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FUEL CONSUMPTION SIMULATION OF HDVS IN THE EU: COMPARISONS AND LIMITATIONS

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TABLE OF CONTENTS

INTRODUCTION

The European Union (EU) has set ambitious targets to reduce greenhouse gas (GHG) emissions by 40% in 2030 relative to 1990. To achieve this goal, the sectors covered by the EU Emissions Trading System (ETS)[1] must deliver a reduction of 43% in GHG emissions by 2030, and the non-ETS sectors a reduction of 30%, both relative to 2005 (European Commission, 2014). Of the non-ETS sectors, road transport is the largest contributor of carbon dioxide (CO_2) emissions, accounting for 32% of the EU's carbon emissions in 2015 (Figure 1). Furthermore, road transport was the only CO_2 source that did not achieve any emissions reductions between 1990 and 2015, increasing by 25% in the same time frame (European Environment Agency, 2017a).

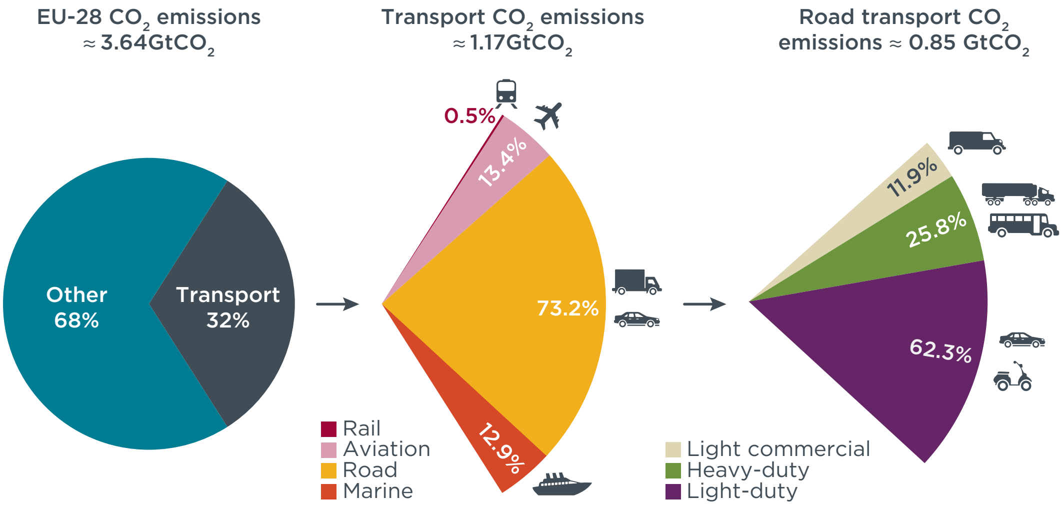

Figure 1. Distribution of total (ETS and non-ETS) direct CO_2 emissions in the EU for 2015. Source: European Environment Agency (2017b).

Heavy-duty vehicles (HDVs) are currently responsible for approximately 25% of the CO_2 emissions from road transportation in the European Union; the latter are predicted to increase by as much as 10% by 2030 (European Commission, 2016) as a result of increasing freight demand and stagnating vehicle efficiency. Previous analyses show that the fuel efficiency of HDVs has seen little improvement over the past decade (Muncrief, 2017). The existence of market barriers hinders the fleet penetration of cost-effective efficiency technologies (Sharpe, 2017) and calls for strong regulatory measures if EU's CO_2 mitigation targets are to be met.

In light of the increasing relevance of the commercial vehicle sector for meeting EU's climate targets, and of the evident ineffectiveness of market forces for increasing the fuel efficiency of HDVs, the European Commission put forward a policy pathway for curbing the CO_2 emissions of HDVs. It has three key elements: (1) a regulation for the declaration of the CO_2 emissions and fuel consumption of HDVs, (2) a monitoring and reporting scheme for the CO_2 emissions and fuel consumption of HDVs, and (3) fuel efficiency standards for new HDVs.

