	-1.8%
6	-0.2%	-0.1%	-0.2%	-0.1%	-0.5%	-0.6%	-0.4%	-0.6%	-1.3%	-1.8%
7/1	-0.5%	-0.2%	-0.1%	-0.3%	-0.9%	-0.6%	-0.8%	-0.7%	-1.3%	-1.8%
7/2	-0.7%	-0.3%	-0.4%	-0.3%	-1.3%	-0.8%	-1.1%	-0.8%	-1.3%	-1.8%
8/1	-0.6%	-0.2%	-0.1%	-0.2%	-0.7%	-0.3%	-0.5%	-0.5%	0.0%	0.0%
8/2	-0.7%	-0.2%	-0.4%	-0.3%	-1.0%	-0.4%	-0.8%	-0.7%	0.0%	0.0%
9/1	-0.6%	-0.2%	-0.2%	-0.3%	-0.8%	-0.4%	-0.6%	-0.6%	0.0%	0.0%
9/2	-0.8%	-0.2%	-0.4%	-0.3%	-1.1%	-0.5%	-0.9%	-0.7%	0.0%	0.0%
10/1	-0.6%	-0.2%	-0.2%	-0.3%	-1.0%	-0.7%	-0.8%	-0.8%	-1.3%	-1.8%
10/2	-0.8%	-0.3%	-0.4%	-0.3%	-1.3%	-0.8%	-1.1%	-1.0%	-1.3%	-1.8%
11/1	-0.7%	-0.3%	-0.2%	-0.3%	-1.1%	-0.8%	-0.9%	-0.9%	-1.3%	-1.8%
11/2	-0.8%	-0.3%	-0.5%	-0.4%	-1.4%	-0.9%	-1.2%	-1.0%	-1.3%	-1.8%

Table 21: ADAS – CO2 credits for Group 9 vehicles (phase 1 implementation)

Comb-ination nr.	Group 9							
	Long Haul				Regional Delivery			
	ref. payload	low payload	EMS ref. payload	EMS low payload	ref. payload	low payload	EMS ref. payload	EMS low payload
1	0.0%	-0.1%	0.0%	0.0%	-0.4%	-0.5%	-0.2%	-0.3%
2	-0.1%	0.0%	0.0%	0.0%	-0.1%	-0.1%	0.0%	0.0%
3	-0.2%	0.0%	-0.1%	0.0%	-0.2%	-0.2%	-0.2%	-0.2%
4/1	-0.4%	-0.1%	-0.1%	-0.2%	-0.3%	-0.1%	-0.6%	-0.3%
4/2	-0.6%	-0.1%	-0.3%	-0.3%	-0.5%	-0.2%	-0.9%	-0.5%
5	-0.1%	-0.1%	-0.1%	-0.1%	-0.5%	-0.6%	-0.3%	-0.3%
6	-0.2%	-0.1%	-0.2%	-0.1%	-0.6%	-0.7%	-0.4%	-0.5%
7/1	-0.5%	-0.2%	-0.1%	-0.3%	-0.7%	-0.6%	-0.8%	-0.6%
7/2	-0.6%	-0.2%	-0.4%	-0.3%	-0.9%	-0.7%	-1.1%	-0.8%
8/1	-0.5%	-0.1%	-0.1%	-0.2%	-0.4%	-0.2%	-0.6%	-0.3%
8/2	-0.7%	-0.1%	-0.4%	-0.3%	-0.5%	-0.2%	-0.9%	-0.5%
9/1	-0.6%	-0.1%	-0.2%	-0.3%	-0.5%	-0.3%	-0.7%	-0.4%
9/2	-0.7%	-0.2%	-0.4%	-0.3%	-0.6%	-0.3%	-1.0%	-0.6%
10/1	-0.5%	-0.2%	-0.2%	-0.3%	-0.8%	-0.6%	-0.8%	-0.6%
10/2	-0.7%	-0.2%	-0.4%	-0.3%	-0.9%	-0.7%	-1.1%	-0.8%
11/1	-0.6%	-0.2%	-0.2%	-0.3%	-0.9%	-0.7%	-0.9%	-0.7%
11/2	-0.8%	-0.2%	-0.4%	-0.3%	-1.0%	-0.8%	-1.2%	-0.9%

Table 22: ADAS – CO2 credits for Group 10 vehicles (phase 1 implementation)

Comb-ination nr.	Group 10							
	Long Haul				Regional Delivery			
	ref. payload	low payload	EMS ref. payload	EMS low payload	ref. payload	low payload	EMS ref. payload	EMS low payload
1	0.0%	-0.1%	0.0%	0.0%	-0.3%	-0.4%	-0.2%	-0.3%
2	-0.1%	0.0%	0.0%	0.0%	-0.1%	-0.1%	0.0%	0.0%
3	-0.2%	-0.1%	-0.1%	0.0%	-0.2%	-0.2%	-0.1%	-0.2%
4/1	-0.5%	-0.2%	-0.1%	-0.2%	-0.6%	-0.3%	-0.6%	-0.4%
4/2	-0.7%	-0.2%	-0.4%	-0.3%	-0.9%	-0.4%	-0.9%	-0.6%
5	-0.1%	-0.1%	-0.1%	0.0%	-0.4%	-0.5%	-0.2%	-0.4%
6	-0.2%	-0.1%	-0.2%	-0.1%	-0.5%	-0.6%	-0.3%	-0.5%
7/1	-0.5%	-0.2%	-0.1%	-0.3%	-1.0%	-0.6%	-0.8%	-0.7%
7/2	-0.7%	-0.3%	-0.4%	-0.4%	-1.3%	-0.8%	-1.1%	-0.9%
8/1	-0.5%	-0.2%	-0.1%	-0.2%	-0.7%	-0.3%	-0.6%	-0.4%
8/2	-0.7%	-0.2%	-0.4%	-0.3%	-1.0%	-0.4%	-0.9%	-0.6%
9/1	-0.6%	-0.2%	-0.2%	-0.3%	-0.8%	-0.4%	-0.7%	-0.5%
9/2	-0.8%	-0.3%	-0.4%	-0.3%	-1.1%	-0.5%	-1.0%	-0.7%
10/1	-0.6%	-0.3%	-0.2%	-0.3%	-1.0%	-0.7%	-0.8%	-0.7%
10/2	-0.8%	-0.3%	-0.4%	-0.4%	-1.3%	-0.8%	-1.1%	-0.9%
11/1	-0.6%	-0.3%	-0.2%	-0.3%	-1.1%	-0.8%	-0.9%	-0.8%
11/2	-0.8%	-0.3%	-0.5%	-0.4%	-1.4%	-0.9%	-1.2%	-1.0%

<u>Phase 2 implementation:</u>

Phase 2 implementation for ADAS was motivated by the following shortcomings of the phase 1 method:

- The particular characteristics of the vehicle (e.g. curb mass, driving resistances) are not considered
- The interactions with other systems which aim to recuperate kinetic energy (e.g. HEV, smart auxiliaries) are not covered
- for other vehicle groups (other lorry groups than 4, 5, 9, and 10, buses) separate sets of CO_2 credits would need to be elaborated. An in-the-loop implementation is able to handle all kinds of HDV using the same algorithms (but with different vehicle speed parameters for lorries and for buses)

Hence after completion of the phase 1 implementation the work on ADAS in VECTO was continued with the implementation of a generic in-the-loop simulation approach for each ADAS function. Based on the analysis performed in in WP2.1 additionally the technology “Eco-roll for AT” transmissions has been considered.

Table 23 gives an overview on the main elements of the phase 2 “generic in-the-loop” simulation approach in VECTO. A full description of simulation approach including state-flow charts is given in section A.2.3 in the Annex to this report.

Table 23: Simplified overview of generic in-the-loop simulation approaches of phase 2 implementation of ADAS in VECTO

ADAS functionality	Simulation approach (simplified explanation)	Remarks
Engine stop-start during vehicle stops (ESS-VS)	The engine is stopped after 2 seconds of standstill. If the vehicle stop exceeds 120 seconds, the engine is restarted. In a post-processing step the following corrections to fuel consumption are applied: • The power consumption for electric system, pneumatic system and HVAC is corrected by an energy balance • Energy demand to re-start the engine is added. To consider that any activation of ESS-VS is limited in real world e.g. due to auxiliary operation, a "utility factor" of 0.8 is introduced. In the simulations the engine is considered to be "on" during standstills to a percentage of (1-0.8)*100. This rate is considered in the post-processing for energy balances accordingly.	Description refers to simulation of ESS-VS for conventional lorries (i.e. non HEV). Approaches for heavy buses are more sophisticated due to interaction with the Advanced Auxiliary Model. In the simulation of HEV, the Engine-Stop start functionality is part of the HEV operation strategy.
Eco-roll <u>without</u> engine stop-start (AMT transmissions)	The gearbox is set to neutral if the following conditions are met: • Vehicle speed at target speed and above 60 km/h • Downhill conditions • Estimation for vehicle acceleration in the range of 0 to 0.1 m/s² • No current intervention from driver (acceleration or braking demand) The Eco-roll phase ends if either: • Vehicle speed drops under target speed • Any intervention from the driver (acceleration or braking demand)	Simulation approach reflects only non-predictive systems, i.e. in certain driving situation the activation of Eco-roll results in a negative fuel impact. If Eco-roll is available in combination with PCC, an integrated algorithm for both systems is used.
Eco-roll <u>with</u> engine stop-start (AMT transmissions)	As above. Additionally, the engine is shut off during the Eco-roll event. In a post-processing step the following corrections to final fuel consumption are applied: • Energy balance on auxiliary power consumption for steering system, electric system, pneumatic system and HVAC is corrected • Energy demand to re-start the engine is added.	As above

ADAS functionality	Simulation approach (simplified explanation)	Remarks
Eco-roll without engine stop-start (AT transmissions)[26]	The main criteria for activation are similar to the functionality for AMT transmissions. For ATs the activation either triggers an opening of the torque converter lockup clutch (with gear still engaged) or shift into neutral.	As above
Predictive cruise control / use case 1: Crest coasting	In a pre-processing step segments in the cycle are identified where PCC might be active. This is done by determining positions in the cycle (X_{Vlow}) with a minimum negative slope Sl_{PCC} of which the vehicle would start accelerating without power supplied by the engine and considering the preview distance. In the actual simulation run within a PCC segment use, case 1 is set active in case the following conditions are met: • The current vehicle speed is higher than the target speed minus a defined hysteresis (8 km/h). • The sum of kinetic and the potential energy at the current position is predicted to be higher compared to the sum of energies on certain relevant positions during the PCC event. • The vehicle position is before the position of X_{Vlow} in the current PCC segment. During the use case 1 event the engine is operated in fuel cut-off (without Eco-roll), operated in idle speed (in combination with Eco-roll) or shut down (in combination with Eco-roll and engine stop-start) until either target speed + 1 km/h is reached or the slope is higher than Sl_{PCC}	The pre-processing is split from the actual in-the-loop simulation performed to optimise VECTO simulation time. PCC is only set active on highway parts i.e. on the long haul cycle and on the part from km 29.760 to km 96.753 on the regional delivery cycle and if the target speed is equal or higher than 80 km/h.
Predictive cruise control / use case 2: Acceleration without engine power	Pre-processing as above In the actual simulation run within a PCC segment use case 2 is set active in case the following conditions are met: • Use case 1 is not active • The vehicle position is after the position of X_{Vlow} in the current PCC segment. • The current vehicle speed is higher than the target speed minus a hysteresis (8 km/h). • The sum of kinetic and the potential energy at the current position is predicted to be higher compared to the sum of energies at the end of the PCC event. During use case 2 vehicle control performs similar as described for use case 1.	As for use case 1.

[26] According to the information from AT transmission manufacturers "Eco-roll with engine stop start is currently not relevant for vehicles with AT transmissions as.

ADAS functionality	Simulation approach (simplified explanation)	Remarks
Predictive cruise control / Use Case 3: Dip coasting	Use case 3 is considered in VECTO by increasing the parameter "overspeed" from 2.5 km/h to 5 km/h. This parameter defines the positive speed hysteresis the vehicle is allowed to accelerate in downhill conditions above target speed.	This simplification compared to the real world system behaviour (where PCC triggers the increased overspeed only for short periods of driving at the very end of downhill sections) is valid as the total energy balance over the cycle stays the same. Only the average cycle speed is biased by a very small amount.

Table 24 and Table 25 summarise the generic control parameters currently implemented in VECTO. Those numbers are based on the recommendations given in the ACEA White books [2], [3]. An independent verification of those parameters was not possible within the project as this would require real world testing of several truck models. Measurements were not part of the current project. Industry announced that they will investigate on the influence of the parameters in the phase 2 VECTO implementation and compare results with savings as calculated by their in-house tools. Thus, it is recommended to review those parameters in a next VECTO board meeting. This issue is further discussed in section 2.2.4.

Table 24: Generic control parameters Eco-roll (w/o PCC)

Eco-roll parameter (only relevant w/o PCC)	Unit	Value
Minimum speed	km/h	60
Activation delay	s	2
Underspeed threshold	km/h	0
Estimated acceleration MIN for activation	m/s²	0
Estimated acceleration MAX for activation	m/s²	0.1

Table 25: Generic control PCC

PCC parameter	Unit	Value	Comment
Vehicle underspeed hysteresis	km/h	8	
Vehicle overspeed hysteresis for v_{pos}	km/h	5 (w/ use case 3) 2.5 (w/o use case 3)	
PCC lower limit v_{active}	km/h	50	Relevant for usecase 2
PCC enabling velocity	km/h	80	Minimum target velocity for PCC
PCC preview distance $d_{preview}$ use case 1	m	1500	
PCC preview distance $d_{preview}$ use case 2	m	1000	

A VECTO beta version was released to industry for testing in Sept '19. The general feedback was very positive. Several test cases were provided by industry which have been used for improving of algorithms and bug fixing.

To demonstrate the CO_2 benefit of ADAS as calculated based on the phase 2 implementation all 17 combinations of ADAS systems have been calculated for a group 5 vehicle. The CO_2 savings compared to a vehicle without ADAS are given in Table 26.

Table 26: ADAS – CO_2 savings for a group 5 vehicle (phase 2 implementation) compared to w/o ADAS

Comb-ination nr.	ESS during vehicle stops	Eco-roll without ESS	Eco-roll with ESS	PCC (1, 2)	PCC (1, 2, 3)	Group 5									
						Long Haul				Regional Delivery				Urban Delivery	
						ref. payload	low payload	EMS ref. payload	EMS low payload	ref. payload	low payload	EMS ref. payload	EMS low payload	ref. payload	low payload
1	yes	no	no	no	no	-0.1%	-0.1%	-0.1%	-0.1%	-0.5%	-0.6%	-0.4%	-0.5%	-1.9%	-2.6%
2	no	yes	no	no	no	-0.1%	-0.1%	0.0%	0.0%	-0.1%	-0.2%	0.0%	-0.1%	0.0%	0.0%
3	no	no	yes	no	no	0.0%	-0.1%	0.0%	0.0%	-0.1%	-0.3%	-0.1%	-0.2%	0.0%	0.0%
4/1	no	no	no	yes	no	-0.3%	-0.1%	-0.4%	-0.2%	-1.1%	-0.6%	-1.2%	-0.8%	0.0%	0.0%
4/2	no	no	no	no	yes	-0.7%	-0.2%	-0.9%	-0.3%	-1.6%	-0.8%	-1.7%	-1.1%	0.0%	0.0%
5	yes	yes	no	no	no	-0.1%	-0.2%	-0.1%	-0.1%	-0.6%	-0.8%	-0.4%	-0.6%	-1.9%	-2.6%
6	yes	no	yes	no	no	-0.1%	-0.1%	-0.1%	-0.1%	-0.6%	-0.9%	-0.5%	-0.7%	-1.9%	-2.6%
7/1	yes	no	no	yes	no	-0.4%	-0.2%	-0.5%	-0.3%	-1.6%	-1.2%	-1.5%	-1.3%	-1.9%	-2.6%
7/2	yes	no	no	no	yes	-0.8%	-0.2%	-0.9%	-0.3%	-2.1%	-1.4%	-2.1%	-1.6%	-1.9%	-2.6%
8/1	no	yes	no	yes	no	-0.6%	-0.3%	-0.7%	-0.2%	-1.2%	-1.1%	-1.2%	-1.1%	0.0%	0.0%
8/2	no	yes	no	no	yes	-1.1%	-0.4%	-1.2%	-0.4%	-1.8%	-1.3%	-1.8%	-1.5%	0.0%	0.0%
9/1	no	no	yes	yes	no	-1.1%	-0.4%	-1.0%	-0.3%	-1.6%	-1.6%	-1.5%	-1.5%	0.0%	0.0%
9/2	no	no	yes	no	yes	-1.5%	-0.5%	-1.6%	-0.5%	-2.2%	-1.9%	-2.1%	-1.8%	0.0%	0.0%
10/1	yes	yes	no	yes	no	-0.7%	-0.4%	-0.8%	-0.3%	-1.7%	-1.7%	-1.6%	-1.6%	-1.9%	-2.6%
10/2	yes	yes	no	no	yes	-1.1%	-0.4%	-1.3%	-0.4%	-2.3%	-1.9%	-2.2%	-1.9%	-1.9%	-2.6%
11/1	yes	no	yes	yes	no	-1.2%	-0.5%	-1.1%	-0.4%	-2.1%	-2.3%	-1.9%	-2.0%	-1.9%	-2.6%
11/2	yes	no	yes	no	yes	-1.6%	-0.6%	-1.6%	-0.6%	-2.7%	-2.5%	-2.5%	-2.3%	-1.9%	-2.6%

In the simulations the same vehicle specifications as applied in the elaboration of the phase 1 ADAS credits have been used. Those numbers hence allow for a direct comparison of results from phase 1 and phase 2 implementation. This comparison is given in Figure 8. The results for phase 1 include the "factor of conservatism" of 0.5, i.e. reflect the methods as currently operational in the official VECTO version. In general, the VECTO results based on phase 2 methods confirm the "raw" reduction potentials as determined by the work in phase 1 by predicting approximately twice the rates from the current numbers in the official tool.

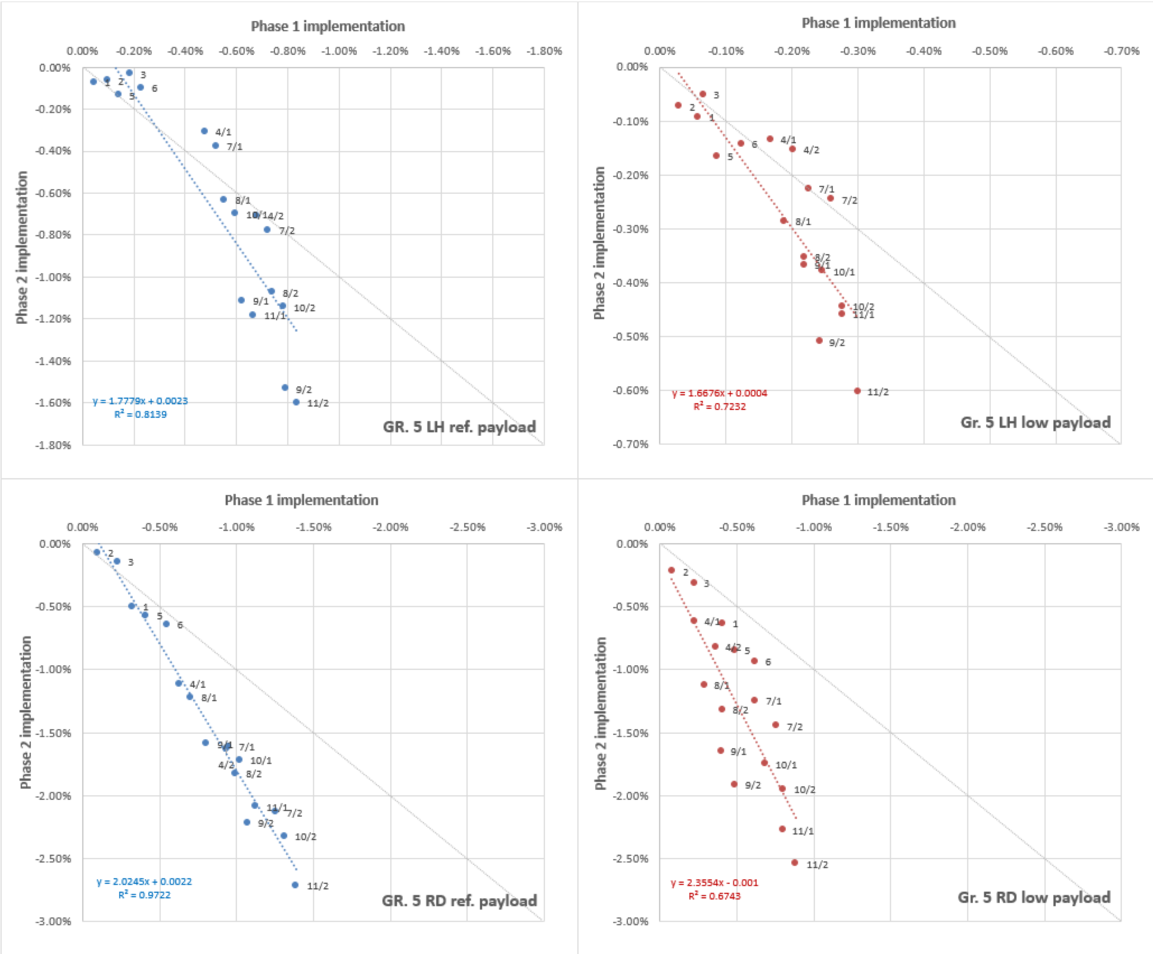


Figure 8: Comparison results for ADAS from implementation phase 1 (including "factor of conservatism") and phase 2 using the generic control parameter as shown in Table 24 and Table 25

From the figures above it can be concluded that once the methods of phase 2 are taken over into the official version of the VECTO tool, the CO_2 emissions calculated for a certain vehicle with ADAS might decrease by more than 5 g/km compared to the previous tool version. As a consequence a procedure to adjust the CO_2 values from the baseline year 2019 will need to be applied. In this adjustment procedure it will need to be considered, that the methods from phase 2 consider the actual vehicle specifications whereas the methods from phase 1 apply fixed CO_2 credits per ADAS technology. It is recommended to investigate on this circumstance based on a set of reference vehicles per sub-group (and not based on a single vehicle).

2.2.2.3 **Status quo and further recommendations**

A simple implementation to consider the most relevant ADAS systems in VECTO based on fixed CO_2 reduction rates was implemented until the end of 2018. This method is currently operational in the official CO_2 determination for the heavy lorry groups 4, 5, 9 and 10.

In a second implementation phase a more advanced generic in-the-loop simulation approach was elaborated. This approach allows for consideration of CO_2 impact of the main relevant ADAS functions considering the actual vehicle specifications and for in principle any kind of HDV configuration. The methods for phase 2 implementation could be taken over for official VECTO either in 07/2020 or in 07/2021 (however triggering a requirement to apply an adjustment procedure for the 2019 baseline) except for Eco-roll for AT transmissions. The latter AT system is not yet covered by Regulation (EU) 2019/318, hence this function can not be considered in VECTO before the next amendment of Regulation (EU) 2017/2400 comes into force.

Regarding the model settings used in the phase 2 methods it is recommended to further collect feedback from industry in a second feedback loop and agree on final parameter sets e.g. in a VECTO board meeting before the method is applied in the official version of the tool.

2.2.3 WP 2.3: Investigate compatibility of VECTO PCC approaches with forward looking model architecture

2.2.3.1 Description of task

The simulation approaches as elaborated in WP 2.2 were analysed for possible incompatibilities with a possible future transition of VECTO to a forward looking simulation algorithm. Since the main driver towards a forward looking VECTO tool might be the demand to include OEM specific control algorithms for engine, auxiliaries, gear boxes etc., also for ADAS systems smart control algorithms may be demanded to be considered as SIL or HIL in future.

2.2.3.2 Work performed and findings

The approach elaborated in the phase 1 implementation is based on a simple multiplicative approach where the final fuel consumption is multiplied by a factor of (1+CO_2 credit). Such a method could be applied to results from any simulation method. However, it is assumed that this approach will not be relevant in future as the phase 2 implementation is more accurate and more flexible.

As the generic algorithms as elaborated in phase 2 implementation define vehicle operation states (engine on/off, clutch actuation, vehicle target speed and throttle actuation) which are controlled by the ADAS functions, they can be also implemented in a straight forward manner into any longitudinal dynamics model with forward architecture.[27]

For the consideration of OEM specific control algorithms – which might be the main driver to change VECTO into forward architecture - the same general issues apply as for gear shift strategies. Hence in this regard all findings and recommendations as laid down in section 2.1.4 also apply here.

2.2.3.3 Status quo and further recommendations

The methods as elaborated in this project on consideration of ADAS impact on CO_2 are compatible with forward model architecture.

[27] In fact the implementation of any ADAS control algorithms as considered in phase 2 would be an issue with any classical "backward" simulation model. However, as VECTO is a not a simple backward model but features a superposed driver model, those issues do not apply for VECTO.

2.2.4 WP 2.4: Elaboration of a validation approach for VECTO reductions calculated for PCC influence

2.2.4.1 Description of task

A concrete and robust validation approach, either via testing or simulation or a combination of both, shall be provided in order to demonstrate that any reductions predicted by VECTO due to the use of ADAS technology remain realistic and reflect the actual performance of vehicles equipped with these systems.

2.2.4.2 Work performed and findings

Figures reported for real world fuel consumption benefit resulting from PCC systems vary widely. The range covers everything from some 1% (value from VECTO phase 2 implementation for a typical group 5 vehicle for current long haul cycle with low payload) to close to double-digit percentages. E.g. the well-known magazine lastauto omnibus in [8] reports fuel savings from PCC in a range of 6.7% to 9.3% measured with different PCC systems compared to the results of a skilled driver which was already familiar with the particular route.

This wide range of figures can be explained by the sensitivity of PCC to several influencing factors. Those are:

1. Features of the specific route profile

   The PCC functionalities as implemented by this project into VECTO are effective on hilly road sections but do not have any impact on flat routes or in pure uphill or downhill driving. Additionally also curvature and traffic conditions do limit the PCC effectivity.

2. Vehicle characteristics and payload conditions

   For a given route PCC typically gives higher fuel consumption benefits for high loaded vehicles and vehicles with low driving resistances (low C_dxA, low RRC)

3. Quality of control algorithms and interaction with other vehicle systems

   Of course the level of sophistication of implemented control algorithms and their interaction with other vehicle systems (e.g. gearbox and engine controls) have a significant impact on the resulting fuel efficiency gain. Furthermore, the actual vehicle mass has to be determined by vehicle control in a considerably accurate manner. As stated by manufacturers and confirmed by professional magazines, in this regard substantial improvements in control algorithms have been achieved since PCC systems have been introduced on the market in the early 2010s.

4. Quality of route data

   The quality of route data is essential for the effectiveness of PCC as the system is mainly active in the +1% to -2% gradient range and already a single tenth of a percent can decide for activation of ADAS. Current systems on the market use different sources of road gradient data. The main source is 3d map data from different data providers, for some OEMs supplemented by cloud data recorded by the vehicles in the fleet.

5. Driver preselection for balancing of fuel consumption and vehicle average speed

PCC use cases 1 and 2 (“crest coasting” and “acceleration without engine power”, descriptions see Table 23 on page 53) gain fuel efficiency on the cost of average speed.[28] In current vehicles, the controller offers the driver the possibility of a stepwise adjustment of the relevant settings (and in some systems on different levels) from an “Economy” mode to a “Fast” mode. As the daily schedule in transport business is known to be time-critical, it can be assumed that PCC systems are not always used in the maximum Eco-mode.

As in all aspects of the HDV CO_2 legislation, the goal for VECTO shall be to reflect fuel consumption benefits from PCC systems in real world conditions as representative as possible. To verify the results from VECTO by a straight forward test procedure based on fuel consumption measurements on a certain route driven w/ and w/o PCC engaged is not judged to be a not feasible option. Some of the reasons are that the test results on fuel consumption are additionally influenced by variation of ambient conditions and that any test route will have different gradient profiles and traffic conditions compared to the cycle defined in the HDV CO_2 mission profile in VECTO.

Alternatively, it is suggested to conclude on the validity of the VECTO results for fuel consumption and CO_2 emissions including the contribution of any ADAS system based on a chain of single validated elements:

I. Since VECTO uses a validated physical simulation approach regarding assessment of driving resistances, powertrain drag losses and energy balances, the fuel consumption resulting from a defined speed and altitude trajectory and engine stop phases can be assumed to be correct. This approach has been successfully reviewed and validated several times (e.g. [9], [10]). Thus, only a validation of the functions adjusting the vehicle speed and engine stops[29] have to be validated.

   This element covers influence factor “vehicle characteristics” as described above.

II. Thus, if an ADAS function is declared in the input to VECTO, it shall be possible to verify the presence of such a system based on real world driving and on system definitions matching with ADAS functionalities as implemented in VECTO. A first version of verification demand has already been incorporated into Regulation (EU) 2019/318. This topic is further discussed in section 2.2.5 below.

   This validation element mainly covers influence factor 3. (quality of control algorithms and interaction with other vehicle systems) and partly 4. (quality of road data) from above. Regarding 4. the validation only covers data related to road sections where the demonstration test have been performed. However, from test reports it can be concluded that currently data quality for the most relevant European transport routes is already on a very high level. Furthermore, it can be assumed that the data availability will further improve in future.

III. The third element in the validation chain is provided by the representativeness of the generic data of the mission profiles. The data used currently in VECTO has been validated in [1] and [12]. for representativeness of vehicle speed and acceleration patterns, however

[28] The PCC function use case 3 “dip coasting” both increases fuel efficiency and average speed. The limitation to this function is to not get in conflict with vehicle speed limits.

[29] The only “physical” element in the simulation approach which was added in the context of ADAS and not yet validated is the assessment of fuel consumption required to re-starting the engine. The impact of this energy demand on the overall fuel savings related to engine-stop-start systems is below 10%, so any related uncertainty is assessed to be acceptable.

hilliness has not been considered so far. ACEA claims that especially the current long haul cycle contains too few hilly sections and thus underestimates technologies like PCC but also hybridisation. Driven by this finding ACEA has subcontracted a study to analyse the hilliness of more relevant European routes and to elaborated updates on mission profiles if necessary. Interim results have been shared at the VECTO board meeting in January 2019. It is recommended to follow up those activities before the step 2 implementation of ADAS in VECTO is released into the official version of the tool.

This element covers influence factor “1. Features of the specific route profile” as described above.

IV. A further element of the validation chain is the representativeness of payload conditions used by VECTO to calculate weighted CO_2 figures per vehicles. This data has been elaborated in [11] in the context of development of CO_2 standards and there is currently no indication obvious that those figures should be revised.

V. The last influence factor which remains open for validation is item “5. Driver preselection for balancing of fuel consumption and vehicle average speed”. Currently these is no particular data on this issue available. However, in both implementation steps as worked out in this study did consider ADAS systems to be non effective to a certain amount. Implementation phase one introduces a “factor of conservatism” of 0.5 which has been applied in a final step when determine the CO_2 reduction rates for VECTO. Phase 2 implementation considers the influence of real world factors as follows:

- Engine-stop-start: Limitations in shutting down the engine are mainly seen resulting from energy demand of auxiliary units (e.g. need for charging of battery or for HVAC or air compressor operation). This is considered in the simulations via introduction of a utility factor (defined with 80%) and by restarting the engine after 120 seconds of continuous standstill.
- Eco-roll: Only a non-predictive functionality was considered which gives small benefits on CO_2. No further limitation factors have been identified.
- PCC: The main reducing factor is seen in driver interventions, which adjust the vehicle control settings to gain higher average speed compared to an “eco-mode”[30]. The main related parameter in the VECTO model is the underspeed hysteresis (i.e. the maximum underspeed the driver tolerates compared to cruise control set speed). The generic parameters for vehicle underspeed hysteresis is currently defined with 8 km/h based on a recommendation by ACEA in their White book. Available systems on the market allow for maximum underspeed hysteresis of up to 10 km/h. Whether the value of 8 km/h reflects current average real world use can not be verified at the moment. Members of ACEA announced that they will further analyse the behaviour of the VECTO phase 2 implementation with several hysteresis settings as applied in their fleet. As already mentioned in section 2.2.2.3 it is proposed to review the generic control parameters used by the phase 2 approach before the method is applied in the official version of the tool.

[30] Based on the provisions as currently laid down in point 8.3 of Annex III any advanced driver assistance system declared in the input into the simulation tool shall by default be set to fuel economy mode after each key-off/key-on cycle.

2.2.4.3 Status quo and further recommendations

Based on the stepwise validation as described above it is concluded that the approach as elaborated by VECTO provides robust estimations for the real world benefit for the implemented ADAS functionalities. Items to be further investigated are mainly the representativeness of mission profiles (hilliness) and representative values for underspeed and overspeed hysteresis used by the generic ADAS algorithm in VECTO.

2.2.5 WP 2.5: Assess possible certification requirements for PCC/ADAS systems

2.2.5.1 Description of task

In WP 2.5 the technical requirements for the provisions related to ADAS technology in Regulation (EU) 2017/2400 have been assessed.

2.2.5.2 Work performed and findings

The current approach in Regulation (EU) 2017/2400 in principle foresees two different options to provide input into the simulation tool:

a) **Certification of input data** in case the specific performance of a component is measured by a dedicated test procedure and the resulting performance parameters are then compiled into a certified input file for VECTO.

b) **Declaration of input data** in case a certain input parameter (e.g. vehicle mass) or vehicle or component technology (e.g. auxiliary technology) is provided to VECTO without certification requirements. The validity of the input in this case has to be safeguarded by the process requirements as laid down in Annex II and by verification requirements to demonstrate the correctness of the input for the vehicles tested in the VTP according to Annex Xa.

Following the approaches as elaborated in WP2.2 it is straight forward that proving input information related to ADAS falls under option b). This is valid both for implementation phase 1 and phase 2.

<u>Provisions as elaborated for phase 1 implementation (i.e. Regulation (EU) 2019/318)</u>

The regulatory text as elaborated for phase 1 implementation consist of the parts:

Point 8.1: Definition of systems (see text in section 2.2.1.2 on page 43)

Point 8.2: List of possible combination of systems (see Table 18 on page 50)

To safeguard the input on available ADAS functions as defined above the accompanying points 8.3 and 8.4 were introduced to Annex III:

8.3 Any advanced driver assistance system declared in the input into the simulation tool shall by default be set to fuel economy mode after each key-off/key-on cycle.

8.4 If an advanced driver assistance system is declared in the input into the simulation tool, it shall be possible to verify the presence of such a system based on real world driving and the system definitions as set out in point 8.1. If a certain combination of systems is declared, also the interaction of functionalities (e.g. predictive cruise control plus eco-roll with engine stop-start) shall be demonstrated. In the verification procedure it shall be taken into consideration, that the systems need certain boundary conditions to be "active" (e.g. engine at operation temperature for engine stop-start, certain vehicle speed ranges for PCC, certain ratios of road gradients with vehicle mass for eco-roll). The vehicle manufacturer needs to submit a functional description of boundary conditions when the systems are "inactive" or their efficiency is reduced. The approval authority may request the technical justifications of these boundary conditions from the applicant for approval and assess them for compliance.

<u>Identified amendments to incorporate phase 2 implementation into a next amendment of Regulation (EU) 2017/2400</u>

In general, the switch in VECTO simulation methods from phase 1 to phase 2 does not require any changes in the regulatory text. Changes only refer to additional covered technologies and - if deemed necessary – more detailed verification requirements.

Point 8.1 (Definitions): Definitions for ADAS technologies in combination with AT transmissions need to be added. Drafts are given in section 2.2.1.2.

Point 8.2 (List of possible combinations): Combinations 3, 6, 9/1, 9/2, 11/1 and 11/2 can not be declared in case of AT transmissions.

Further verification requirements (related to points 8.3 and 8.4):

In the current framework as given by Regulation (EU) 2017/2400 there is no element where the provisions as currently stated by points 8.3 and 8.4 are subject to actual verification. The VTP as currently in force does not include such a requirement and also for the next amendment of Annex Xa DG GROW advised not to include verification requirements for ADAS functions. This appears reasonable as any ADAS related verification tests would add significant extra efforts and it appears very unlikely that - in the current CoP like VTP procedure - an OEM prepares a vehicle with incorrectly declared vehicle technologies.

For a later application of the VTP test procedure as a third party testing ISC test it appears worthwhile that verification requirements for ADAS are an available option. For this purpose it is recommended that the verification requirements as currently rather vaguely worded in point 8.4 should be formulated more precisely. Verification of any of the ADAS functions could be done based on real world driving on a suitable route with a sufficient length. Only recording of a certain set of CAN signals is required. Those CAN signals are:

- Vehicle speed
- Road gradient
- Engine speed
- Engine torque
- Engine coolant/oil temperature
- Cruise Control Set Speed

For each ADAS function (and for PCC for each use case) a checklist with criteria to identify the function during the trip in the measurement data could be elaborated, e.g.:

- Engine stop start system - use case “engine shut down”: Check if vehicle control turns of the engine after certain seconds of standstill automatically.
- PCC system - use case “crest coasting”: Check if vehicle control reduces vehicle speed by a certain minimum amount when driving over a crest fulfilling certain criteria.
- PCC system - use case “acceleration without engine power”: Check if at downhill driving after a use case “crest coasting” the vehicle acceleration is performed without engine power (just by gravitational force).

A crucial point in a PCC verification procedure is to define the hysteresis parameters (vehicle speed drop or increase against cruise control set speed) which the need to be verified for a successful check. Options are:

Option 1): take over the parameters used by the generic control into the system definitions in point 8.1. Such an approach would need careful preparation because it could lead to the situation that systems which can currently be declared in VECTO would then fall out of the scope of the regulation.

Option 2) An OEM is allowed to declare the values for the ADAS parameters used in the generic controls specifically for his vehicles. In this case the declared parameters could be used in the verification.

To decide on either Option 1) or 2), sufficient test data from real world trips and comparative simulations in VECTO would be required. In the current project there was no measurement budget available and the project duration was much too short to collect further data from industry after the completion of implementation phase 2. So, at the current point both options are not recommended.

The remaining option 3) is to keep the parameters used in the verification open to judgement of the executing approval authorities according to the general definitions already stated in point 8.4 of the current regulation.

2.2.5.3 **Status quo and further recommendations**

The technical requirements for the provisions related to ADAS technology in Regulation (EU) 2017/2400 have been assessed. For ADAS implementation phase 1 the regulatory text was elaborated in detail and adopted in Regulation (EU) 2019/318. For the implementation of the methods of ADAS phase 2 into the next amendment detailed recommendation are given. Those should be the basis for the drafting to be performed by the HDV CO_2 Editing board.

2.2.6 WP 2.6: Participate in data collection and analysis

Participation in data collection and analysis from tests executed by the industry or the Commission (JRC) was not possible as no testing activity was performed.

2.3 Task 3: Waste / Exhaust Heat Recovery (W/EHR) Systems

2.3.1 The Excess Heat Recovery Technology

Typical internal combustion engines in heavy duty missions convert approximately 40% of the chemical energy from the fuel into work provided at the crank shaft. The remaining energy is released to the environment via the exhaust gas, the engine coolant system and via the exhaust gas recirculation (EGR) cooler. This high share of energy lost to the ambient is available at rather low temperatures and thus can be converted to mechanical work only with low efficiency. Nevertheless, exhaust heat recovery systems are assessed to reduce the fuel consumption by approximately 2 to 3%, depending on the mission profile and the technology used.

Current exhaust heat recovery (EHR) systems use the waste energy in the exhaust gas and in the EGR cooler to run a so called Organic Rankine Cycle (ORC). In this cycle, an organic fluid is vaporised by the exhaust heat and then expanded in an expander machine (e.g. piston expander or scroll expander). Then the medium is condensed and brought to the starting pressure by a pump again (Figure 9).

The process only provides work as long as the exhaust temperature is above the condensation temperature. The condensation temperature is typically on coolant level.

The energy output of the system is the heat energy fed into the boiler minus the energy released at the condenser, minus the energy demand of the pump, minus mechanical losses.

Thus a high temperature of the heat source and a low condenser temperature gives higher power output from the expander[31].

[31] The cooling energy in Figure 9 is the integral of T*ds of the blue line, the heat energy is the integral of T*ds of the red line with T being the temperature and s being the entropy.

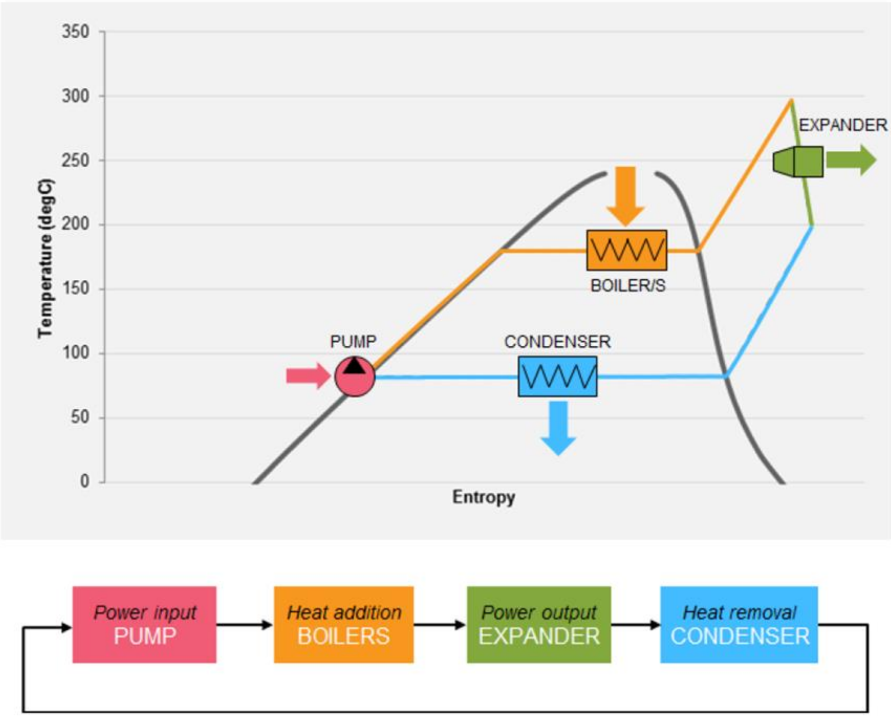


Figure 9: T-S diagram of Rankine cycle, [6]

With increasing exhaust temperature, the efficiency of the ORC increases as shown in Figure 10. Due to the thermal inertia of the exhaust system and of the ORC components, a stable efficiency of the ORC will be reached only at some minutes after torque and speed of the engine have stabilised at a certain load point.

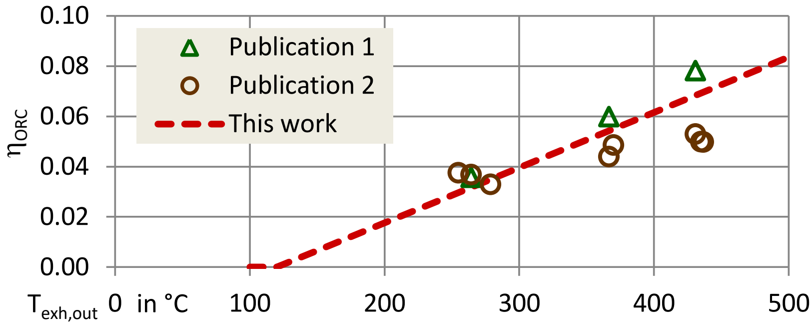


Figure 10: ORC efficiency as function of exhaust temperature [7]

This delayed response of heat recovery systems needed special care in the development of suitable test and simulation methods for the CO_2 determination of HDVs, which is discussed in chapter 2.3.3.

2.3.2 Analysis of the market situation

For the integration of WHR systems into VECTO and into the test procedures for the HDV components described in Regulation (EU) 2017/2400 the technologies expected in the future marked were analysed:

a) Expected energy source of the system (exhaust, EGR, coolant, others)
b) Integration level (part of the engine system, add-on box, others)
c) Output of the system (current & voltage and/or torque & rpm)
d) Energy storage (none, RESS[32], others).

These questions were discussed in the "WHR Expert group" and the assessment of the stakeholders was collected in a questionnaire.

The "WHR Expert group" had members from Borgwarner, Bosch, CLEPA, CNH, DAF, Daimler, DG Clima, DG JRC, ICCT, MAHLE, MAN, Scania, T&E, Volvo. One face to face meeting at TU Graz on 5th March 2019 and three Audioweb meetings were organised.

The questionnaire was answered by Borgwarner, CNH, DAF, Daimler, MAHLE, MAN, Scania and Volvo.

The results of the discussions and of the questionnaire on the expected market situation are summarised below.

As a heat source the exhaust gas is assumed to be the major component, EGR and coolant may also be used but rather in addition to the exhaust and not as standalone solutions (Table 27).

Table 27: Relevance of heat sources for WHR (1 = high, 5 low); feedback from the questionnaire (A to F represent different stakeholders)

	TUG	A	B	C	D	E	F
Exhaust Heat Recovery	1	1	1	1	1	1	1
Coolant Heat Recovery	4	4	3		3	3	3
EGR	3		3	3	4	5	3
Others	5		5			5	5

The relevance of installation options was assessed as follows in the questionnaire:

Option 1): Installed by OEM end of tailpipe; conversion to mechanical energy and recovered energy used by mechanical connection to drivetrain. Overall the ranking was 2, reaching from 1 to 3. The system has the best efficiency chain with current electric systems on HDVs since no conversion from/to electric energy is needed. With introduction of 48V mild hybrid systems the mechanical systems are assumed to be replaced by electric systems.

Option 2): Installed by OEM end of tailpipe; conversion to electrical energy; recovered energy used for electric system demand. Overall the ranking was 2, reaching from 1 to 3. With introduction of 48V mild hybrid systems more electrical driven auxiliaries will be on board consuming the energy produced by the WHR and also batteries with more storage capacity will be installed. Electric

[32] Rechargeable Energy Storage System, e.g. battery or capacitor

systems can be more flexible compared to the mechanical WHR systems since they can store energy produced during coasting and stop times. With current 24V electric board systems the electric energy consumption on board is too low to make such WHR options attractive.

Option 3): "Supplier system"; conversion to mechanical energy; certified separately independent of engine test. Overall the ranking was 3, reaching from 1 to 5. In general it was assumed that a mechanical integration is too complex to be attractive for systems delivered by suppliers.

Option 4): "Supplier system"; conversion to electrical energy; certified separately independent of engine test. Overall the ranking was 2, reaching from 1 to 3. Such a system is basically the only option to install a WHR without direct impact on OEM specific issues, such as the cooling system, the connection to the engine, load shift, etc. The limitations with current electric board systems are similar to option 2.

Within the WHR Expert group the options were discussed and it was agreed in the meeting in Graz to follow a WHR certification combined with the engine certification. An independent certification of WHR systems makes only sense, if similar systems are mounted without modifications to different engines. Such a development was not expected by the group. A separate WHR certification leads also to a more complex CO_2 determination for the HDVs, since the engine certification needs to provide information to calculate the exhaust gas mass flow and temperature levels for all different VECTO cycle/loading combinations as input for the simulation of the WHR power output.

As input to the development of suited methods for certification and for simulation in VECTO, the assessment of different options was asked in the questionnaire. The options have been explained in the meeting before:

- Consider WHR effect by WHTC correction factors only: not suggested since WHTC is not similarly representative for all VECTO missions.
- Consider WHR effect by engine map test plus WHTC correction factors: this option was the favourite solution in most responds. It was suggested to analyse the impact of thermal inertia on the engine map efficiencies in this method. Several proposals to improve and amend the method were provided by the expert group, which have been taken on board in the further development phase.

An important feedback concerned the physical test procedure, which needs a definition of the cooling conditions close to real world to avoid overestimations of the WHR power output by too high cooling capacities.

2.3.3 Simulation approaches for WHR Systems in VECTO

As described above, the measurement of the WHR system together with the engine was identified as most promising option. The base VECTO method, to measure the fuel consumption in the fuel map and to interpolate the fuel flow in each computation step from the simulated engine speed and engine torque got the highest rankings and was used as base case.

Since the fuel map is measured with only 55 seconds stabilisation phase before each load point, the temperature at the WHR heat exchanger (boiler) is influenced by the test point measured before due to the thermal inertia of the entire exhaust system (turbo charger, DOC, DPF, SCR and tubing). Since the VECTO fuel consumption mapping cycle (FCMC) is starting from the high power part of the engine map, the low load points have a higher temperature than in steady state conditions and thus the WHR power output will be overestimated. In contrary, the full load points are reached after idling load and thus have a lower temperature and lower WHR power output compared to steady state driving.

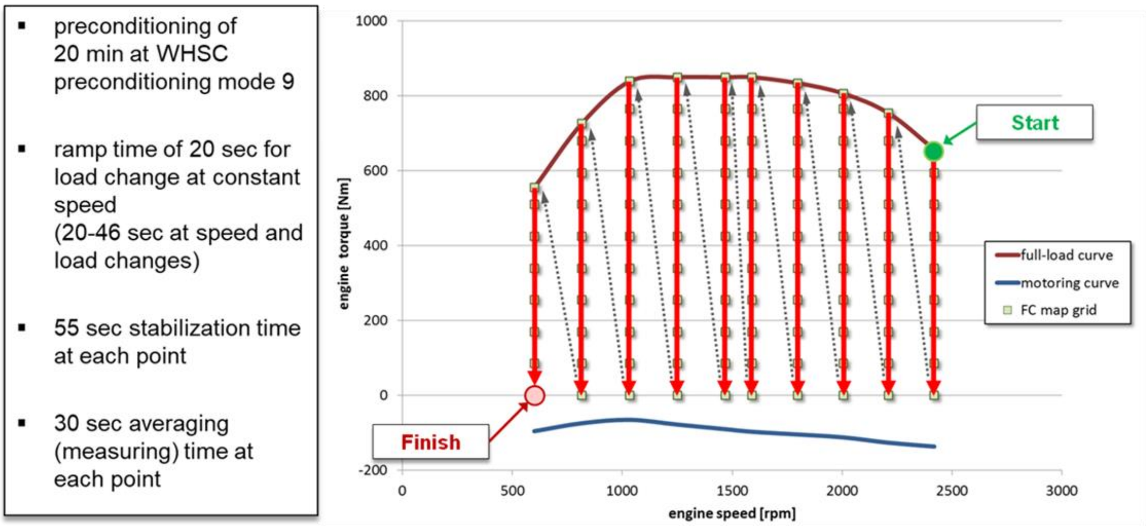


Figure 11: Schematic picture of the VECTO fuel consumption mapping cycle (FCMC)

This effect was expected in the method development and was confirmed by the analysis shown later in this chapter. Since changing the duration or the sequence of test points for WHR systems should be avoided, since conventional engines are already certified according to the current definitions, a proper correction of the results interpolated from the engine map is needed.

In a first step the correction factors based on the WHTC, implemented already in VECTO for calculating the final fuel consumption in the mission profiles for conventional engines were applied. In addition, the cold-hot-balancing factor based on the WHTC can also be applied to consider the cold start phases with heat up of the WHR system and thus no power output.

The development work was supported by measurements from MAN. In the tests a WHR system with exhaust gas as heat source and a mechanical connection to the engine, a 12.4 litre EURO VI engine with 346 kW, was measured on the engine test bed. Fuel flow, engine speed and torque as well as power delivered by the WHR system were measured in the fuel map cycle (FCMC), the cold and hot WHTC and in four VECTO cycles (regional delivers (RD) with low load and with reference load and in the long haul cycle (LH) again with low and reference load). The engine speed and torque trajectories for the VECTO cycles were simulated for a tractor trailer combination.

The validation of the methods to simulate the fuel consumption used the fuel map and the WHTC correction factors to calculate the fuel consumption in the four VECTO cycles. In a second step additional correction methods were applied to the result from the fuel map and WHTC correction as explained later. The cold-hot balancing factor was not applied, since the VECTO missions were tested in hot start conditions[33].

[33] The preconditioning of the VECTO cycles was always 15 minutes at 1200 rpm with 50% alpha (throttle position). This represents a higher average power than the power of the mission profiles, thus the WHR state at test start was rather hot.

The application of the WHTC correction factor proved to be very efficient to shift the WHR results from the rather hot conditions in the fuel map test towards the WHTC conditions in terms of exhaust gas temperature and WHR power output. The WHTC correction is a standard procedure in VECTO. The fuel consumption in the WHTC is measured and also interpolated from the fuel map. The ratio of measured to interpolated fuel consumption is the correction factor (Figure 12), which is calculated for the 3 parts of the WHTC separately. Depending in the mission profile, the 3 correction factors (urban, rural, motorway) are weighted to one WHTC correction (Table 28).

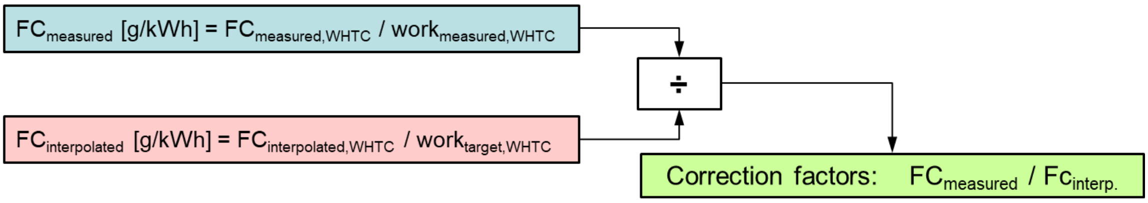


Figure 12: method to calculate the WHTC correction factors in VECTO

Table 28: weighting of the 3 WHTC correction factors according to the mission profile (VECTO cycle)

mission profile	$WF_{motorway}$	WF_{rural}	WF_{urban}
long haul	89%	0%	11%
regional	53%	30%	17%
urban	4%	27%	69%
municipial utility	2%	0%	98%
construction	6%	32%	62%
citybus	0%	0%	100%
interurban bus	19%	36%	45%
coach	78%	22%	0%

Figure 13 shows the results for the exhaust gas temperature upstream of the WHR boiler (T_{WHR}), interpolated for the four VECTO cycles. For this calculation T_{WHR} was interpolated from the fuel map and then the WHTC correction was applied as otherwise done for the fuel consumption. It can be seen, that the temperature from the interpolation overestimated the measured temperature. After the WHTC correction, the temperature levels meet the measured temperatures on average well.

However, for the low loaded cycles the temperature levels are still slightly overestimated, while for the high loaded cycles the temperature was underestimated. This is in line with the expectations from the fuel map test procedure, which overestimates low load map points and underestimates full load points. In addition the temperatures in the VECTO cycle tests were on a higher level than in the WHTC due to the preconditioning (WHTC was preconditioned according to Regulation (EU) 582/2011 with a cold start WHTC and a 10 minute stop phase before the hot WHTC[34]).

[34] Without the different preconditioning, the measured average VECTO cycle temperatures would be a bit lower than shown here. Which preconditioning reflects typical real world use is yet open, will be different between urban, rural distribution and long haul and possibly will be not relevant for the final test procedure. Thus the effect is mentioned here to understand offsets in the validation.

However, after the WHTC correction the offsets in the fuel map temperature is aligned to WHTC temperature levels. Cycles with low engine load (here RD_ll and LH_ll) have rather lower engine loads compared to the WHTC and thus also a bit higher offsets in the interpolated T_{WHR}. Cycles with high load (here RD_rl and LH_rl) have rather higher engine loads compared to the WHTC and thus a slightly lower offsets in the interpolated T_{WHR}.

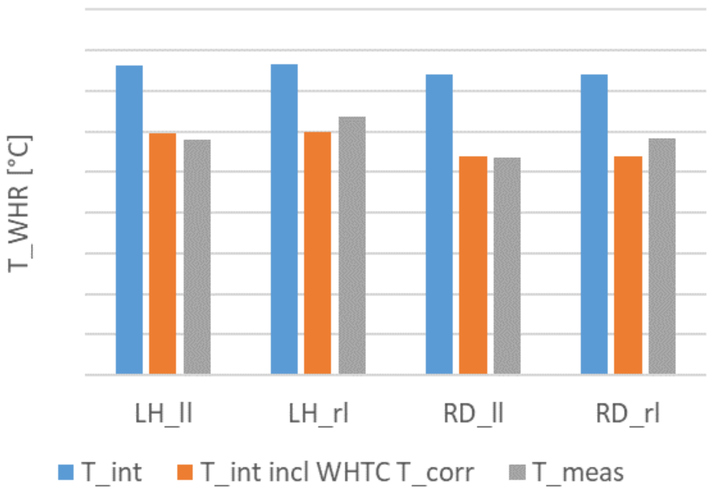


Figure 13: Comparison of measured and interpolated temperature upstream of the WHR boiler

The interpolation of the fuel consumption from the fuel map consequently leads to an overestimation of the fuel efficiency compared to the measured values in the VECTO cycles (Figure 14). This is well in line with the overestimation of T_{WHR} shown before. The WHTC correction shifts the fuel efficiency to the levels measured in the VECTO cycles. Again the effect is in line with the finding for T_{WHR}. The differences between measured and calculated fuel consumption after WHTC correction are in the range of 1%, looking at the weighted result between low and reference loaded cycles, the difference is close to zero.

As a conclusion we can state, that the WHTC correction shifts the results from the temperature levels of the FCMC to the WHTC-hot levels, which are more representative for real driving and the results have already a good accuracy. This statement is at least correct for the measured WHR system.

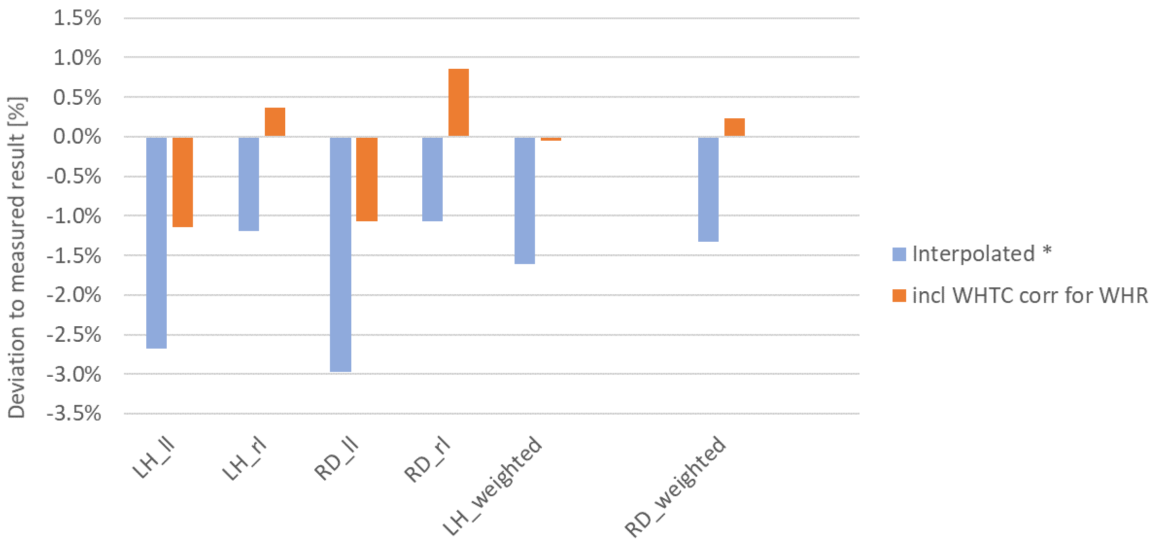


*Figure 14: Comparison of measured and interpolated fuel consumption in the VECTO cycles (*in the "interpolated" result, the WHTC corrections for the engine without WHR were applied)*

The same effect as in low loaded cycles will be seen, if a vehicle has a high power to mass ratio. In these cases the WHR efficiency may be slightly overestimated after the WHTC correction and vice versa for vehicles with low power to mass ratio.

Different options for an additional correction for this load influence were analysed ("WHR work correction"). In all cases the basic idea is the following:

- The average temperature T_{WHR} in the VECTO cycles is calculated.
- From the difference of the average T_{WHR} of the VECTO cycle to the WHTC-hot (measured) a correction of the resulting WHR work "W_{WHR_c}" is calculated.

This relative difference in WHR work is then added to the denominator in the g/kWh calculated from the fuel map and the WHTC-correction described before:

Equation 1

$$BSFC_{WHR\_c} = \frac{FC_{base}}{(W_{engine\ base} + W_{WHR_c})}$$

With:

$BSFC_{WHR\_c}$ ...... brake specific fuel consumption corrected for temperature offsets compared to WHTC level [g/kWh]

FC_{base} .... Fuel consumption in a VECTO cycle calculated from the fuel map interpolation and with WHTC correction [g]

$W_{engine\ base}$ .... positive engine work calculated in the VECTO cycle [kWh]

W_{WHR_c}............ correction of the WHR work delivered in the VECTO cycle to the cycle specific temperature level [kWh]

In case of overestimated WHR work in low load cycles, W_{WHR_c} is negative, the denominator is thus reduced and the g/kWh increase, i.e. the fuel efficiency drops. In case of high load cycles the opposite effect shall apply.

For the calculation of W_{WHR_c} according to ii) three options were analysed:

a) A correction according to the exhaust gas temperature
b) A correction according to the exhaust gas Enthalpy flow
c) A correction according to the exhaust gas Exergy flow

The Enthalpy flow represents the energy available in the exhaust gas mass flow:

Equation 2 $$\dot{H} = \dot{m} * C_p * (\dot{T}_{exh} - T_u)$$

The Exergy flow represents the maximum energy of the exhaust gas, which could be converted under ideal conditions (Carnot process) into mechanical energy:

Equation 3 $$\dot{E} = \dot{m} * \left\{C_p * (T_{exh} - T_u) - T_u * (C_p * \ln(\frac{T_{exh}}{T_u})\right\}$$

T_u.......... Ambient temperature, here defined with 20°C

c_p.......... specific heat capacity of the exhaust gas, here fixed with 1 kJ/kg*k

b) and c) have a quite similar effect, in a) the exhaust gas mass flow is not considered. Thus the same engine power at low engine speeds with low exhaust mass flows but high temperature has a too high energy rating compared to the same power at high engine speeds. For average values of real world cycles this effect may be negligible but physically more sounded are approaches b) and c).

The methods were again validated by comparison of the fully corrected fuel efficiency values in the VECTO cycles with the measured values for the engine with WHR. “Fully corrected” means the interpolation result from the fuel map with WHTC correction and the WHR work correction.

From the existing test data the temperature and exhaust gas mass flow in the VECTO cycles and in the WHTC was available. Thus for each cycle the average temperature, Enthalpy and Exergy was calculated from the test data on one correction version (“ideal correction”).

In the engine certification certainly no VECTO cycles can be measured, since different vehicle properties give different VECTO cycles for one and the same engine. Thus the temperature, Enthalpy and Exergy were interpolated from an extra stationary test, which would be needed for the additional WHR work correction. This test consisted here of 10 load points, which were measured until steady state conditions were reached at WHR. Then the steady state has not the offset from preconditioning of the test point measured before as discussed for the fuel map test.

Figure 15 shows the result of the stationary test for version c) of the WHR work correction. For each point the Exergy flow is plotted over the engine power and the WHR power output is plotted over the Exergy flow. For this test consequently the engine has to run once with the WHR active and once with the WHR deactivated (e.g. the boiler bypassed).

The application of the correction is as follows:

1) From the average positive engine power calculated with VECTO in a VECTO-cycle, the Exergy flow is calculated according to the regression line in Figure 15 left chart.
2) From this Exergy flow the corresponding average WHR power output in the VECTO cycle is calculated from the regression line in Figure 15 right chart.
3) From the measured Exergy flow in the WHTC the WHR power output is also calculated according to the regression line in Figure 15 left chart.
4) The difference between the WHR power calculated for the VECTO cycle and for the WHTC is converted into the difference of WHR work in the cycle (power * cycle time[s] / 3600) which then represents W_{WHR_c}. in Equation 1.

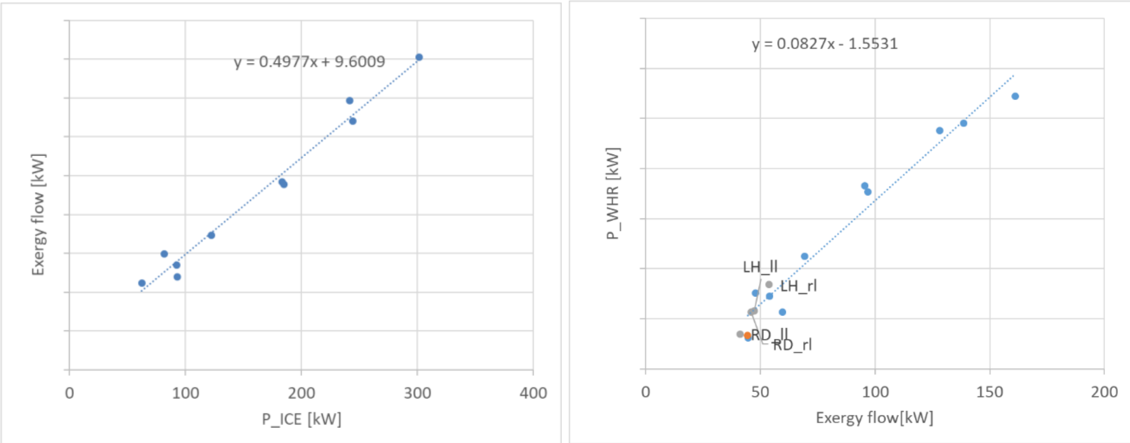


Figure 15: Example of the characteristic lines calculated from the extra stationary engine test for the WHR work correction method (version c))

In Figure 15 also the measured values for the VECTO cycles are shown in the right chart. The measured Exergy flow values have been used instead of the interpolated values for the "ideal correction" described above.

Figure 16 summarises the results for the four VECTO cycles simulated and for the weighted results from low and high loaded.

- The result "incl. WHTC correction for WHR" is the base approach explained above and shown already in Figure 14.
- The "ideal correction" is the benchmark for the additional "WHR work correction", where the measured values for temperature, Enthalpy- and Exergy flow are used, which are not available later in type approval.
- The "WHR work corr…" show the results with the WHR work correction method interpolating the temperature, Enthalpy- and Exergy flow from the extra stationary test.

The results suggest that the additional WHR work correction does not increase the accuracy of the results. The correction based on the correlation to the temperature before WHR leads to the highest deviations. Since it is also from the physical background rather incorrect, it may be omitted from further analysis in a pilot phase. The version c) based on the correlation to the Exergy flow is closest to the physical dependencies expected in the WHR system and may be further investigated in the pilot phase.

When interpreting the deviations against the measured fuel consumption it has to be considered, that the test results in the VECTO cycles were produced with different preconditioning than the WHTC and the stationary test. Thus, the corrections with WHTC-correction and with the WHR work correction produce a result for slightly different temperature conditions and an offset between measurement and simulation has to be expected even for a perfect correction.

In case that the WHR work correction shall be further elaborated in the pilot phase, an agreement needs to be found, which preconditioning is representative for the VECTO cycles (e.g. running 15 minutes the average rpm and torque from the cycle driven afterwards).

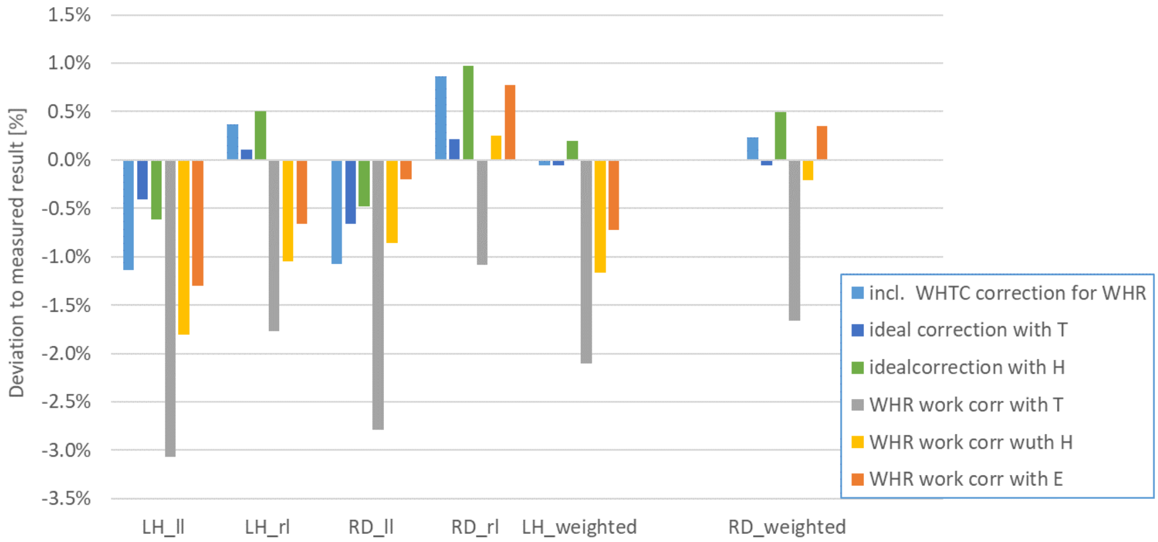


Figure 16: Deviations of fuel consumption simulated for VECTO cycles according to the different options against the measured fuel consumption

2.3.3.1 **Status quo and further recommendations**

The findings from the analysis and stakeholder consultations are:

- The basic approach with the engine fuel map and the WHTC correction function worked well for the tested engine. We assume the method will give similar accuracies for other WHR systems but this needs to be validated in an upcoming pilot phase (suggested to use pilot phase II of the DG grow project)
- The engine test procedure does not need amendments compared to the method for the conventional engines. Just the settings of the cooling system for WHR has to be defined to limit the maximum cooling power, as described later.
- For WHR systems which provide electric power as output, the same approach can be applied. For these systems an extra column in the fuel map and in the WHTC result data was added for the measured electric power. The measured electric power can be treated similar to the fuel flow, i.e. interpolation from the engine map and then application of the WHTC correction factor (which will be calculated by VECTO engine similar as for the fuel consumption). The total electric energy produced by the WHR in the cycle is then converted

in post processing into a fuel saving using generic alternator efficiencies for the conversion. This method is already implemented in VECTO to be tested in the pilot phase.

- For WHR systems which provide extra mechanical power as output, e.g. not connected to the crank shaft but to the power train downstream of the transmission, the same approach seems to be applicable. For these systems an extra column in the fuel map and in the WHTC result data mechanical power is introduced. The measured mechanical power can be treated similar to the fuel flow, i.e. interpolation from the engine map and then application of the WHTC correction factor (which will be calculated by VECTO engine similar as for the fuel consumption)
- How well the method works for electric systems and/or systems with external mechanical power delivery also needs to be tested in the pilot phase. The existing data indicates no concerns for such systems but without physical tests uncertainty remains.
- A further correction to consider also offsets due to different power/mass ratios of the vehicles in the VECTO cycle is theoretically possible but needs additional test efforts (stationary test of more than approx. 5 points with and without WHR active). For the WHR system tested here, this additional correction did not show pronounced benefits, which would justify these additional efforts and evaluation complexity. However, we suggest to include this WHR work correction also into the activities of the pilot phase. If it proves not to be effective for further WHR systems tested, the simple approach with the engine map interpolation and the WHTC correction is a good fall back option.
- Since the cooling power on board of HDVs is limited due to the possible dimensions of the heat exchangers, also the cooling power on the engine test bed shall be limited in the engine test procedures with WHR, i.e. in the fuel map test FCMC, the WHTC cold and in the WHTC hot. In on-road driving the maximum cooling power is proportional to the temperature difference between the WHR medium and the ambient air and to the coolant mass flow. Thus a generic equation for such a limit for the engine test bed may be:

  $P_{cool} = k * (T_{cond} - 20°C)$

  k .... generic factor, possibly different per vehicle group and mission

  T_{cond} ...... temperature of the WHR medium at the condenser of the WHR system

  Consequently also the temperature of the WHR medium at the condenser of the WHR system has to be defined, since this value influences the equation above and also the WHR power output directly from the energy balance (lowers heat released from the system and thus leaves more energy to be converted into work).

  The current idea is to limit the pressure of the medium of the WHR before entering the pump (i.e. after the condenser) to be at minimum at ambient pressure. This proposal is based on the simple assumption, that with high under pressure the expander and pump can hardly be tight over the lifetime. And that low pressures before the pump lead to quite high volume flows of in the gas phase. Details of this proposal need to be discussed during the pilot phase.

Thus it is concluded that WHR systems with mechanical and electrical power output can be integrated into VECTO for conventional vehicles.

For modelling of hybrid electric vehicles with WHR it is foreseen to feed the electrical power output from WHR into the VECTO model for the electrical system. This approach appears straight forward and shall be tested as well in the pilot phases in 2020.

2.3.4 WP 3.6: Check influence forward looking VECTO tool

The component test procedures and the simulation approach as described for WHR above have been analysed for potential incompatibilities with a possible future transition to a forward looking VECTO tool. As the approach is based on measured engine maps and WHTC based correction functions, no incompatibilities do exist. Also any of the candidates for “additional correction algorithms” as drafted in the section above do not have any implications on the core architecture of the simulation tool.

2.4 Task 4: Gas and dual-fuelled engines

Gaseous fuels with lower carbon content than diesel fuel pose the opportunity to reduce CO_2 emissions of vehicles. Currently several different concepts of gas-fuelled engine technologies exist. Those are either based on liquefied petroleum gas (LPG) or natural gas (NG). LPG is produced during refining of crude oil and mainly consists of propane or butane. Whereas NG is a naturally occurring hydrocarbon gas mixture consisting primarily of methane plus a varying amount of other combustible and inert gases.

In order to allow a certain driving range of the vehicle, NG needs to be stored in the vehicle tank under conditions that lead to a higher energy density per volume of fuel. Therefore, NG is either stored in gaseous phase under high pressure of around 200 bar (called CNG for compressed NG) or in liquid phase at very low temperatures of around -160 degrees Celsius and only slightly increased pressure of around 8 bar (called LNG for liquefied NG).

When this project was launched the fuel properties used in VECTO and in the VECTO engine evaluation tool were those of a generic NG and did not distinguish between CNG and LNG. However, typical CNG and LNG available on the European market vary quite significantly in their composition. Thus, commonly accepted standards for the fuel properties (lower heating value, carbon content) of both NG fuels, CNG and LNG, had to be elaborated and defined in the European CO_2 certification framework allowing a fair assessment of CO_2 emissions and fuel consumption of these fuels as compared to other technologies.

Furthermore, there are engine concepts close to market introduction that burn both diesel and gas fuels simultaneously in different relative shares depending on the operating conditions of the engine system. Those concepts, called dual-fuel engines, were so far not considered in the European CO_2 certification framework.

Therefore, two important topics needed to be addressed for this task:

1. Commonly accepted standards for the fuel properties for CNG and LNG needed to be elaborated and defined in the European CO_2 certification framework resulting in correct figures for CO_2 emissions and fuel consumption for such vehicles.
2. A holistic method for considering dual-fuel engines in the engine test procedure as well as in the vehicle simulation needed to be developed for the European CO_2 certification framework.

The related work performed and the methods elaborated are described below.

2.4.1 WP 4.1: Consultation of stakeholders on the simulation of gas and dual-fuelled engines

At the beginning of the project all HD engine manufacturers have been asked to provide feedback on:

- overview on engine technologies related to NG available or to be expected on the market within the next few years, and
- on how gas and dual-fuelled engines could be considered in the simulation in VECTO.

Based on the feedback it was agreed that:

1. The use of LNG should be accounted for in determination of CO_2 emissions by VECTO. Related methods should already be available in 2019, i.e. the necessary amendments to Regulation (EU) 2017/2400 needed to be incorporated in Regulation (EU) 2019/318 and into the official VECTO software until the end of 2018.
2. Methods related to determination dual-fuel engines should be elaborated, verified and implemented into VECTO until the end of the project. Those activities shall be followed up in pilot phase 2 as organised by DG GROW where related draft provisions are applied and any further feedback shall be collected for a final version.

Besides the two mentioned items no further needs for VECTO related to the use of gaseous fuels have been indicated.

2.4.2 WP 4.2: Report on current type approval of gas and dual-fuelled engines

Since the current engine test procedure for the European CO_2 certification is closely linked to the procedures for pollutant emission type approval, the base regulation on UN/ECE level – Regulation No 49 – was thoroughly scanned for items that could have an impact on the test procedures for gas and especially dual-fuelled engines. The main findings were:

1. Engine pollutant type approval does not differentiate between different NG supply systems to the engine, i.e. whether it is supplied from a compressed or liquefied storage system. In both cases the fuel is injected to the intake air or – in case of direct injection engines - to the combustion chamber in gaseous state. In order to do so in the fuel supply for LNG either flows through some kind of heat exchanger for injection into the intake air outside of the combustion chamber or the transition from liquid to gaseous state happens during the high pressure injection directly into the combustion chamber. Pollutant type approved NG engines can be either operated in combination with a CNG or LNG tank system (or even with both types of supply).

   As a consequence for the implementation in the European CO_2 certification method, the fuel properties cannot be defined on engine component level but need to be set on vehicle level, once the type of tank system is known. Thus, the fuel mass flow values in the engine fuel map for NG engines are standardized during the component test procedure to a net calorific value which is located somewhere between the one for typical CNG and LNG composition. In a second step, these standardized fuel mass flow figures are then converted in the vehicle simulation in the VECTO tool based on the specific energy content of typical CNG and LNG market fuels in Europe. More details and the respective standardized fuel properties used are explained in paragraph 2.4.3 below. Additionally, the method for standardizing and converting the fuel mass flow based on the specific energy content is explained in detail in Annex A.3.

   In addition, "G_R" reference fuel in accordance with UN/ECE Regulation No 49 was introduced as second reference fuel for NG engine testing, to allow testing for engines that have a specific calibration to be operated only on NG fuels with higher energy content.

   All these amendments mentioned above were already introduced with Regulation (EU) 2019/318.

2. For dual-fuel engines specifically, the most important finding is that there are several different sub-categories of these engines defined in UN/ECE Regulation No 49. The main distinctive features are:
    a. The “Gas Energy Ratio (GER)", which means the ratio (expressed as a percentage) of the energy content of the gaseous fuel over the energy content of both fuels (Diesel and gaseous) over the hot part of the WHTC.
    b. The possibility to operate in a pure Diesel mode for the so-called “type B” dual-fuel engines.

    Based on these two features, dual-fuel engines can be grouped into five different sub-categories as shown in Table 29 below, with the need to handle type B engines differently during the engine component test as well as during the VECTO vehicle simulation.

Table 29: Types of dual-fuel engines

Type of DF engine	GER	Operation in pure Diesel mode	Idling on Diesel fuel only
Type 1A	≥ 90%	Not allowed (only in dedicated service mode)	Not allowed (only in dedicated service mode)
Type 1B	≥ 90%	Allowed only in Diesel and in dedicated service mode	Allowed only in Diesel and in dedicated service mode
Type 2A	> 10% and < 90%	Not allowed (only in dedicated service mode)	Allowed
Type 2B	> 10% and < 90%	Allowed only in Diesel and in dedicated service mode	Allowed
Type 3A	Neither defined nor allowed		
Type 3B	≤ 10%	Allowed only in Diesel and in dedicated service mode	Allowed

These main findings set the baseline for the development of the procedure for dual-fuelled engines in VECTO described in paragraphs 2.4.4 and 2.4.5.

2.4.3 Draft necessary amendments to the existing technical annex to include LNG vehicles

To provide the information whether either compressed or liquefied natural gas is used by the vehicle, the VECTO input parameter "NG tank system" was added to the input data. As this parameter is linked to the vehicle configuration – and not linked to the engine certification – this parameter was incorporated into Annex III (input information relating to the characteristic of the vehicle) and already put into force with Regulation (EU) 2019/318. To cover also vehicles which provide tank systems for CNG and LNG in parallel[35], it is proposed for the next amendment of Regulation (EU) 2017/2400 to add the following provision: "In case both tank systems are present on a vehicle, the system which is able to contain the higher amount of fuel energy shall be declared as input to the simulation tool."

For correct calculation of CO_2 emissions of CNG and LNG vehicles in VECTO also fuel properties representative for average European conditions need to be considered. Those part of the generic parameters in VECTO and not part of the provisions of Regulation (EU) 2017/2400 and its amendments.

With the VECTO release end of 2018 all fuel properties used by the tool to calculate fuel consumption and CO_2 emissions have been updated. Furthermore LNG was added as a fuel type. As source the fuel data as elaborated by CONCAWE in 2018 for the 5th version on "Well-To-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context" have been used.[36] For CNG the properties of H-CNG (H… high calorific value gas) are used in VECTO. H-CNG represents the EU mix but with the L-CNG (L… low calorific value gas) excluded.[37] This set of fuel specification has been discussed and agreed with DG CLIMA. The complete set of fuel properties as part of the generic data in VECTO is given in Table 30.

[35] Such vehicle configurations where not mentioned by industry during the stakeholder consultation. However, current online HDV vehicle configurators indicate that such vehicles can be ordered.

[36] The complete study is announced to be published end of 2019. The data on fuel specifications was made available in spring 2018.

[37] L-gas is only available in some regions such as the Netherlands, Belgium, France and parts of northern Germany. It was decided to exclude L-gas in the average CNG specifications because picking a random CNG fuel station in the EU H-CNG will be correct in most cases, but wrong in case of L-gas. The average CNG mix would be little bit wrong in most cases, and quite a lot wrong in case of L-gas.

Table 30: VECTO fuel properties

Fuel type	Reference for fuel properties	Density	CO2 emission factor	Lower Heating Value
[-]	[-]	[kg/m³]	[g_CO2/g_Fuel]	[MJ/kg]
Diesel	B7	836	3.13	42.7
ED95	ED95	820	1.81	25.4
Petrol	E10	748	3.04	41.5
E85	E85	786	2.10	29.3
LPG	LPG	not required*	3.02	46.0
CNG	CNG (H-Gas)	not required*	2.69	48.0
LNG	LNG (EU mix)	not required*	2.77	49.1
* VECTO does not provide volume based figures for gaseous fuels				

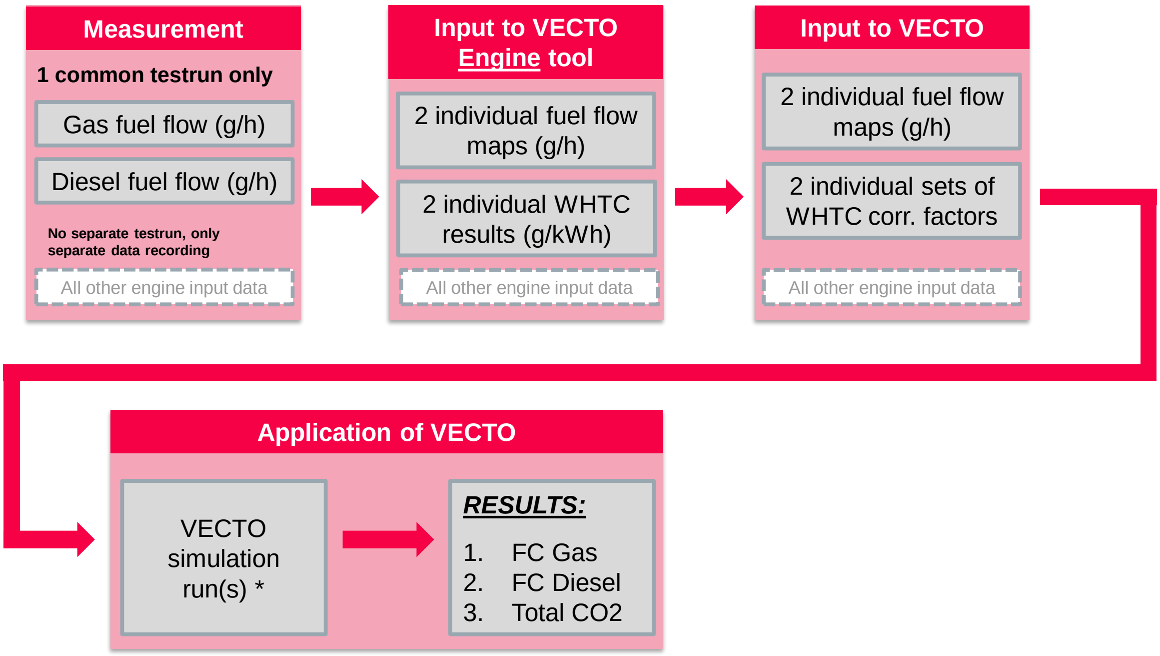
Differences in fuel properties of CNG and LNG are not only linked to the use of the fuel (e.g. liquefaction removes parts of the inert gases of the NG) but also to the geographical origin. So fuel properties of typical CNG and LNG used in Europe may change over the years. From a scientific point of view it should be considered to update the VECTO fuel properties on a regular basis based on actual market surveys. Such changes in fuel varying fuel properties of would have to be considered carefully in the context of the CO_2 emission standards for 2025 and 2030.

2.4.4 WP 4.3: Extend the existing engine test procedure for dual-fuelled engines

The first step in this work package was to discuss the findings from paragraph 2.4.2 with all relevant engine OEMs, most of them members of the former engine expert group that developed the methods and the original legislative text for engine component testing. As a result from this step a first draft was provided to engine OEMs in 08/2018 for review before a measurement campaign was planned to analyse the reachable accuracy with the envisaged method.

After the basic method was agreed between the engine experts, a working group where several experts on gas engines from different OEMs participated was established that elaborated the details of the test method as well as the measurement campaign. One OEM was willing to perform actual engine tests as foreseen in the detailed testing description. The description for the test runs to be performed as well as the methods for post-processing of measurement data were fine-tuned and provided to all members of the group. In parallel, TUG performed a similar measurement campaign in their lab in 10/2018 on a regular EURO VI Diesel engine to provide a reference value for the reachable accuracy to be used for comparison in the upcoming dual-fuel tests. The preparation of the dual-fuel measurements started in 01/2019 with the actual testing done in 04/2019. TUG supported the OEM experts during the whole period from preparation until the post-processing and evaluation of the recorded data. Even a special version of the VECTO Engine evaluation tool was provided in order to handle specific data characteristics that occurred during the measurement campaign.

The basic approach chosen for handling dual-fuel engines in VECTO is shown in Figure 17 below. The detailed description of the test campaign can be found in Annex A.4.



** **2 separate VECTO runs** for dual-fuel engines of **type B** (1B, 2B, 3B)*
(one in Diesel-only mode and one in Dual-fuel mode)

Figure 17: Basic method for dual-fuel engines in VECTO

As a result, the testing campaign showed that the reachable accuracy of the chosen approach is comparable to the one for a regular Diesel engine (detailed results in Table 31). Thus, the conclusion was that the approach is able to capture also the transient behaviour of a dual-fuel engine with a sufficient accuracy.

Table 31: Results of dual-fuel test campaign

Mission profile	regular EU-VI Diesel engine	Dual-fuel engine
long-haul cycle	+0.78%	+2.38%
urban-delivery cycle	+1.74%	+1.78%

Comments:

BSFC results (brake specific fuel consumption in g/kWh) from VECTO compared to measurement; results averaged over several repeated measurements; results weighted for different payloads according to declaration mode in VECTO

2.4.5 WP 4.4: Develop options to cover engine control strategies for dual-fuelled engines

The testing campaign described in paragraph 2.4.4 showed that the approach chosen seems to deliver reasonable accuracy, which is in the range as for a conventional Diesel engine. Engine fuel flow maps in combination with the whole set of correction factors derived from the WHTC data are deemed sufficient to capture the engine fuel control strategies.

However, there was only one dual-fuel engine tested – being of the type 1A – since there was neither a different type of engine nor any information available from OEMs if any other types of dual-fuel engines will be introduced in the near future. From a theoretical point of view the method should also work for all other types of dual-fuel engines and the characteristics of type B engines were already considered in the method development. Nevertheless, engine OEMs are encouraged to perform more testing during the pilot phase 2 foreseen for Q1 and Q2 in 2020 or once such systems are close to be introduced to the market.

2.4.6 WP 4.5: Draft necessary amendments to the existing technical annex to include dual-fuelled engines

From all the findings in the preceding work packages the following list of necessary amendments to the existing technical annex for engines was drafted in order to include dual-fuelled engines in the VECTO method.

Table 32: List of necessary amendments to technical annex

Item	Location in engine annex	Comment
Reference fuel	§ 3.2	Use of a second fuel needs to be introduced
Fuel flow measurement	§ 3.4	Measurement of fuel flow of second fuel needs to be introduced
Engine full load curve	§ 4.3.1	Measurement of two dedicated full load curves, one for dual-fuel mode and one for Diesel mode, needs to be introduced
WHTC / Measurement signals and data recording	§ 4.3.3.1	Measurement of fuel flow of second fuel needs to be introduced
WHSC / Measurement signals and data recording	§ 4.3.4.1	Measurement of fuel flow of second fuel needs to be introduced
Definition of grid of target setpoints	§ 4.3.5.2	Separate definitions based on the dedicated full load curve need to be introduced for dual-fuel engines of type B
FCMC / Measurement signals and data recording	§ 4.3.5.3	Definitions for data recording during the fuel flow mapping procedure need to be extended to dual-fuel engines

Item	Location in engine annex	Comment
Data evaluation for emission monitoring	§ 4.3.5.6	Definitions for data evaluation during the fuel flow mapping procedure need to be extended to dual-fuel engines based on the provisions defined in UN/ECE Regulation No 49 Type A and type B engines need to be addressed specifically for data evaluation
Validity of data	§ 4.3.5.7	Definitions for data evaluation during the fuel flow mapping procedure need to be extended to dual-fuel engines based on the provisions defined in UN/ECE Regulation No 49 Type A and type B engines need to be addressed specifically for data evaluation
Calculation of specific fuel consumption figures	§ 5.3	Provisions need to be adapted for a second set of data generated for the second test fuel
Correction factor for engines equipped with exhaust after-treatment systems that are regenerated on a periodic basis	§ 5.4	Provisions need to be adapted for a second set of data generated for the second test fuel
Application of engine pre-processing tool	§ 6	Input data format to VECTO Engine pre-processing tool needs to be extended for all values for second test fuel
Engine Information Document	Appendix 2	Data format template needs to be extended for all values for second test fuel
Conformity of CO_2 emissions and fuel consumption related properties	Appendix 4	Provisions and pass/fail statistics need to be adapted to handle a second set of data for the second test fuel
Input parameters for the simulation tool	Appendix 7	Data format needs to be extended for all values for second test fuel

If in future type B dual-fuel engines are announced to enter the market definitions need to be elaborated how to weight CO_2 emissions from “Diesel mode” and “Dual-fuel mode” to a consolidated CO_2 figure in VECTO. This task is not a technical issue but a strategic question to be discussed in the VECTO and/or in the HDV CO_2 Editing board.

2.4.7 Update VECTO for covering dual-fuelled engines

VECTO needed to be adapted to handle a complete second fuel dataset in order to be able to perform simulation of a dual-fuel vehicle. More details about the necessary adaption in the software are given in paragraph 2.5.4.

Furthermore, the VECTO Engine pre-processing tool needed to be adapted in the same way in order to provide the correct input data format of the engine component data to the VECTO tool. Therefore, the GUI needed to be extended for inputting a complete second dataset for the second test fuel. Also the internal data evaluation routines needed to be updated to handle the additional data.

During conducting the actual engine test campaign described in paragraph 2.4.4 experience was gained on what requires special attention in data evaluation for these specific type of engines. One example is that negative gradient for fuel mass flow with increasing load can occur which causes problems in the extrapolation routine for the fuel map to cover points in a certain tolerance area above the full load curve. Those features were implemented into VECTO Engine.

2.4.8 WP 4.6: Extend any generic data and respective lists in VECTO

For implementation of gas and dual fuelled engines the generic data related to fuel properties have been updated and extended. This work is described in section 2.4.3 (Draft necessary amendments to the existing technical annex to include LNG vehicles).

2.5 Task 5: VECTO software update

The TUG project team has developed the current version of the VECTO simulation tool and refactored the previous implementation to a modular, component-based architecture during the LOT4/SR7 project. The code-base of the simulation tool itself (i.e., without graphical user interface, test projects, component tools) has grown to more than 45kLoC[38]. More than 1500 test cases (unit tests, integration tests, and system tests) cover approximately 90% of the simulation tool codebase (without graphical user interface). The simulation tool has proven its capabilities by successfully simulating more than 200 000 vehicles produced by ACEA in 2016 for the purpose of the elaboration of future CO_2 limits. Official certification started on January 1st 2019 and in the first 6 months the number of reported vehicles with simulation aborts is estimated to be in the range between 0.1 % and 0.2 %.

For the implementation of further functionality according to tasks 1 to 4 applied the same methods and processes already established during the implementation of VECTO 3 in the LOT4/SR7 project. The lean software processes and workflows roughly follow the SPICE quality framework (ISO 15504, software lifecycle processes: ISO 12207). CITnet/JIRA has been used as issue-tracker for all new features or adaptations of existing features. All implementations were done in separate branches and then merged into the main development tree once the implementation is done. In addition to the implementation of functionality in the simulation tool itself, additional test cases for the new functionality have been implemented and run successfully and the documentation was updated accordingly.

The updates of VECTO according to tasks 1 to 4 were done in a development fork separated from the official VECTO version used for certification. This allows to maintain the current VECTO version and apply bug fixes and at the same time work on the development of the new features.

The implementation of new functionality according to tasks 1 to 4 has been done both in the engineering and declaration mode in parallel. The engineering mode allows for easily adjusting and exploring the effect of certain model parameters while in declaration mode generic values are used for most parameters. Development versions of VECTO including certain functionality implemented in tasks 1 to 4 (i.e., adapted gearshift models, ADAS simulation in the loop, etc.) were distributed to industry partners for further testing.

Task 5 is split into the following work packages:

- WP 5.1: Implementation, testing and optimization of gear shift model
- WP 5.2: Implementation, testing and optimization of ADAS model
- WP 5.3: Implementation, testing and optimization of W/EHR systems
- WP 5.4: Implementation and testing of dual-fuel and LNG

2.5.1 WP 5.1: Implementation, testing and optimization of gear shift model

The new gear shift model required certain adaptations of the VECTO architecture. Although the gearshift strategy was already a separate component model with a defined interface between the

[38] thousand lines of code

transmission model and shift strategy, certain extensions were required. As the new gearshift model triggers a gearshift based on the fuel consumption in the current gear and the estimated fuel consumption in the adjacent gears the shift strategy needs some means to estimate the fuel consumption in a certain gear.

Therefore, we extended the VECTO architecture in such a way that the gearshift strategy has a simplified copy of the component models used for the simulation that uses the same model data. This simplified copy of the simulated powertrain is kind of a meta-model of the real simulated powertrain and called test-powertrain. The benefit is that the shift strategy can initialize this test-powertrain in a certain state (vehicle speed, acceleration demand, etc.) with a certain gear and get the engine operating point for this state and thus the estimated fuel consumption in a certain gear. This estimation is the basis for deciding whether a gearshift is triggered as described in section 2.1. This meta-model also is a crucial part for connecting the gearshift model with the controller of a hybrid electric powertrain.

2.5.2 WP 5.2: Implementation, testing and optimization of ADAS model

The implementation of advanced driver assistant systems in phase 1 was done as a post-processing step. Depending on the vehicle group, loading, and cycle type a correction factor is looked up as provided in Table 19 to Table 22. The fuel consumption is corrected by this factor after the simulation.

For the phase 2 implementation the VECTO architecture was extended, existing component models were extended and the post-processing had to be extended. The central component for all ADAS functionality is the VECTO driver model. As the driver model is one of the first components that handles a request for simulating the next time interval it has the authority to control the subsequent components (i.e. switch off the combustion engine, disengage the gearbox, etc.) or perform the according driving action (perform a coast action during PCC events). Hence, the driver model was extended significantly to implement the ADAS functionality for in-the-loop simulations.

In order to consider engine stop/start the combustion engine model needs to support switching the combustion engine off. During engine-off periods the power demand of certain auxiliaries needs to be accounted as well as the number of engine starts. The fuel consumption for the auxiliary power demand as well as the power demand for starting the combustion engine is corrected in a post-processing step using the vehicle-line method.

Implementing predictive cruise control requires certain pre-processing steps. Hence, the VECTO architecture has been extended such that a component can register a so-called simulation-pre-processor. These pre-processors are called before the actual simulation so that the model can obtain vehicle and cycle specific parameters. For the predictive cruise control two pre-processors are necessary. The first pre-processor determines the road gradient where the vehicle accelerates on its own without engine power for different vehicle speeds. This is done on a test-powertrain as implemented for the gearshift strategy (see Section 2.5.1). In a second pre-processor the driving cycle is analysed and potential PCC-segments are identified (i.e. highway sections in the cycle where the road gradient is lower than the minimum slope required for vehicle acceleration without engine power and the target speed is constant). These PCC-segments are stored in the driver model and used as basis for deciding when to activate certain PCC events as described in Section 2.2.

Post-processing has been extended to correct the fuel consumption for the energy demand of certain auxiliaries during engine-off periods and energy demand for starting the combustion engine using the vehicle line.

2.5.3 WP 5.3: Implementation, testing and optimization of W/EHR systems

Three different W/EHR systems are considered in VECTO: (i) mechanical W/EHR connected to the combustion engine, (ii) mechanical W/EHR connected to the drivetrain, (iii) electrical W/EHR systems. The first one is covered by the engine test procedure and thus requires no adaptations in VECTO. The latter two, however, require certain changes. The input data structure has to be extended to allow specifying the electrical respectively mechanical power provided by the W/EHR system. Thus, the fuel consumption map contains two additional optional fields for the mechanical and electrical power from the W/HER system. The combustion engine model is extended by two additional maps, one for the electrical and one for the mechanical W/EHR system. During the simulation the generated electrical and mechanical power is interpolated from these maps in the same way as the engine's fuel consumption. Both the mechanical and electrical power are accounted separately. In a post-processing step the engine's fuel consumption is corrected for the electrical power from a W/EHR system considering the alternator efficiency and the mechanical power from a W/EHR system via the vehicle-line approach in the same way as engine stop/start correction.

2.5.4 WP 5.4: Implementation and testing of dual-fuel and LNG

To support dual-fuel engines the input data for VECTO needs to be extended in order to allow providing a second fuel-consumption map. VECTO moreover supports specifying engines operated in multiple modes (only in XML format), i.e., an engine that can be operated either in single-fuel mode or dual-fuel mode with different full-load curves in each mode. For dual-fuel engines the software implementation is in principle able to cover any combination of type of fuels (fuel A, fuel B to specified with a fuel identifier which refers to the engine fuel references in Annex V). Currently only the combination of Diesel with Natural gas is allowed in the input as only for this fuel combination the accuracy of the simulation approach and the technical feasibility was proven (see 2.4.4 for details). The simulator factory module generates additional simulation runs for each engine mode. For a dual-mode dual-fuel engine for example the number of simulation runs doubles.

The simulation of dual-fuel vehicles itself is not affected, the only difference is that for dual-fuel engines the fuel consumption is interpolated from two separate fuel-consumption maps. The fuel consumption is accounted for each fuel separately and the CO_2 figures are for both fuels together.

When combining dual-fuel engines with the other technologies added to VECTO (engine stop/start, W/EHR systems) the fuel consumption is corrected for every fuel separately and the final CO_2 emissions are obtained from the corrected fuel consumption.

3 Meetings

Table 33 lists the main meetings held with the Commission and stakeholders during the project duration.

Table 33: Meetings held during the project

Date	Location	Participants	Topic
2018-05-04	WebEx	DG CLIMA, DG JRC, TUG	Inception Meeting
2018-05-16	WebEx	ACEA (Scania), TUG	Gearshift models
2018-07-05	WebEx	ACEA, CLEPA, NGOs, DG CLIMA, TUG	ADAS, Gearshift models
2018-07-05	WebEx	CLEPA (AT OEMs), TUG	Gearshift models
2018-09-27	WebEx	ACEA (Volvo), TUG	Dual Fuel
2018-10-04	Graz f2f + WebEx	ACEA, CLEPA, NGOs, DG CLIMA, DG JRC, TUG	ADAS
2018-10-08	WebEx	ACEA, CLEPA, NGOs, TUG	Gearshift models
2018-10-30	WebEx	CLEPA (AT OEMs), TUG	Gearshift models
2018-11-27	WebEx	DG JRC, TUG	Gearshift models (CO2MPAS)
2018-11-29	WebEx	ACEA, CLEPA, NGOs, DG CLIMA, DG JRC, TUG	ADAS
2018-12-07	WebEx	ACEA, CLEPA, NGOs, DG CLIMA, DG JRC, TUG	ADAS
2019-01-22	WebEx	ACEA	ADAS
2018-01-29	Brussels f2f	ACEA, CLEPA, NGOs, DG CLIMA, DG GROW, DG JRC, TUG	VECTO Board
2019-02-04	WebEx	ACEA (Volvo), TUG	Dual Fuel

Date	Location	Participants	Topic
2019-04-09	Graz f2f + WebEx	ACEA, CLEPA, NGOs, DG CLIMA, DG JRC, TUG	ADAS
2019-04-12	WebEx	ACEA (Volvo), TUG	Dual Fuel
2019-04-26	WebEx	ACEA (Volvo), TUG	Dual Fuel
2019-05-13	WebEx	CLEPA (AT OEMs), TUG	Gearshift models
2019-06-05	WebEx	CLEPA (AT OEMs), TUG	Gearshift models
2019-06-18	Ispra	ACEA, CLEPA, NGOs, DG CLIMA, DG JRC, TUG	VECTO long term strategy workshop
2019-06-24	WebEx	CLEPA (AT OEMs), TUG	Gearshift models
2019-07-12	WebEx	ACEA, CLEPA, NGOs, DG CLIMA, DG JRC, TUG	WHR
2019-07-19	WebEx	CLEPA (AT OEMs), TUG	Gearshift models
2019-09-09	Graz	ACEA (MAN), TUG	WHR
2019-09-10	WebEx	CLEPA (AT OEMs), TUG	Gearshift models
2019-09-19	WebEx	ACEA, CLEPA, COM, TUG	VECTO Gearshift Models
2019-10-22	WebEx	CLEPA (AT OEMs), TUG	VECTO Gearshift Models
2019-11-06	WebEx	ACEA, CLEPA, TUG	VECTO Gearshift Models
2019-11-13	WebEx	ACEA, CLEPA, TUG	VECTO ADAS in-the-loop implementation
2019-11-18	WebEx	CLEPA (AT OEMs), TUG	Gearshift models
2019-11-22	WebEx	ACEA, CLEPA (AT OEMs), TUG	ADAS for AT transmissions

4 References

[1] Rexeis M., Quaritsch M., Hausberger S., et.al: VECTO tool development: Completion of methodology to simulate Heavy Duty Vehicles' fuel consumption and CO2 emissions: Upgrades to the existing version of VECTO and completion of certification methodology to be incorporated into a Commission legislative proposal; Specific Contract N° 4020112014/695203/SERJCLIMA.C.2 Framework contract CLIMA.C.2/FRA/2013/0007; By order of EUROPEAN COMMISSION, DG CLIMA; Report No. I 15/17/Rex EM-I 2013/08 1670 from 12.10.2017

[2] ACEA Workgroup CO2HDV: White Book on CO_2 declaration procedure HDV ACEA Workgroup-CO_2HDV, Version April 2016;. Document shared with the European Commission and their consultants

[3] ACEA Workgroup CO2HDV: White Book on CO_2 declaration procedure HDV ACEA Workgroup-CO_2HDV, Version September 2018;. Document shared with the European Commission and their consultants

[4] Rodríguez F. et al.: Market penetration of fuel efficiency technologies for heavy-duty technologies in the EU, the US and in China. The ICCT. White paper May 2017

[5] Rexeis M., Röck M., N. Ligterink, S. Hausberger et.al: Support for preparation of the impact assessment for CO2 emissions standards for Heavy Duty Vehicles; Final Report; Service Request 9 under Framework Contract no CLIMA.C.2./FRA/2013/0007; TNO report TNO 2018 R10332; 13.09.2018

[6] Frederick M. Huscher: Organic Rankine cycle turbine expander design, development, and 48 V mild hybrid system integration; BorgWarner Inc.; International Conference Baden-Baden, 2017

[7] Kies A.: A contribution to the analysis of fuel efficiency measures for heavy duty vehicles; Doctoral Thesis at TU Graz; 2017

[8] Lastauto omnibus, 1-2/2019, p.13ff

[9] Rodríguez F.: Fuel consumption simulation of HDVs in the EU: Comparisons and limitations. ICCT, 2018-03-06. https://theicct.org/publications/fuel-consumption-simulation-hdvs-eu-comparisons-and-limitations

[10] Georgios Fontaras: Development of a CO2 certification and monitoring methodology for Heavy Duty Vehicles – Proof of Concept. DG JRC 2014. doi: 10.2790/12582

[11] Rexeis M., Röck M., N. Ligtering, S. Hausberger et.al.: Support for preparation of the impact assessment for CO2 emissions standards for Heavy Duty Vehicles; Final Report; Service Request 9 under Framework Contract no CLIMA.C.2./FRA/2013/0007; TNO report TNO 2018 R10332; 13.09.2018

[12] Luz R., Rexeis M., Hausberger S., Schulte L, Hammer J., Steven H., Verbeek R., et.al: Development and validation of a methodology for monitoring and certification of greenhouse gas emissions from heavy duty vehicles through vehicle simulation,

Final report; Service contract CLIMA.C.2/SER/2012/0004; Report No. I 07/14/Rex EM-I 2012/08 699 from 15.05.2014

A. Annexes

A.1. Gearshift algorithms

A.1.1. **Nomenclature**

n_{idle}	Engine idling speed
n_{T99}	Engine speed where 99% of full–load torque is reached at lowest engine speed
n_{rated}	Engine rated speed
$T_{98max}(n_2)$	98% of maximum engine torque at n_2 engine speed
T_{99max}	99% of overall maximum engine torque
$T(P_{rated})$	Engine torque at rated point (rated speed and power)
$t_{lastshift}$	Time of last gearshift
$t_{between\ shifts}$	Time between gearshifts
t_{act}	Actual time step
$t_{lastUpshift}$	Time of last upshift
$t_{lastDownshift}$	Time of last downshift
$Downshift\ delay$	Minimum time delay for a downshift after an upshift
$Upshift\ delay$	Minimum time delay for an upshift after a downshift
n_{95h}	The highest engine speed where the power is 95% of the maximum power
$RatioEarlyDownshift$	Maximum gear ratio (axle + gearbox) for efficiency downshifts
$RatioEarlyUpshift$	Maximum gear ratio (axle + gearbox) for efficiency upshifts
P_{eng}	Actual engine power at current engine speed
$Peng\_max$	Maximum engine power at current engine speed
$T_{reserve}$	Torque reserve in % (1-((full load torque – actual torque)/ full load torque))*100
FC_{gear}	Specific fuel consumption (g/kWh cardan work) in a candidate gear
$FC_{current\ gear}$	Specific fuel consumption (g/kWh cardan work) in the current gear

$Rating\ current\ gear$	Minimum fuel consumption benefit of a candidate gear to make an EffShift happen (hysteresis function)
$i_{nextGear}$	Transmission ratio in the next gear
$i_{currentGear}$	Transmission ration in the current gear
$T_{\max\_stat}$	Maximum stationary engine torque
$T_{\text{eng}\_inertia}$	Engine inertia torque
$a_{estimated}$	Estimated acceleration in the next gear
$CCMinAcceleration$	Parameter for minimum acceleration after an upshift from 1C gear in 2C gear
$DriverAcceleration$	Demand driver acceleration according to the driver model
P_{acc}	Acceleration Power
v_{act}	Actual vehicle velocity
m_{veh}	Vehicle mass
m_{red_wheels}	Equivalent wheel mass
$P_{G\ b_{loss}}$	Gearbox losses
$P_{Axle_{loss}}$	Axle losses
$P_{Air\ drag_{loss}}$	Air drag
P_{RR}	Rolling resistance
P_{slope}	Resistance of grade
$maxGear$	Highest gear number of the transmission
v_{target}	Target speed
$UpshiftMinAcceleration$	Parameter for minimum acceleration after an upshift for locked TC
$CLUpshiftMinAcceleration$	Parameter for minimum acceleration after an upshift from open to locked TC
$Allowed\ gear\ range$	Number of allowed gear skips rfor shifts according to the efficiency shift rule
$DeltaFullLoad$	Difference to full load operation

A.1.2. **"EffShift" model**

A.1.2.1. Model structure

The shift strategy is on a first level based on gearshift lines for upshift and downshift (similar to the classic VECTO gearshift strategy). Additionally "Efficiency shifts" can be triggered between the shift lines, if the fuel efficiency (g/kWh cardan) in a candidate gear is better than in the current gear. To cover all possible efficient operation areas for any combination of engine map and transmission configuration, the "Efficiency shift" area between the downshift and upshift line has to be of sufficient size. Hence, the shift lines are defined as shown in Figure 18, with the downshift line (green) to the left and the up-shift line (red) to the right. Due to the superposition of the gear-shift lines with the EffShift algorithm as described below the upshift line is not relevant for upshifts in most cases.

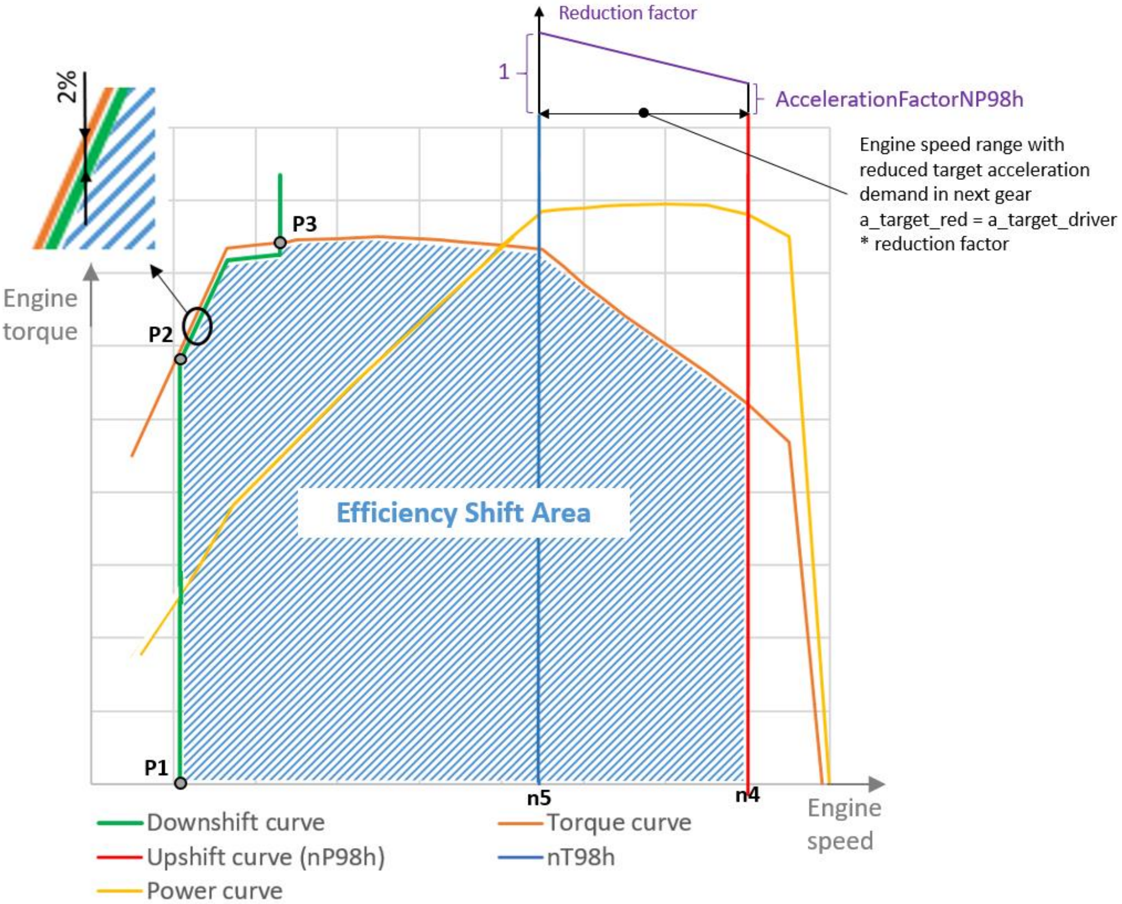


Figure 18: Shift lines for "EffShift" model with the downshift line (orange) to the left and the up-shift line (grey) to the right

The points P1 to P4 are calculated according to Table 34. The definition of the upshift line depends on the transmission type: for AMT, the pre-shift engine speed is considered for the upshift line and for AT the post-shift engine speed is used.

Additionally, the demanded acceleration to be available after a gearshift is reduced compared to the actual acceleration: This is done for engine speeds between n_T98h and n_P98h (Figure

13).This shall reduce reving up the engine during full-load accelerations. The demanded acceleration is calculated as follows:

$a_{demand} = a_{act} * a_{red}$ for $(n_{act} > n\_T98h)$ Equation 4

$a_{red} = 1 + \frac{(AccelerationFactorNP98h-1)}{n_{P98h}-n_{T98h}} * (n - n_{T98h})$ for $(n_{act} > n\_T98h)$ Equation 5

Table 34: Characteristic points for shift lines

Point / curve	Engine speed (n)	Engine torque /T)
P1 (downshift line)	$n_1 = n_{idle} * 1.1$	T_1 =0
P2 (downshift line)	$n_2 = n_{idle} * 1.1$	$T_2 = T_{98\,@\,n2}$
P3 (downshift line)	$n_3 = n_{T99\,low}$	$T_3 = T_{99\,low}$
n4 (upshift line)	$n_4 = n_{P98\,high}$	(vertical)
n5 (left boundary for engine speed range with reduced target acceleration demand in next gear)	$n_5 = n_{T98\,high}$	(vertical)

A.1.2.2. EffShift shift algorithm for AMT

The Effshift control algorithm differentiates between the shift rules:

- emergency shifts,
- polygon shifts, and
- efficiency gear shifts.

For the EffShift model general shift conditions apply regardless of the shift rule, with exception of emergency shifts, these have always priority.

The general gearshift conditions for downshifting are:

- $t_{lastshift} + t_{between\ shifts} < t_{act}$
- $t_{lastUpshift} + Downshift\ delay < t_{act}$

The general gearshift conditions for upshifting are:

- $Driver\ behaviour\ is\ accelerating\ or\ driving$
- $t_{lastshift} + t_{between\ shifts} < t_{act}$
- $t_{lastDownshift} + Upshift\ delay < t_{act}$

The general shift conditions are checked first in the shift algorithm. Table 35 lists the generic values for the parameters used in the declaration mode settings of current version of the AMT Effshift model.

Table 35: Parameters in the AMT Effshift model

Parameter	**Value**
$t_{between\ shifts}$	2 [s]
$Downshift\ delay$	6 [s]
$Upshift\ delay$	6 [s]
$Allowed\ gear\ range$	2
$RatioEarlyDownshift, RatioEarlyUpshift$	24
$Rating\ current\ gear$	0.97
$T_{reserve}$	0

A.1.2.2.1. Emergency shifts

Emergency shifts depend on the actual gear and the engine speed. The shifting rules for emergency shifts have been adopted from the “Classic” gearshift strategy in VECTO. In case of application of emergency rule no skipping of gears is applied.

Shift to neutral, if:

- Actual gear = 1 and
- $n_{eng} < n_{idle}$

Downshift conditions:

- Actual gear > 1 and
- $n_{eng} < n_{idle}$

Upshift conditions:

- Actual gear < highest gear
- $n_{eng} > n_{95h}$

A.1.2.2.2. Polygon shifts

The second level of the gearshift algorithm is the polygon shift rule. If the actual operating point is outside of the shift polygons (seeFigure 18), the polygon shift rule applies:

Downshift behaviour:

If the operating point (T_{eng}, n_{eng}) is left of the downshift line, shift to the next lower gear

Upshift behaviour:

If the operating point (T_{eng}, n_{eng}) is right of the upshift line, shift to the highest gear which is right of the downshift line and below the full load torque considering similar engine power output.

It should be noted, that there is no skip gears at downshifting in the polygon shift mode.

A.1.2.2.3. Efficiency shifts

The efficiency shift rule is added on top of the polygon shift rule. The EffShift strategy allows gear shifts if the current engine operating point is in between the gearshift lines and the combined fuel efficiency considering engine and gearbox characteristics in the candidate gear is better than in the current gear. Therefore the fuel consumption of the current gear and the gears within an allowed gear shift range (parameter allowed +/- gears) is calculated. For AMT transmissions, the current operating point is used for this efficiency evaluation. Since, the velocity drop due to traction interruption is not relevant for this evaluation as this operating point only occurs for a short period of time. Efficiency shifts are only allowed under a limited gear ratio (gearbox + axle) to prevent frequent gear changes in the very lowest gears.

$$FC_{gear} = \min\{FC_{gear+i}\} \ \forall i \in Allowed\ gear\ range \qquad \text{Equation 6}$$

Additionally the following boundary conditions must be fulfilled for an efficiency upshift to happen:

- $i_{gear+axle} \leq RatioEarlyUpshift$
- $Not\ left\ to\ downshift\ line$
- $1 - \frac{P_{eng(candidate\ gear)}}{P_{eng\_\max(candidate\ gear)}} > T_{reserve}$ $\qquad (T_{reserve}\ is\ set\ to\ 0\ for\ efficiency\ shifts)$
- $P_{eng_{act}} \leq P_{eng_{post\_shift}}$

  This condition is based on the assumption that sufficient power for the current acceleration is available in the next gear. The check for sufficient power in a candidate gear considers the velocity drop during traction interruption.
- $FC_{gear} < FC_{current\ gear} * HysteresisFactor$

For an efficiency downshift following conditions are met:

- $i_{gear+axle} \leq RatioEarlyDownshift$
- $Not\ right\ upshift\ line$
- $1 - \frac{P_{eng(next\ gear)}}{P_{eng\_max}} > T_{reserve}$ $\qquad (T_{reserve}\ is\ set\ to\ 0\ for\ efficiency\ shifts)$
- $FC_{gear} < FC_{current\ gear} * Rating\ current\ gear$

A.1.2.3. EffShift shift algorithm for AT

The model structure for shifting of “locked” gears for AT does not differ from the AMT algorithm. That means that the shift logic also differentiates between emergency shifts, efficiency shifts and polygon gearshifts and proceeds in the same sequence.

In addition rules for shifting of torque converter (TC) gears apply. These rules are described in this section. First step in the algorithm is the check of general conditions.

General gearshift conditions for downshifting:

- $t_{lastshift} + t_{between\ shifts} < t_{act}$

General gearshift conditions for the upshift in a locked gear (1C→1L, 2C→2L, L→L):

- $t_{lastshift} + t_{between\ shifts} < t_{act}$

Table 36 lists the generic values for the parameters used in the AT Effshift model.

Table 36: Parameters used in the AT Effshift model

Parameter	Value
$t_{between\ shifts}$	1.8 [s]
$Downshift\ delay$	6 [s]
$Upshift\ delay$	6 [s]
$Allowed\ gear\ range$ (skip of gears)	Total number of mechanical gears ≤ 6: 1; else: 2
$CCMinAcceleration$	0.1 [m/s²]
$CLMinAcceleration$	0.1 [m/s²]
$UpshiftMinAcceleration$	0.1 [m/s²]
$RatioEarlyDownshift$	24
$RatioEarlyUpshift$	24
$Rating\ current\ gear$	0.97
$T_{reserve}$	0

For triggering gear shifts between gears "1C" and "2C" (if applicable for a certain transmission) the same function as in the VECTO Classic model is applied.

Upshift between TC gears (1C → 2C):

- $n_{eng} > min\left\{700, (n_{80h} - 150) * \frac{i_{nextGear}}{i_{currentGear}}\right\}$
- $T_{eng} < T_{\max\_stat} - T_{\mathrm{eng}\_inertia}$
- $a_{estimated} > min\{CCMinAcceleration, DriverAcceleration\}$

With:

$$a_{estimated} = \frac{P_{acc}}{v_{act} * (m_{veh} + m_{red\_wheels}} \qquad \text{Equation 7}$$

and

$$P_{acc} = P_{eng\_max} - P_{G\ b_{loss}} - P_{Axl\ e_{loss}} - P_{Air\ drag_{loss}} - P_{RR} - P_{slope} \qquad \text{Equation 8}$$

A.1.2.3.4. Emergency shifts

The Emergency shift strategy for AT transmission looks as follows.

Downshift:

- $n_{eng} < n_{idle}$

Upshift (all conditions are met):

- $n_{eng} > min\{n_{\max}(gear), n_{95h}\}$

- $gear < maxGear$
- $a_{estimated} > 0$ (see Equation 7)
- $TC = locked$
- $Gear + 1\ is\ above\ downshift\ line$

A.1.2.3.5. Polygon shifts

The Polygon shift rule for AT works on the same principle as for AMT. But, as already mentioned above the calculation of the upshift line is based on the post shift engine speed. If the general requirements are fulfilled and it is not an emergency shift, the algorithm of the EffShift model uses the polygon shift rule. In this regard, two different cases related to a downshift are distinguished.

Conditions for downshift case 1:

- *Operation point* (T_{eng}, n_{eng}) *before downshift is left to downshift line.*

Conditions for downshift case 2 (all conditions have to be met):

- $DriverAction = Accelerating$
- $a_{act} < 0$
- $v_{veh} < v_{target} - 10km/h$
- $Locked\ gear$
- *DeltaFullLoad(gear – 1) < DeltaFullLoad(gear)*

Conditions for an upshift:

- *Operation point* (T_{eng}, n_{eng}) *before upshift is right to upshift line.*
- $a_{estimated}$ (see Equation 7) $> min\{UpshiftMinAcceleration, DriverAcceleration\}$ *(if TC is locked)*

  Or
- $a_{estimated}$ (Equation 7) $> min\{CLUpshiftMinAcceleration, DriverAcceleration\}$ *(if TC is unlocked)*

A.1.2.3.6. Efficiency shifts

The efficiency shift algorithm for AT works similar to the AMT algorithm (see A.1.2.2.3), in case of locked gears. In order to depict differences in gear selection which result from the different shifting sequences (AT: powershift, AMT: traction interruption) the operation points used for rating of fuel efficiency and for checking the power requirements in a candidate gear are calculated differently. More specifically, this assessment looks 0.8 seconds to the future, so that a relevant operating point after the shift is considered.

For up-shifts from a torque converter gear (“C”) to a locked gear (“L”) the relevant part of the VOITH gearshift model (see A.1.3) was taken over into the VECTO EffShift AT model.

Shift rules for L→L shifts (Efficiency shifts):

The search algorithm for the next gear is as follows:

$$FC_{gear} = \min\{FC_{gear+i}\} \ \forall i \in Allowed\ gear\ range \quad \text{Equation 9}$$

Additionally the candidate gear has to fulfil the boundary conditions below for an efficiency upshift.

- $i_{gear+axle} \leq RatioEarlyDownshift$
- $Not\ left\ to\ downshift\ line$
- $1 - \frac{Peng}{Peng\_max} > T_{reserve}$ $\quad (T_{reserve}\ is\ set\ to\ 0)$
- $FC_{gear} < FC_{current\ gear} * Rating\ current\ gear$

For an efficiency downshift following conditions are met for the potential gear:

- $i_{gear+axle} \leq RatioEarlyDownshift$
- $Not\ right\ upshift\ line$
- $1 - \frac{Peng}{Peng\_max} > T_{reserve}$ $\quad (T_{reserve}\ is\ set\ to\ 0)$
- $FC_{gear} < FC_{current\ gear} * Rating\ current\ gear$

Shift rules for C→L shifts (Efficiency shifts):

- The used algorithm can be summarised as follows:
  1) Definitions:

Table 37: Definitions for C→L shifts

Parameter	Unit	Description
torque ratio	[%]	current engine torque / maximum engine torque at actual engine speed
a_min	[m/s²]	available acceleration at actual engine torque for maximum loaded vehicle
a_max	[m/s²]	available acceleration at actual engine torque for empty vehicle
a_curr	[m/s²]	available acceleration at actual engine torque for current vehicle mass

  2) In each time-step a target post-shift engine speed from the shift strategy is calculated in a three step approach a. to c.:
     a. The current engine load stage is determined based on current torque ratio and a set of hysteresis thresholds (example see Table 38)
     b. For the current engine load stage and the current slope each a rpm value is interpolated from a parameter table (example see Table 39 for a_min and for a_max)

c. The final value for target post-shift engine speed is interpolated for the current value of a_curr from the results of step b.

3) If the estimated engine speed after a C→L shift is calculated to be equal or higher than the target engine speed as calculated above, the gear shift is initiated. This approach in combination with the proposed parameters as shown in Table 39 reflects the strategy the shifts from C→L are performed with absolute priority in order to minimise driveline losses from torque converter operation.

Table 38: Boundary values between engine load stages (values for torque ratio in [%]) (relevant for C→L shifts)

	1<->2	2<->3	3<->4	4<->5	5<->6
Hysteresis upper	19.70	36.34	53.01	69.68	86.35
Hysteresis lower	13.70	30.34	47.01	63.68	80.35

Table 39: Matrix with target post-shift engine speed defined as delta to engine idling speed (values in rpm, relevant for C→L shifts)

	a_max			**a_min**		
engine load stage	**slope ≤ -5%**	**slope 0%**	**slope ≥ 5%**	**slope ≤ -5%**	**slope 0%**	**slope ≥5%**
1	90	120	165	90	120	165
2	90	120	165	90	120	165
3	90	120	165	90	120	165
4	90	120	165	110	140	185
5	100	130	175	120	150	195
6	110	140	185	130	160	205

A.1.3. **“VOITH” model**

This algorithm is based on shift matrices for each gear shift with fixed values for post shift engine speed rpm as a function of engine load stage (torque ratio), gradient and acceleration. A detailed description of the “VOITH” gear shift approach can be found in the following slides.

Definition of load stages

VOITH

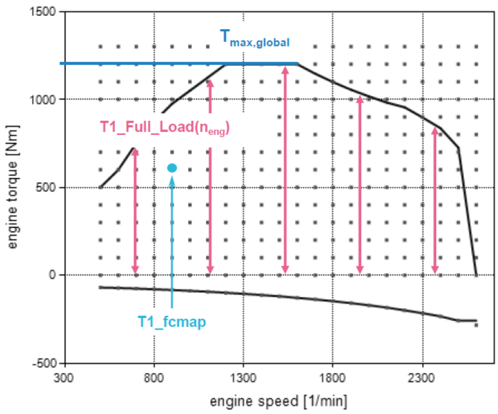
- Aceleration pedal position can be estimated from the torque ratio, which can be defined as below:

$$Torque\ Ratio = \frac{T1\_fcmap}{T1\_Full\_Load} * 100$$

where,

T1_Full_Load is the maximum available torque for the given engine speed from the full load curve.

T1_fcmap is the actual vehicle torque that is used to drive the vehicle.



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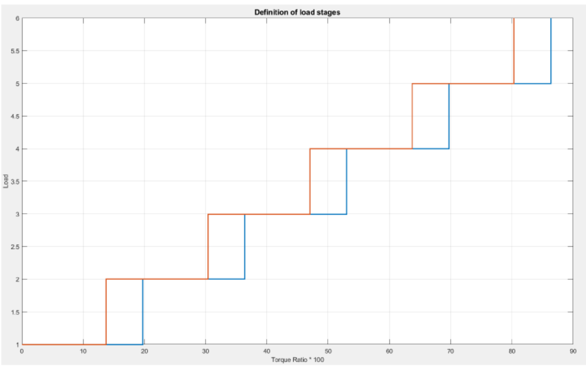
Definition of load stages

VOITH

- The variations of the torque ratio between 0-100 are equally divided in 1-6 load stages through an hysteresis as shown in the figure.



Torque Ratio [%] for Up				
19.7	36.34	53.01	69.68	86.35
Torque Ratio [%] for Down				
13.7	30.34	47.01	63.68	80.35

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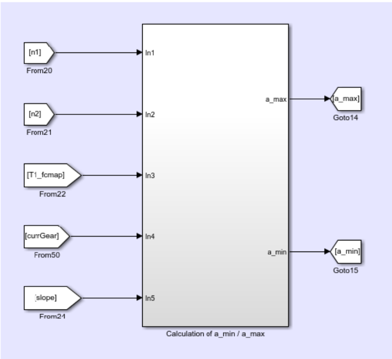
Calculation of minimum & maximum acceleration

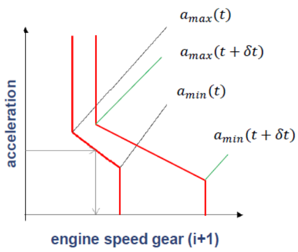
VOITH



$$a_{min} = \frac{F_z - F_w}{mVeh_{max}}$$

$$a_{max} = \frac{F_z - F_w}{mVeh_{min}}$$

a_{min}	Minimum vehicle acceleration
a_{max}	Maximum vehicle acceleration
F_z	Traction force
F_w	Driving resistance
$mFzg_{min}$	Minimum vehicle mass
$mFzg_{max}$	Maximum/Full vehicle mass



- The minimum and maximum values for vehicle acceleration are calculated for every time step.
- Hence, the new characteristic lines are created for each time step as well.

Load stages & shift points

VOITH

- Shift points are defined for basic slope lines corresponding to the uphill (5%), downhill (-5%) and plain (0%)
- One example of the shift points table is shown below:

	Slope		
	-5%	0%	5%
1	650	680	700
2	650	680	725
3	675	700	725
4	700	725	745
5	725	750	750
6	750	775	800

Note:
The maximum & minimum values of the slope (5%, -5%) are just assumed values and can be changed as required.

In real gear shift logics, the shift matrices of the VOITH model are individually adjusted and adapted for each vehicle. This approach is not possible in VECTO, hence one generic shift matrix has to be used. VOITH elaborated and provided shift parameters for a generic shift matrix with the main goal to close the gap between VECTO and real world for AT-P and AT-S. The generic parameters for upshifts and downshifts as well as for the definition of load stages are listed in Table 40 to Table 42.

Table 40: Upshift parameters of the generic shift matrix

Shift	engine load stage	a_max			a_min		
		slope ≤ -5%	slope 0%	slope ≥ 5%	slope ≤ -5%	slope 0%	slope ≥ 5%
1C-1L	1	650	680	725	650	680	725
	2	650	680	725	650	680	725
	3	650	680	725	650	680	725
	4	650	680	725	670	700	745
	5	660	690	735	680	710	755
	6	670	700	745	690	720	765
1L-2L	1	700	725	750	700	725	750
	2	700	725	750	700	725	750
	3	700	725	750	700	725	750
	4	700	725	750	720	745	770
	5	715	740	765	735	760	785
	6	725	750	775	745	770	795
2C-3L	1	735	760	785	735	760	785
	2	735	760	785	735	760	785
	3	735	760	785	735	760	785
	4	735	760	785	755	780	805
	5	785	810	835	805	830	855
	6	845	870	895	865	890	915
3L-4L	1	1075	1100	1125	1075	1100	1125
	2	1075	1100	1125	1075	1100	1125
	3	1075	1100	1125	1075	1100	1125
	4	1075	1100	1125	1095	1120	1145
	5	1075	1100	1125	1095	1120	1145
	6	1075	1100	1125	1095	1120	1145
4L-5L	1	1075	1100	1125	1075	1100	1125
	2	1075	1100	1125	1075	1100	1125
	3	1075	1100	1125	1075	1100	1125
	4	1075	1100	1125	1095	1120	1145
	5	1075	1100	1125	1095	1120	1145
	6	1075	1100	1125	1095	1120	1145
5L-6L	1	1075	1100	1125	1075	1100	1125
	2	1075	1100	1125	1075	1100	1125
	3	1075	1100	1125	1075	1100	1125
	4	1075	1100	1125	1095	1120	1145
	5	1075	1100	1125	1095	1120	1145
	6	1075	1100	1125	1095	1120	1145

Table 41: Downshift parameters of the generic shift matrix

Shift	engine load stage	a_max			a_min		
		slope ≤ -5%	slope 0%	slope ≥ 5%	slope ≤ -5%	slope 0%	slope ≥ 5%
1L-1C	1	625	655	700	650	680	725
	2	625	655	700	650	680	725
	3	625	655	700	650	680	725
	4	625	655	700	645	675	720
	5	635	665	710	655	685	730
	6	645	675	720	665	695	740
2L-1L	1	680	705	730	650	680	725
	2	680	705	730	650	680	725
	3	680	705	730	650	680	725
	4	680	705	730	700	725	750
	5	695	720	745	715	740	765
	6	705	730	755	725	750	775
3L-2L	1	710	735	760	650	680	725
	2	710	735	760	650	680	725
	3	710	735	760	650	680	725
	4	710	735	760	730	755	780
	5	760	785	810	780	805	830
	6	820	845	870	840	865	890
4L-3L	1	1050	1075	1100	650	680	725
	2	1050	1075	1100	650	680	725
	3	1050	1075	1100	650	680	725
	4	1050	1075	1100	1070	1095	1125
	5	1050	1075	1100	1070	1095	1125
	6	1050	1075	1100	1070	1095	1125
5L-4L	1	1050	1075	1100	650	680	725
	2	1050	1075	1100	650	680	725
	3	1050	1075	1100	650	680	725
	4	1050	1075	1100	1070	1095	1125
	5	1050	1075	1100	1070	1095	1125
	6	1050	1075	1100	1070	1095	1125
6L-5L	1	1050	1075	1100	650	680	725
	2	1050	1075	1100	650	680	725
	3	1050	1075	1100	650	680	725
	4	1050	1075	1100	1070	1095	1125
	5	1050	1075	1100	1070	1095	1125
	6	1050	1075	1100	1070	1095	1125

Table 42: Boundary values between engine load stages (values for torque ratio in [%])

	1<->2	2<->3	3<->4	4<->5	5<->6
Hysteresis upper	19.70	36.34	53.01	69.68	86.35
Hysteresis lower	13.70	30.34	47.01	63.68	80.35

A.2. Advanced Driver Assistance Systems (ADAS)

A.2.1. General approach to estimate change of fuel consumption based on change in required engine work over a cycle

The determination of the change in fuel consumption per change in ICE power is approximated as follows:

$$\Delta FC\ [g] = \Delta fc\ [\frac{g}{kWh}] * \Delta W\ [kWh]$$ Equation 10

With:

ΔFC	Change in fuel consumption in g
Δfc	Average change in fuel consumption per change in positive ICE power in g/ΔkWh
ΔW	Change in engine work over a cycle in kWh

Equation 10 is derived from a linear regression of the fuel flow and the positive power output (Figure 19).

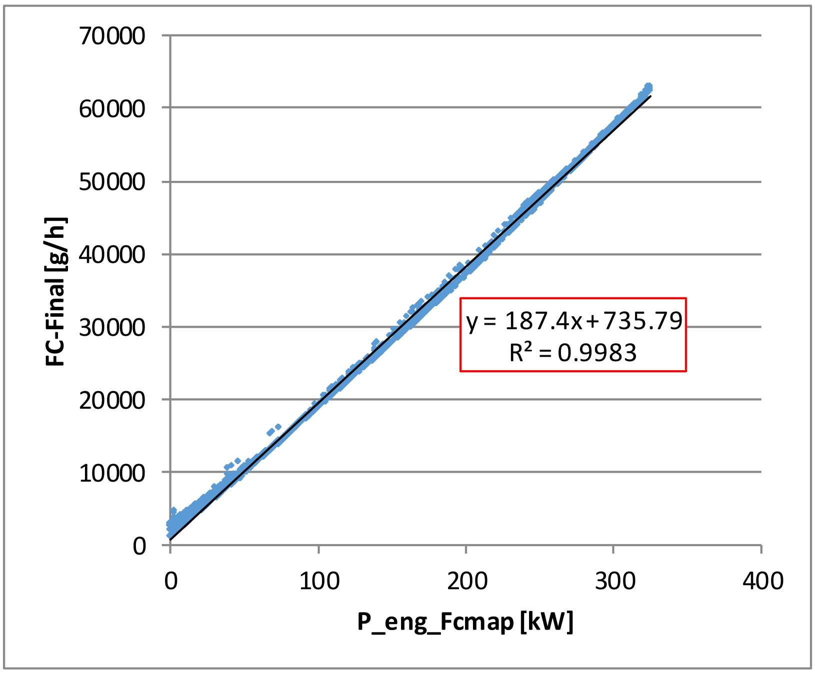


Figure 19: Regression for FC correction

The average change in fuel consumption per change in positive ICE power (Δfc) is based on VECTO simulations of “typical vehicles” described in A.2.2. This results in a figure of some 187.4 [g/kWh] for Δfc. This value was used for all vehicles of the entire phase 1 implementation.

The determination of Δfc the phase 2 implementation, is based on the above mentioned approach, but individual determined for each vehicle.

A.2.2. **Methods elaborated for phase 1 implementation**

The approach as implemented in phase 1 is to apply generic CO_2 credits to values for fuel consumption and CO_2 emissions.

*FC / CO2 incl. ADAS = FC / CO2 * (1 + CO_2 credit)*[39]

The CO_2 credits are determined separately for each combination of the following items:

- ADAS technology and all reasonable combinations (in total 17 combinations, based on the definition of single systems as listed in section 2.2.1.2)
- Vehicle groups 4, 5, 9, and 10 (the lorry groups which are regulated in the CO_2 standards legislation)
- Mission profile
- Payload

The generic CO_2 credits have been determined based on the work steps as listed below.

- Definition of ADAS functionalities taken from the ACEA White Book version April 2016 [2] and further discussions in expert group meetings
- Post-processing of instantaneous VECTO results for „typical vehicles“ to estimate potential fuel savings per ADAS technology. As “typical vehicles” the VECTO vehicle models as elaborated in [5] have been used. The main relevant vehicle specs are listed in Table 43 below. The post processing algorithms are described in section A.2.2.1.

[39] CO2 credits are defined calculated to have negative values

Table 43: Vehicle specifications

	Group 4 (LH, RD)	Group 4 (UD)	Group 5	Group 9	Group 10
Engine power [kW]	325	250	325	325	325
Displacement [ccm]	12700	7700	12700	12700	12700
Max. Torque [Nm]	2134 (1000-1400 rpm)	1295 (1100 - 1600 rpm)	2134 (1000-1400 rpm)	2134 (1000-1400 rpm)	2134 (1000-1400 rpm)
Rated speed [rpm]	1800	2200	1800	1800	1800
Idling speed [rpm]	600	600	600	600	600
Vehicle curb mass [kg]	8200	5633	8229	9300	9010
Engine peak BTE (%)	45.8	44.3	45.8	45.8	45.8
RRC [N/kN] (Steer/Drive/Trailer)	5.21/6.12/5.50	5.50/6.12	5.21/6.12/5.50	5.21/6.12/5.50	5.21/6.12/5.50
CdA [m2]	5.4	5.6	5.57	5.5	5.67
Transmission type	AMT	AMT	AMT	AMT	AMT
Efficiency indirect gear	96%	96%	96%	96%	96%
Efficiency direct gear	98%	98%	98%	98%	98%
Axle Ratio	2.64	4.11	2.64	2.64	2.64
Axle Efficiency	96%	96%	96%	96%	96%

A.2.2.1. Post-processing algorithms

The calculation approach for the phase 1 implementation was performed as post process using the VECTO output data. This approach provides fixed %-credits per vehicle group (4,5,9,10), mission profile and payload.

A.2.2.1.1. Engine stop-start during vehicle stops (ESS-VS)

The ADAS function ESS-VS covers all stops caused by traffic situations. Such a system is activated for the first 120 seconds of a stop. For the activation of the system, following criteria have to be fulfilled:

- $vact < 0.5 [kmh]$
- $tstop > 2 [s]$ (2 s delay)

with:

$vact$	Simulated actual vehicle velocity from VECTO
$tstop$	Stop time

The engine speed and thus the fuel consumption is 0 during engine off. The fuel consumption reduction is reduced by the energy request of the compressor, alternator and the air conditioning system during engine off as well as of the energy for the restart. Fuel saving for the phase 1 implementation of ESS-VS has been calculated based on Equation 11 to Equation 14.

$$\Delta FC = FC_{stop} - FC_{aux} - FC_{engstart}$$ Equation 11

$$FC_{stop} = \Sigma_{stop}(FC_{Final}) * \frac{t_{stop}}{3600}$$ Equation 12

$$FC_{aux_{ESS-VS}} = \Delta fc * (\Sigma_{stop} \frac{P_{aux} * t_{stop}}{3600})$$ Equation 13

$$FC_{engstart} = \frac{\frac{1}{2} * J_{eng} * \left(\frac{n_{idle} \pi}{30}\right)^2 * \Delta fc}{\eta alt}$$ Equation 14

With:

ΔFC	Change in fuel consumption
FC_{stop}	Fuel consumption during vehicle stop
$FC_{aux_{ESS-VS}}$	Fuel consumption induced from the auxiliary power for compressor, alternator and air conditioning during vehicle stop
$FC_{engstart}$	Fuel consumption for starting the engine
FC_{Final}	Instantaneous fuel consumption from the VECTO simulation
t_{stop}	Stop time
Δfc	Average change in fuel consumption per change in positive ICE power in g/ΔkWh, taken from the regression from Figure 19.
P_{aux}	Auxiliary power in
J_{eng}	Inertia moment of the ICE in kgm^2 (assumed with 5.5 kgm^2)
n_{idle}	Idling speed
ηalt	Alternator efficiency

For the calculation according to Equation 14, the inertia moment of the ICE was assumed to be 5.5 kgm^2 and the alternator efficiency to be 0.7.

A.2.2.1.2. Eco-roll

EcoRoll is decoupling of the engine speed from wheel speed during certain downhill driving conditions. A distinction must be made between:

- EcoRoll without engine stop

  The Engine is operating in idle speed during EcoRoll phases. Fuel consumption is reduced by reducing the engine drag losses.

- EcoRoll with engine stop

  The Engine has been switched off during EcoRoll phases. Thereby the reduction of fuel consumption is reached by a reduction of drag losses and fuel cut off.

The post processing algorithm identifies an EcoRoll phase if the following attributes are true for more than 1.9s:

- $slope < 0$
- $v_{act\_VECTO} > 60 \ and \ v_{act\_VECTO} > v_{targ}$
- $0 \leq a \leq 0.1 \ with \ a = \frac{F_{slope} + F_{air} + F_{roll}}{m_{veh} + mrot}$
- $P_{brakeloss} = 0$

With:

v_{act_VECTO}	Actual speed of from the VECTO output file
a	Acceleration without engine power (in sailing operation)
$P_{brakeloss}$	Power of brake losses in kW

During an EcoRoll situation a corrected velocity has been calculated. Therefore the current CdA value used by VECTO is calculated and with the corrected velocity from the previous simulation step corrected F_{air} and acceleration are determined.

Eco Roll is activated as long as following conditions are met:

- $v_{act} > v_{targ@start} - hysteresis^{-} \ and$
- $v_{act} < v_{targ@start} + hysteresis^{+} \ and$
- $slope < 0 \ and$
- $v_{act} = v_{targ@start} \ and$
- $P_{brakeloss} = 0$

With:

v_{act}	Corrected in post-processing during an EcoRoll event
$v_{targ@start}$	Target velocity at beginning of EcoRoll situation
$P_{brakeloss}$	Power of brake losses in kW
$hysteresis^{-}$	Vehicle underspeed hysteresis (set to 0 km/h for EcoRoll)

$hysteresis^{+}$	Vehicle overspeed hysteresis (set to 2.5 km/h for EcoRoll)

Additionally, EcoRoll is deactivated, if the driver intervenes in the cycle (e.g. due to a change of target speed).

Fuel saving for the phase 1 implementation of EcoRoll without ESS has been calculated based on Equation 15 to Equation 22:

$$\Delta FC = \Delta FC_{ecoRoll} + \Delta E_{kin} * \frac{\Delta fc}{3600}$$ Equation 15

$$\Delta FC_{ecoRoll} = \sum_{ecoRoll}(FC_{Final}) * \frac{t_{ecoRoll}}{3600} - \sum_{ecoRoll} idleFC * t_{ecoRoll}$$ Equation 16

$$\Delta E_{kin} = \frac{\frac{1}{2} m_{veh}(v^2_{ecoRollEnd} - v^2_{baseEnd})}{1000}$$ Equation 17

and for EcoRoll with engine stop according to Equation 18 to Equation 19:

$$\Delta FC = \Delta FC_{ecoRoll} + \Delta E_{kin} * \frac{\Delta fc}{3600}$$ Equation 20

$$\Delta FC_{ecoRoll} = \sum_{ecoRoll}(FC_{Final})\frac{\Delta t}{3600} - \left(\sum_{ecoRoll} FC_{aux} + FC_{engstart}\right)$$ Equation 21

$$\Delta E_{kin} = \frac{\frac{1}{2} m_{veh}(v^2_{ecoRollEnd} - v^2_{accEnd})}{1000}$$ Equation 22

With:

ΔFC	Change in fuel consumption
$\Delta FC_{ecoRoll}$	Fuel consumption during EcoRoll events
ΔE_{kin}	Change in kinetic energy before and after an EcoRoll event in kWs, ΔE_{kin} is set to 0, if the vehicle brakes in VECTO after EcoRoll situation
FC_{aux}	Fuel consumption induced from the auxiliary power during vehicle stop
$FC_{engstart}$	Fuel consumption for starting the engine in g (see Equation 14)
FC_{Final}	Instantaneous fuel consumption from the VECTO simulation
Δfc	Average change in fuel consumption per change in positive ICE power in g/ΔkWh, taken from the regression from Figure 19.
Δt	time step of the VECTO output
m_{veh}	Vehicle mass inclusive payload
$v_{EcoRollEnd}$	Corrected velocity at the end of the EcoRoll situation
v_{accEnd}	Velocity from VECTO baseline simulation where the vehicle does not accelerate anymore, after the EcoRoll situation

A.2.2.1.3. Predictive Cruise Control (PCC)

In accordance with chapter 2.2.1, the PCC functionality is subdivided into three "use cases". General requirement for the activation of PCC is driving on highway with a minimum velocity of 80km/h. Thus, PCC is only activated on the Long Haul cycle and the segment 29760 m to 96753 m of the Regional Delivery cycle.

Usecase 1

This case describes crest coasting. The vehicle reduces the velocity at uphill driving to reduce downhill braking. A segment is defined as usecase 1, if the following criteria are met:

- *Transition from positive to negative slope ("crest")*
- $v_{targ@crest} \geq 80 \left[\frac{km}{h}\right]$
- $v_{act@crest} > v_{targ} - hysteresis^{-}$
- $(\exists i \in segment)\ v_{act@i} \geq v_{targ} + hysteresis^{+}$ *(vehicle reaches downhill overspeed (+2.5 km/h) after crest)*

Change in fuel consumption of usecase 1 is based on the following equations:

$$\Delta FC = \min\{\Delta FC_{brake}, \Delta FC_{kin1}\}$$ Equation 23

$$\Delta FC_{kin1} = \frac{1}{2} m \left(v_{act@crest}^2 - \left(v_{targ} - hysteresis^{-}\right)^2\right) \frac{\Delta fc}{3.6^2 1000} \frac{1}{3600}$$ Equation 24

$$FC_{brake} = \sum_{usecase} \Delta fc\ \ P_{brakeloss} \frac{\Delta t}{3600}\ (if v\_veh > v\_targ)$$ Equation 25

Usecase 2

Usecase 2 describes the acceleration without engine power. This case occurs, if following criteria are fulfilled:

- *Segment is not usecase 1*
- $v_{act@crest} < v_{targ} - hysteresis^{-}$
- $v_{act@crest} \geq 50 \left[\frac{km}{h}\right]$
- $(\exists i \in segment)\ v_{act@i} \geq v_{targ}$

This case results in a fuel reduction according to Equation 26 to Equation 28

$$\Delta FC = min\{\Delta FC_{brake}, \Delta FC_{kin2}\}$$ Equation 26

$$\Delta FC_{kin2} = \frac{1}{2} m_{veh} \left(v_{targ}^2 - v_{act@crest}^2\right) \frac{\Delta fc}{3.6^2 1000} \frac{1}{3600}$$ Equation 27

$$FC_{brake} = \sum_{usecase} \Delta fc\ \ P_{brakeloss} \frac{\Delta t}{3600}\ \ (if v\_veh > v\_targ)$$ Equation 28

Usecase 3

Credits for PCC Usecase 3 have been simulated by changing the overspeed parameter in VECTO from 2.5 km/h to 5 km/h. Which means an increase of the downhill speed from 87.5 km/h to 90 km/h for a target speed of 85 km/h. This is a simplification against the real PCC usecase 3 behaviour, which increase the overspeed only during a short period at the bottom of the dip. However, the simplified approach results in the identical fuel saving, only the driving time is slightly wrong.

With:

$v_{act@crest}$	Velocity from VECTO baseline simulation at the top of the crest
$v_{act@i}$	Current velocity from VECTO baseline simulation
v_{targ}	Current target velocity during a PCC event from the VECTO cycle
ΔFC	Change in fuel consumption
ΔFC_{brake}	Fuel consumption reduction due to reduced braking
ΔFC_{kin}	Change in fuel consumption calculated from velocity difference
Δfc	Average change in fuel consumption per change in positive ICE power in g/ΔkWh, taken from the regression from Figure 19.
Δt	Time step of the VECTO output

A.2.2.1.4. Calculation of CO2 credits for combination of ADAS systems

The CO2 benefits for certain combinations of ADAS systems (especially for the interaction of Eco-roll and PCC) can not be calculated by a post-processing approach as precise definitions of interaction of systems and analysis of in-the-loop simulations would be required. For those combinations the CO_2 credits were estimated based on expert judgement using rather conservative assumptions (i.e. resulting in lower CO_2 credits).

- Prevention of Eco-roll events with negative fuel impacts via predictive functions not considered
- Only 80% of Eco-roll considered in package with PCC1&2
- Only 60% of Eco-roll considered in package with PCC1&2&3
- Combined effects of Eco-roll and PCC cannot be less than for Eco-roll and PCC alone

A.2.2.2. Results

Below tables with final results for CO2 reductions as determined based on the methods as elaborated in phase 1 are shown. Those figures do not include the "factor of conservatism". The combination number characterises the respective ADAS technology or rather the combination of ADAS technologies. Explanation of the combination number is given in Table 18 of section 2.2.2.2.

Table 44: Post processing results for ADAS of vehicle group 4

Comb-ination nr.	Group 4					
	Long Haul		Regional Delivery LH vehicle		Urban Delivery	
	ref. payload	low payload	ref. payload	low payload	ref. payload	low payload
1	-0.1%	-0.1%	-0.9%	-1.0%	-2.5%	-3.0%
2	0.0%	0.0%	-0.2%	-0.2%	0.0%	0.0%
3	-0.1%	-0.1%	-0.4%	-0.3%	0.0%	0.0%
4/1	-0.7%	-0.2%	-0.3%	-0.1%	0.0%	0.0%
4/2	-1.0%	-0.2%	-0.5%	-0.1%	0.0%	0.0%
5	-0.1%	-0.1%	-1.1%	-1.2%	-2.5%	-3.0%
6	-0.2%	-0.2%	-1.4%	-1.3%	-2.5%	-3.0%
7/1	-0.8%	-0.3%	-1.2%	-1.1%	-2.5%	-3.0%
7/2	-1.1%	-0.3%	-1.4%	-1.1%	-2.5%	-3.0%
8/1	-0.7%	-0.2%	-0.4%	-0.2%	0.0%	0.0%
8/2	-1.0%	-0.2%	-0.6%	-0.2%	0.0%	0.0%
9/1	-0.8%	-0.3%	-0.6%	-0.3%	0.0%	0.0%
9/2	-1.1%	-0.3%	-0.7%	-0.3%	0.0%	0.0%
10/1	-0.8%	-0.3%	-1.3%	-1.2%	-2.5%	-3.0%
10/2	-1.1%	-0.3%	-1.5%	-1.2%	-2.5%	-3.0%
11/1	-0.9%	-0.4%	-1.5%	-1.3%	-2.5%	-3.0%
11/2	-1.2%	-0.4%	-1.6%	-1.3%	-2.5%	-3.0%

Table 45: Post processing results for ADAS of vehicle group 5

Comb-ination nr.	Group 5									
	Long Haul				Regional Delivery				Urban Delivery	
	ref. payload	low payload	EMS ref. payload	EMS low payload	ref. payload	low payload	EMS ref. payload	EMS low payload	ref. payload	low payload
1	-0.1%	-0.1%	-0.1%	-0.1%	-0.6%	-0.8%	-0.5%	-0.6%	-2.7%	-3.6%
2	-0.2%	-0.1%	-0.1%	0.0%	-0.2%	-0.2%	0.0%	-0.4%	0.0%	0.0%
3	-0.4%	-0.1%	-0.3%	-0.1%	-0.4%	-0.4%	-0.2%	-0.6%	0.0%	0.0%
4/1	-1.0%	-0.3%	-0.2%	-0.5%	-1.2%	-0.4%	-1.0%	-0.7%	0.0%	0.0%
4/2	-1.4%	-0.4%	-0.7%	-0.6%	-1.9%	-0.7%	-1.7%	-1.0%	0.0%	0.0%
5	-0.3%	-0.2%	-0.2%	-0.1%	-0.8%	-1.0%	-0.5%	-1.1%	-2.7%	-3.6%
6	-0.5%	-0.2%	-0.3%	-0.2%	-1.1%	-1.2%	-0.7%	-1.2%	-2.7%	-3.6%
7/1	-1.0%	-0.4%	-0.3%	-0.6%	-1.9%	-1.2%	-1.5%	-1.3%	-2.7%	-3.6%
7/2	-1.4%	-0.5%	-0.8%	-0.7%	-2.5%	-1.5%	-2.2%	-1.7%	-2.7%	-3.6%
8/1	-1.1%	-0.4%	-0.3%	-0.5%	-1.4%	-0.6%	-1.0%	-1.0%	0.0%	0.0%
8/2	-1.5%	-0.4%	-0.8%	-0.6%	-2.0%	-0.8%	-1.7%	-1.3%	0.0%	0.0%
9/1	-1.2%	-0.4%	-0.4%	-0.5%	-1.6%	-0.8%	-1.2%	-1.2%	0.0%	0.0%
9/2	-1.6%	-0.5%	-0.9%	-0.6%	-2.1%	-1.0%	-1.8%	-1.4%	0.0%	0.0%
10/1	-1.2%	-0.5%	-0.3%	-0.6%	-2.0%	-1.4%	-1.5%	-1.7%	-2.7%	-3.6%
10/2	-1.6%	-0.6%	-0.8%	-0.7%	-2.6%	-1.6%	-2.2%	-1.9%	-2.7%	-3.6%
11/1	-1.3%	-0.6%	-0.5%	-0.6%	-2.2%	-1.6%	-1.7%	-1.8%	-2.7%	-3.6%
11/2	-1.7%	-0.6%	-0.9%	-0.7%	-2.8%	-1.8%	-2.3%	-2.0%	-2.7%	-3.6%

Table 46: Post processing results for ADAS of vehicle group 9

Comb-ination nr.	Group 9							
	Long Haul				Regional Delivery			
	ref. payload	low payload	EMS ref. payload	EMS low payload	ref. payload	low payload	EMS ref. payload	EMS low payload
1	-0.1%	-0.1%	-0.1%	-0.1%	-0.8%	-0.9%	-0.5%	-0.6%
2	-0.2%	0.0%	-0.1%	0.0%	-0.2%	-0.2%	-0.1%	-0.1%
3	-0.4%	-0.1%	-0.2%	-0.1%	-0.4%	-0.4%	-0.3%	-0.3%
4/1	-0.8%	-0.2%	-0.2%	-0.4%	-0.6%	-0.2%	-1.1%	-0.6%
4/2	-1.2%	-0.3%	-0.7%	-0.5%	-0.9%	-0.4%	-1.8%	-1.0%
5	-0.3%	-0.1%	-0.2%	-0.1%	-1.0%	-1.1%	-0.6%	-0.7%
6	-0.5%	-0.2%	-0.3%	-0.2%	-1.2%	-1.3%	-0.8%	-0.9%
7/1	-0.9%	-0.3%	-0.3%	-0.5%	-1.4%	-1.2%	-1.6%	-1.2%
7/2	-1.3%	-0.4%	-0.7%	-0.6%	-1.7%	-1.3%	-2.2%	-1.6%
8/1	-1.0%	-0.3%	-0.3%	-0.5%	-0.7%	-0.4%	-1.2%	-0.7%
8/2	-1.3%	-0.3%	-0.7%	-0.6%	-1.0%	-0.5%	-1.8%	-1.0%
9/1	-1.2%	-0.3%	-0.4%	-0.5%	-0.9%	-0.5%	-1.4%	-0.9%
9/2	-1.4%	-0.3%	-0.8%	-0.6%	-1.2%	-0.6%	-1.9%	-1.1%
10/1	-1.1%	-0.4%	-0.3%	-0.5%	-1.5%	-1.3%	-1.7%	-1.3%
10/2	-1.4%	-0.4%	-0.8%	-0.6%	-1.8%	-1.4%	-2.3%	-1.6%
11/1	-1.2%	-0.4%	-0.5%	-0.6%	-1.7%	-1.5%	-1.9%	-1.5%
11/2	-1.5%	-0.4%	-0.9%	-0.7%	-2.0%	-1.5%	-2.4%	-1.7%

Table 47: Post processing results for ADAS of vehicle group 10

Comb-ination nr.	Group 10							
	Long Haul				Regional Delivery			
	ref. payload	low payload	EMS ref. payload	EMS low payload	ref. payload	low payload	EMS ref. payload	EMS low payload
1	-0.1%	-0.1%	-0.1%	-0.1%	-0.6%	-0.8%	-0.5%	-0.6%
2	-0.2%	-0.1%	-0.1%	0.0%	-0.2%	-0.1%	0.0%	-0.1%
3	-0.3%	-0.1%	-0.2%	-0.1%	-0.4%	-0.4%	-0.2%	-0.3%
4/1	-1.0%	-0.4%	-0.2%	-0.5%	-1.3%	-0.5%	-1.2%	-0.7%
4/2	-1.4%	-0.5%	-0.7%	-0.6%	-1.9%	-0.8%	-1.8%	-1.1%
5	-0.2%	-0.2%	-0.2%	-0.1%	-0.8%	-0.9%	-0.5%	-0.7%
6	-0.4%	-0.2%	-0.3%	-0.1%	-1.0%	-1.2%	-0.7%	-0.9%
7/1	-1.0%	-0.5%	-0.3%	-0.6%	-1.9%	-1.3%	-1.7%	-1.4%
7/2	-1.5%	-0.6%	-0.8%	-0.7%	-2.5%	-1.6%	-2.3%	-1.7%
8/1	-1.1%	-0.4%	-0.3%	-0.5%	-1.4%	-0.6%	-1.2%	-0.8%
8/2	-1.5%	-0.5%	-0.8%	-0.6%	-2.0%	-0.9%	-1.8%	-1.2%
9/1	-1.2%	-0.5%	-0.4%	-0.5%	-1.6%	-0.8%	-1.3%	-1.0%
9/2	-1.6%	-0.5%	-0.9%	-0.7%	-2.1%	-1.0%	-1.9%	-1.3%
10/1	-1.2%	-0.5%	-0.3%	-0.6%	-2.0%	-1.4%	-1.7%	-1.4%
10/2	-1.5%	-0.6%	-0.8%	-0.7%	-2.6%	-1.7%	-2.3%	-1.8%
11/1	-1.3%	-0.6%	-0.5%	-0.6%	-2.3%	-1.6%	-1.8%	-1.6%
11/2	-1.6%	-0.7%	-0.9%	-0.8%	-2.8%	-1.8%	-2.4%	-1.9%

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A.2.3. **Methods elaborated for phase 2 implementation**

The phase 2 of the ADAS implementation in VECTO is based on in the loop simulation. This approach considers the impact of ADAS with particular vehicle specifications as well as the interaction of different ADAS functions. The VECTO in the loop simulation is based on generic control strategies plus generic control parameters, which are described in this section.

A.2.3.3. Engine stop start during vehicle stops (ESS-VS)

The generic ADAS function ESS-VS turns off the engine if the following criteria are fulfilled:

- $vact$ < 0.5 $[km/h]$
- $tstop$ > 2 $[s]$ (delay)

with:

$vact$ Simulated actual vehicle velocity from VECTO

$tstop$ Stop time

If not forced before by driving away, the engine is re-started again after 120 seconds.

The engine speed and thus the fuel consumption is 0 during engine off. The fuel consumption reduction is reduced by the energy request of the compressor, alternator and the air conditioning system during engine off as well as of the energy for the restart.

In addition a utility factor of 0.8 has been assumed, this factor takes into consideration that in reality the engine is not off in each vehicle stop.

The Fuel consumption reduction are determined as follows:

$$\Delta FC = (FC_{stop} - FC_{aux} - FC_{engstart}) * 0.8$$ Equation 29

$$FC_{stop} = \Sigma_{stop}(FC_{Final}) * \frac{t_{stop}}{3600}$$ Equation 30

$$FC_{aux\_ESS-VS} = \Delta fc * (\Sigma_{stop} \frac{P_{aux_{ESS-VS}} * t_{stop}}{3600})$$ Equation 31

$$FC_{engstart} = FC_{RampUp} + FC_{Drag}$$ Equation 32

$$FC_{RampUp} = \frac{\frac{1}{2} * J_{eng} * \left(\frac{n_{idle}\pi}{30}\right)^2 * \Delta fc}{\eta alt^2}$$ Equation 33

$$FC_{Drag} = \frac{T_{Drag\_idle} * \left(\frac{n_{idle}}{2}\right) * \frac{\pi}{30} * t_{start} * \Delta fc}{\eta alt^2}$$ Equation 34

With:

ΔFC Change in fuel consumption

FC_{stop} Fuel consumption during vehicle stop

$FC_{aux_{ESS-VS}}$ Fuel consumption induced from the auxiliary power during vehicle stop

$FC_{engstart}$	Fuel consumption for starting the engine
FC_{RampUp}	Fuel consumption for starting caused by the engine inertia
FC_{Drag}	Fuel consumption caused by the engine drag during vehicle start
FC_{Final}	Instantaneous fuel consumption from the VECTO simulation
t_{stop}	Stop time
t_{start}	Engine start time in s (assumed with 1s)
Δfc	Average change in fuel consumption per change in positive ICE power in g/ΔkWh, see Figure 19.
$P_{auxESS-VS}$	Auxiliary power for compressor, alternator and air conditioning
J_{eng}	Inertia moment of the ICE
T_{Drag_idle}	Drag torque at idle speed
n_{idle}	Idling speed
ηalt	Alternator efficiency

For the calculations according to Equation 33 and Equation 34, the alternator efficiency was assumed to be 0.7.

A.2.3.4. Eco-roll

The in the loop simulation is based on the conditions shown in Figure 20. If all conditions for an Eco-roll are met, the generic controller goes into the pre activation phase. Eco-roll is activated if conditions are still valid after a delay time of 2 seconds. One requirement is a minimum vehicle speed, for Eco-roll this speed is established at 60 km/h. It should be noted, that Eco-roll without predictive function do not necessarily reflect in a fuel consumption reduction, since operating points with engine idling have a higher fuel consumption than motoring operation. Generic default values of ECO-roll parameters are listed in Table 48.

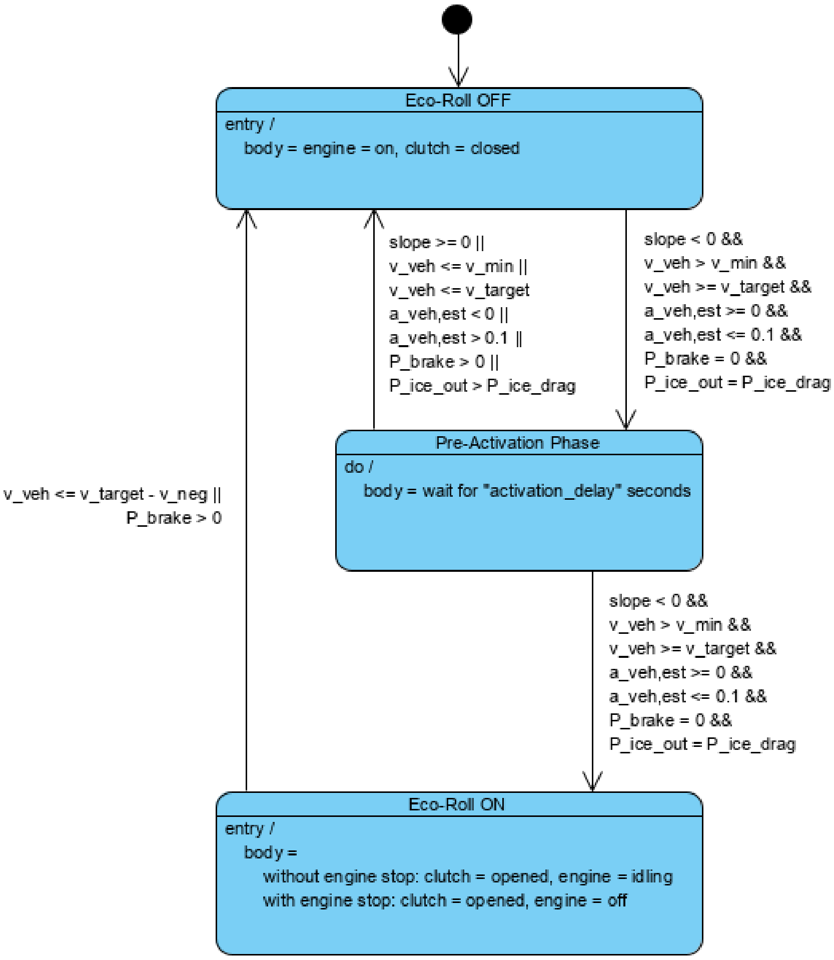


Figure 20: State flow chart Eco-Roll

Table 48: Generic ECO-roll model parameters

Eco-roll parameter - AMT	**Unit**	**Value**
Minimum speed	km/h	60
Activation delay	s	2
Underspeed threshold	km/h	0
Estimated acceleration MIN	m/s²	0
Estimated acceleration MAX	m/s²	0.1

A.2.3.5. Engine stop start during Eco-roll events

Eco-roll systems including a stop/start model turn off the engine if:

- Eco-roll $=$ active (see Figure 20)
- $t_{\text{Eco-roll}} > 2[s]$(2 s delay)

If above conditions are met, the engine speed and the fuel consumption is set to 0. For stop start situation during Eco-roll events is also a utility factor of 0.8 applied. The fuel consumption induced by the required energy demand of needed auxiliaries and for the restart of the engine is considered according to Equation 35 to Equation 36.

$$FC_{aux\_ER\_ESS} = \Delta fc * \left(\sum_{Engine\ off} \frac{P_{auxER\_ESS} * t_{Engine\ off}}{3600}\right)$$ Equation 35

$$FC_{engstart} = FC_{RampUp} + FC_{Drag}$$ Equation 36

$$FC_{RampUp} = \frac{\frac{1}{2} * J_{eng} * \left(\frac{n_{idle}\pi}{30}\right)^2 * \Delta fc}{\eta alt^2}$$ Equation 37

$$FC_{Drag} = \frac{T_{Drag\_idle} * \left(\frac{n_{idle}}{2}\right) * \frac{\pi}{30} * t_{start} * \Delta fc}{\eta alt^2}$$ Equation 38

With:

$FC_{aux\_ER\_ESS}$	Fuel consumption induced from the auxiliary power during engine off
$FC_{engstart}$	Fuel consumption for starting the engine
FC_{RampUp}	Fuel consumption for starting caused by the engine inertia
FC_{Drag}	Fuel consumption caused by the engine drag during vehicle start
FC_{Final}	Instantaneous fuel consumption from the VECTO simulation
$t_{Engine\ off}$	Time period engine off during Eco-roll
t_{start}	Engine start time in s (assumed with 1s)
Δfc	Average change in fuel consumption per change in positive ICE power in g/ΔkWh, see Figure 19.
$P_{aux\_ER\_ESS}$	Auxiliary power for compressor, alternator, steering pump and air conditioning in kW
J_{eng}	Inertia moment of the ICE
T_{Drag_idle}	Drag torque at idle speed
n_{idle}	Idling speed in 1/s
ηalt	Alternator efficiency

A.2.3.6. Predictive Cruise Control

The Phase 2 implementation of predictive cruise control deals with the same "usecases" as described in section A.2.2.1.3. The integrated simulation of PCC calculates the change of velocity induced by a PCC event on the basis of the difference of potential and kinetic energies. Therefore the determination some key positions (Figure 21) in a pre-processing step is necessary. The earliest start of a PCC segment is defined with X_{start}. This position is calculated by Equation 39.

$$X_{start} = X_{Vlow} - d_{preview}$$ Equation 39

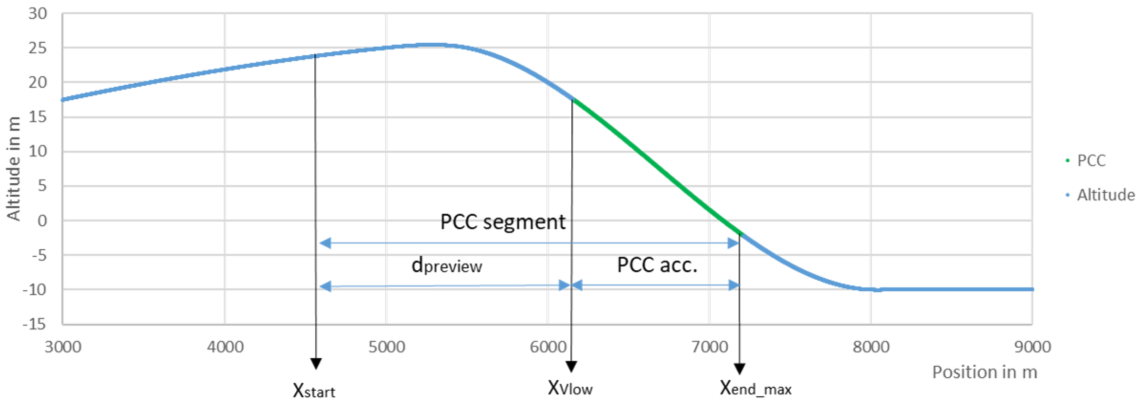


Figure 21: Definition of PCC a segment

X_{Vlow} is defined as the position with the lowest velocity of a PCC event, derived from the minimum negative slope of which the vehicle would start accelerating without engine power. The latest end of a PCC event X_{end_max} is characterised as the last position where the actual slope is lower than the calculated minimum slope for acceleration without engine power. The slope where the vehicle accelerates without engine power depends on the availability of Eco-roll. For vehicles without Eco-roll during PCC events the slope is calculated according to Equation 40.

$$slope_{acc\_PCC} = -\frac{P_{aero}(v_{target}) + P_{RR} + P_{drag}}{v_{target} * m_{veh} * g}$$ Equation 40

And with the following equation for vehicles with Eco-roll during PCC:

$$slope_{acc_{PCC_{Eco-roll}}} = -\frac{P_{aero}(v_{target}) + P_{RR}}{v_{target} * m_{veh} * g}$$ Equation 41

For every potential PCC event, X_{start}, X_{end_max} and X_{Vlow} as well as the vehicle energy at the position X_{Vlow} (Equation 42) and X_{end_max} (Equation 43) are calculated in a pre-processing step.

$$E_{X_{Vlow}} = m_{veh} * g * h(X_{Vlow}) + \frac{m_{veh} * (v_{target}(X_{Vlow}) - v_{neg})^2}{2}$$ Equation 42

$$E_{X_{end\_max}} = m_{veh} * g * h\left(X_{end\_max}\right) + \frac{m_{veh} * v_{target}(X_{end\_max})^2}{2}$$ Equation 43

With:

$P_{aero(v_{target})}$ Air resistance power with target speed at the actual position in W

P_{RR} Rolling resistance power in W

P_{drag} Engine drag power calculated with medium engine speed in W

v_{target} Target speed in m/s

m_{veh} Vehicle mass in kg

g Acceleration of gravity in m/s^2

h Altitude in m

$E_{X_{Vlow}}$ Vehicle energy at X_{vlow} in Ws

$E_{X_{end\_max}}$ Vehicle energy at X_{end_max} in Ws

A potential PCC section is defined with above mentioned positions. If the vehicle enters a potential PCC section, the following calculations are performed to decide on starting a PCC event:

1. Current vehicle position: X

2. End position of PCC event:

$$X_{end} = \min(X + d_{preview}, X_{end\_max})$$ Equation 44

3. Estimation of coasting resistance force:

$$F_{coast} = -\frac{P_{aero(v_{target})} + P_{RR} + P_{drag}}{v_{target}}$$ Equation 45

P_{drag} is set to 0 in case the vehicle is equipped with eco-roll

4. Energy demand/gain for coasting from the vehicle's current position to the point with the minimum velocity X_{Vlow}:

$$E_{coast,vlow} = F_{coast} * (x_{vlow} - x)$$ Equation 46

5. Energy demand/gain for coasting from the vehicle's current position to the end of the PCC event X_{end}:

$$E_{coast,Xend} = F_{coast} * (x_{end} - x)$$ Equation 47

6. Vehicle's current energy:

$$E_{veh(x)} = m_{veh} * g * h(x) + \frac{m_{veh} * v_{(x)}^2}{2}$$ Equation 48

7. Vehicle's energy at the end of a PCC event:

$$E_{Xend} = m_{veh} * g * h(x_{end}) + \frac{m_{veh} * v_{(x_{end})}^2}{2}$$ Equation 49

For a PCC event according to usecase 1, where the vehicle reduces the velocity at uphill driving is only applicable, if the starting vehicle velocity is higher than the target speed minus a defined hysteresis v_{neg}. The starting point for the reduction of the velocity is where the actual vehicle energy $E_{veh(x)}$ is higher than the energy E_{Xend} and $E_{X_{Vlow}}$ plus the coasting losses from beginning to the end of a PCC event.

Usecase 2 where the vehicle accelerates on the negative slope without engine power is only applicable, if the starting vehicle velocity is less or equal than the target speed minus a defined hysteresis v_{neg} and higher or equal than the minimum allowed velocity for usecase 2 (v_{active}). The start decision for use case 2 that the actual vehicle position X_{veh} is greater or equal than the position $X_{v\,low}$ and the actual vehicle energy must be at least as high as the energy at the end of the PCC event plus the coasting losses from beginning to the end of a PCC event.

Figure 22 showed a detailed state flow chart for the decision-making process relating to usecases 1 and 2. Generic default values of PCC parameters are listed in Table 28.

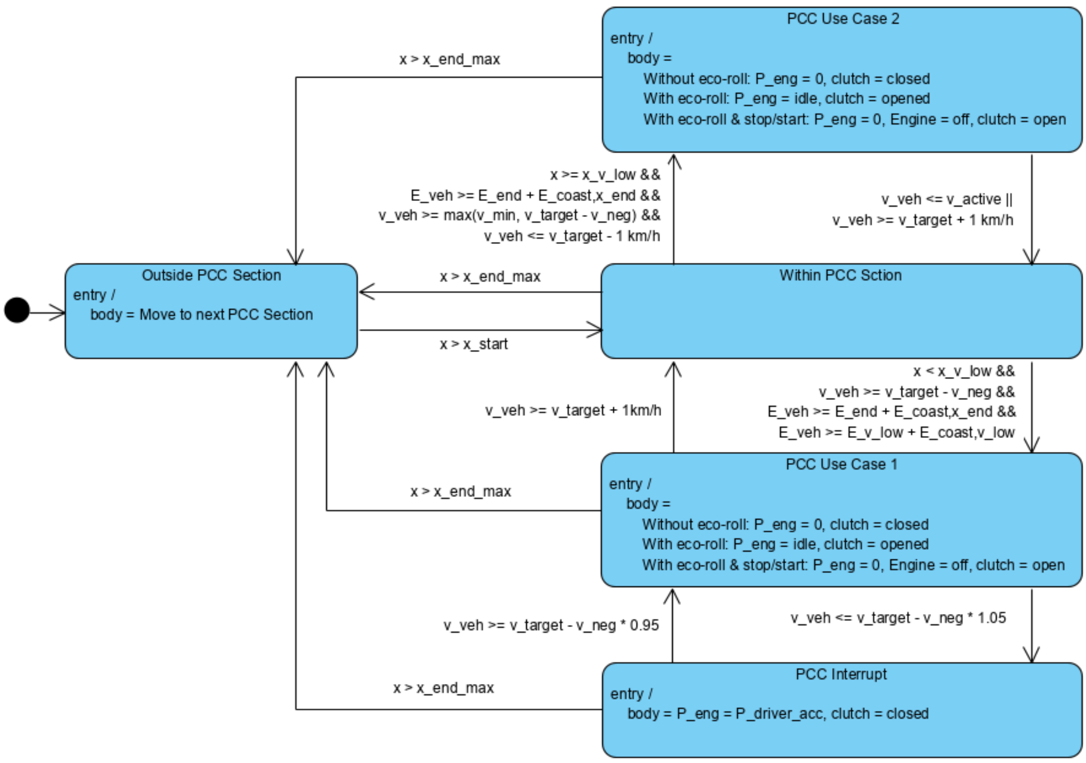


Figure 22: State flow chart Predictive cruise control for usecases 1 and 2

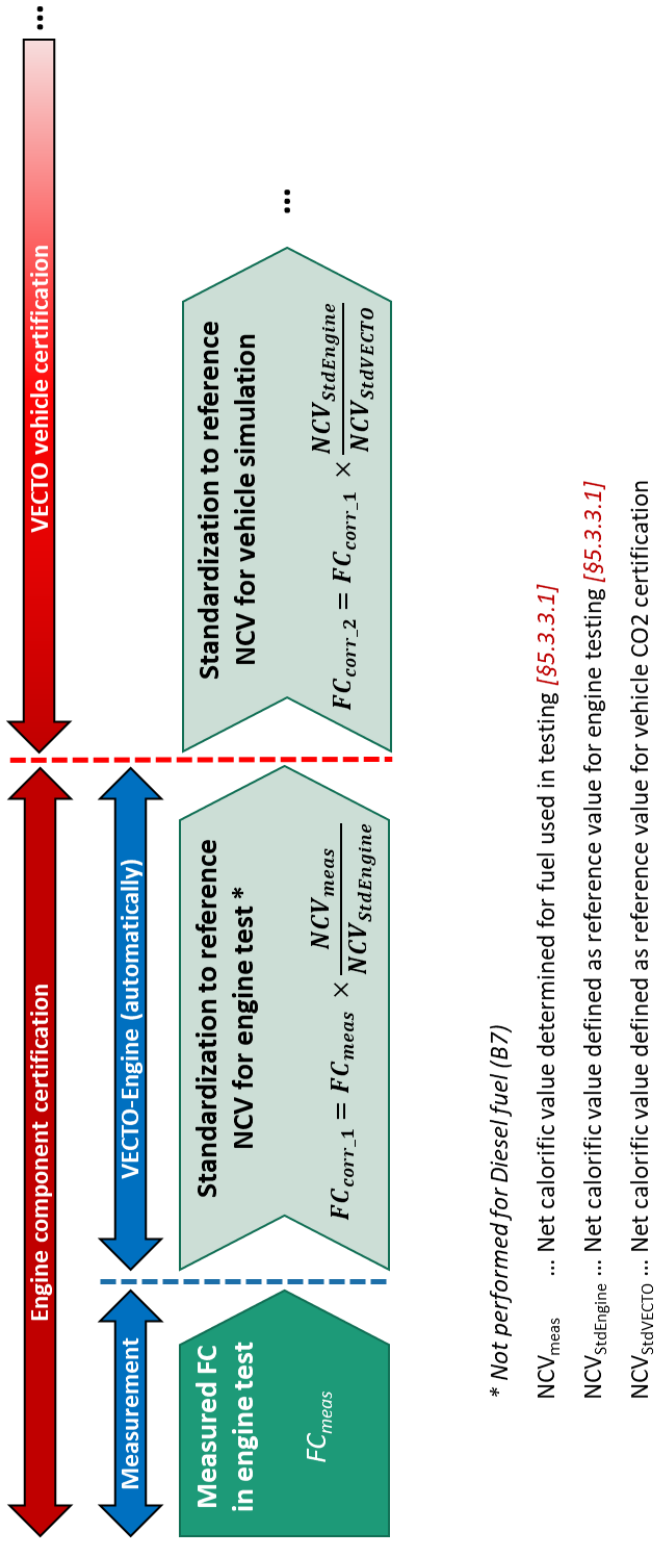
The fuel consumption of vehicles equipped with PCC option 1 & 2 and eco-roll with engine stop/start will be corrected for engine stop/start as described in section A.2.3.5.

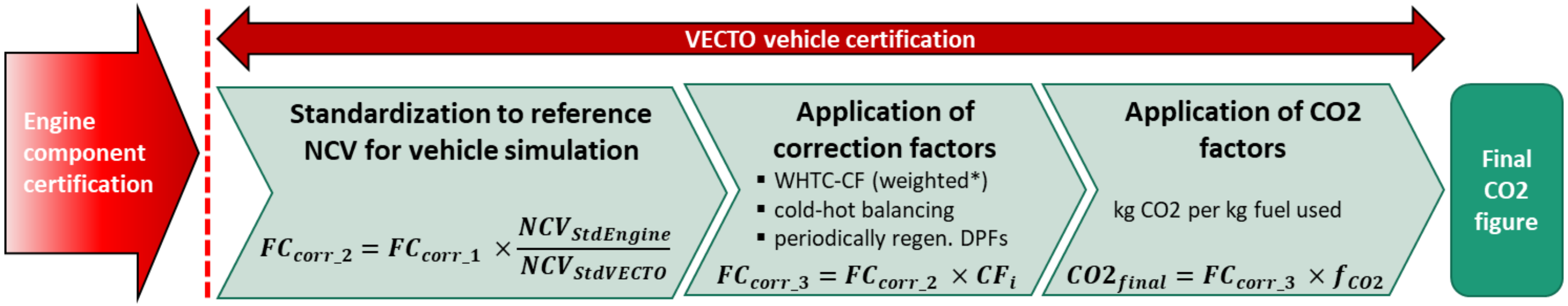
The simulation principle of usecase 3 in the phase 2 implementation does not differ from the phase 1 implementation, which is described in A.2.3.6.

Table 49: Generic PCC parameters

Parameter	**Unit**	**Value**	**Comment**
Vehicle underspeed hysteresis v_{neg}	km/h	8	
Vehicle overspeed hysteresis for v_{pos}	km/h	5	Relate to usecase 3
PCC lower limit v_{active}	km/h	50	Relevant for usecase 2
PCC enabling velocity	km/h	80	Minimum target velocity for PCC
PCC preview distance $d_{preview}$ usecase 1	m	1500	
PCC preview distance $d_{preview}$ usecase 2	m	1000	

A.3. Method for standardizing and converting the fuel mass flow based on the specific energy content





* explained on next slide

$NCV_{StdEngine}$ … Net calorific value defined as reference value for engine testing *[§5.3.3.1]*

$NCV_{StdVECTO}$ … Net calorific value defined as reference value for vehicle CO2 certification

CF_i … Combined correction factor (= WHTC-CF x $BF_{cold\text{-}hot}$ x CF_{RegPer})

f_{CO2} … Standard factors for kg CO2 per kg fuel combustion in VECTO

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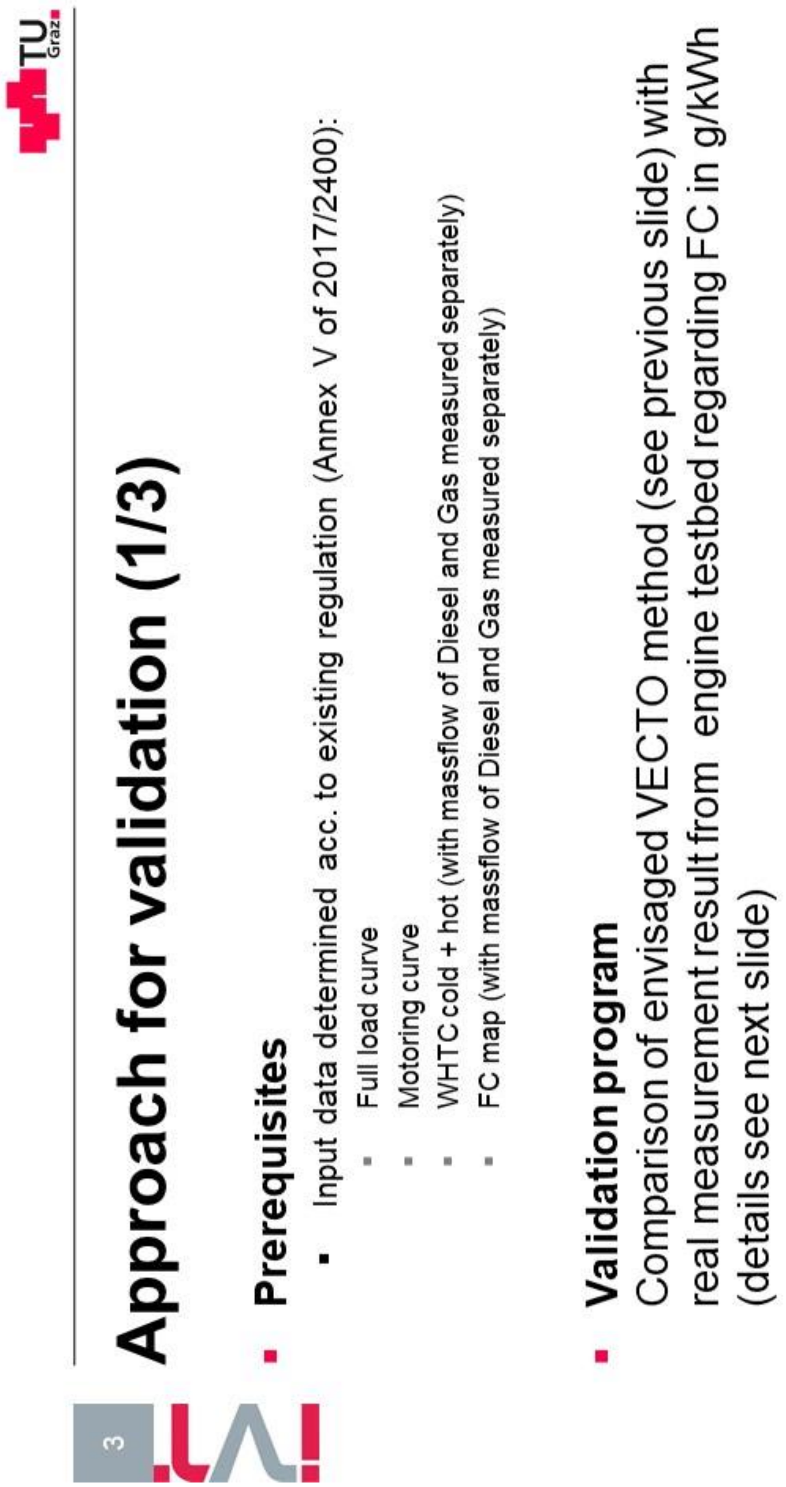
A.4. Provisions for test campaign of dual-fuel engines



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Approach for validation (2/3)

- **Necessary steps for validation**
  1. Generate 2 separate sets of input data for VECTO by application of VECTO-Engine for both fuel maps (Diesel and Gas)
     - Differences are correction factors and fuel map
     - Rest of data is the same
  2. Generate engine cycles with representative vehicles (VECTO or OEM tool)
     - Low-dynamic cycle: Long-haul (2 different loadings)
     - High-dynamic cycle: Urban/Regional delivery cycle (2 different loadings)
  3. Run cycles on engine testbed
     - Measurement of massflow for Diesel and Gas separately (but in same engine testrun)
     - *!!! To be considered: Auxiliary loads applied on testbed (and correction in testbed control)*
       → real engine torque on testbed (inkl. aux config.) needs to fit torque applied in VECTO simulation
     - *!!! Different control modes: speed/torque, speed/alpha, idle depending on vehicle and clutch state in VECTO (needs post-processing of output of step 2)*
     - *!!! Engine cycle on the testbed should be run after the engine was fully warmed-up*
     - *!!! After warm-up the engine should go to idle but not stopped.*
       Actual test cycle should continue directly from idling without stalling the engine.
       (Unlike WHTC common practice)

Approach for validation (3/3)

5

- **Necessary steps for validation**

4. Simulate speed/torque trace from step 3 in Engine-Only mode in VECTO *
   - 2 simulation runs for each cycle (as workaround):
     - 1x Gas and 1x Diesel input data for FC map and g/kWh figures over WHTC
     - Rest of component data is the same (full load curve, motoring curve etc.)
   - Check which option for input gives better results:
     a. Target traces or actual traces for speed and torque
     b. Engine inertia set to 0 or actual inertia (from dyno setup) used

5. Corrections of Diesel and Gas mass with individual factors from step 1 *
   - Multiplied with weighted WHTC-CF (acc. to mission profile) and Cold-Hot-Balancing factor as done for regular engines in VECTO

6. Comparison of g/kWh for Diesel and Gas

7. Evaluation of total CO_2 (Gas+Diesel) in g/kWh measured vs. simulated

** Please contact G. Silberholz TUG (Silberholz@ivt.tugraz.at) for details/help on this steps of the procedure*