European Commission Regulation (EU) 2017/2400, for the declaration of CO_2 emissions and fuel consumption of HDVs, was adopted on May 11, 2017 during the 67th meeting of the Technical Committee–Motor Vehicles and was published in the Official Journal

1 The EU Emissions Trading System covers power and heat generation, energy-intensive industry sectors (e.g., oil refining, steel and iron production, cement production), and domestic commercial aviation. Non-ETS sectors include transport, residential, small business, and agriculture.

of the European Union in December 2017 (European Commission, 2017c). The CO_2 declaration procedure uses a combination of component testing and vehicle simulation to assign official CO_2 emission and fuel consumption values to each new HDV sold in the EU belonging to one of the vehicle groups affected by the regulation. A related ICCT policy update summarizes the key elements of the HDV CO_2 declaration regulation (Rodríguez, 2018).

The remaining two elements of the European Commission's strategy for reducing HDV CO_2 emissions are still under development. On May 31, 2017, the European Commission released a regulatory proposal for the monitoring and reporting of HDV CO_2 emissions and fuel consumption (European Commission, 2017b). A regulatory proposal for fuel efficiency standards for new HDVs is envisaged for the first half of 2018 (European Commission, 2017a).

A well-designed, technology-neutral fuel efficiency standard incentivizes innovation across the full spectrum of fuel-saving technologies, minimizing the market distortions that would result from favoring specific technologies. Such a technology-neutral standard depends, in turn, on an underlying CO_2 declaration process that accounts for a wide set of fuel efficiency technologies. In the EU, the current regulation for the declaration of CO_2 emissions and fuel consumption of HDVs does not consider a number of well-known fuel-saving technologies. It is therefore desirable to explore suitable alternatives to extend the technology scope of the HDV CO_2 declaration procedure.

This paper is the first of a series of papers providing research to inform future development of the EU HDV CO_2 declaration procedure, so as to ensure the consideration of known technologies with demonstrated fuel savings potential (such as hybrid powertrains, waste heat recovery systems, and trailer aerodynamics). In this delivery, the Vehicle Energy Consumption Calculation Tool, VECTO, is analyzed in detail and is compared to GEM, the regulatory vehicle simulation tool used in the United States for HDV certification (U.S. EPA, 2016).

EU'S HDV CO_2 DECLARATION AND VECTO

The CO_2 declaration procedure for HDVs in the EU uses a combination of component testing and vehicle simulation to determine the CO_2 emissions and fuel consumption of a given HDV. The vehicle simulation tool, called VECTO,[2] is publicly available, open-source, downloadable, executable software. VECTO is programmed in C#, a multipurpose, object-oriented computer programming language.

VECTO includes two operating modes: *declaration* and *engineering*. In VECTO's declaration mode, all generic data, payloads, driver model parameters, and test cycles are allocated automatically as a function of vehicle group. In VECTO's engineering mode, the user has greater flexibility to select and change all the boundary conditions of the simulations, as well as the underlying generic assumptions for the simulation of the individual components.

For a given driving cycle and vehicle payload, VECTO uses the component data gathered during the certification process to simulate the longitudinal dynamics of the vehicle. These certified component data constitute the input to VECTO. Seven vehicle component groups are considered by VECTO: engine, transmission, axle, aerodynamic drag, tires, auxiliaries, and vehicle. For each component group, several input parameters are required for constructing the corresponding mathematical models of the respective components. The main VECTO inputs required for running the simulation tool in declaration mode are summarized in Table 1. VECTO's graphical user interfaces for the input parameters are shown in Figure 2.

Table 1. Main VECTO inputs in declaration mode.

Component	VECTO input
Engine	Displacement, idle speed, fuel consumption map, full-load torque curve, motoring friction curve, brake-specific fuel consumption over the urban, rural, and motorway sections of the World Harmonized Transient Cycle (WHTC). Also part of the inputs are the correction factors for the fuel's heating value, aftertreatment system regeneration, and cold start.
Transmission	Transmission type, gear ratios, torque loss map as a function of torque and speed for each gear, maximum torque and speed per gear
Axle	Axle ratio and torque loss map as a function of torque and speed
Aerodynamic drag	Air drag area as determined during the constant-speed procedure. For rigid trucks, a standard box is used. For tractors, a standard trailer is used.
Tires	Tire dimensions, rolling resistance coefficient (C_{rr}), and load applied during the rolling resistance test for each axle
Auxiliaries	Technology used for the following auxiliaries: cooling fan, steering system, electric system, pneumatic system, power take-off. Also noted is the presence or absence of an air conditioning (A/C) system.
Vehicle	Curb vehicle weight, gross vehicle weight rating, axle configuration

2 The VECTO version used for this paper is VECTO 3.2.1.1054.

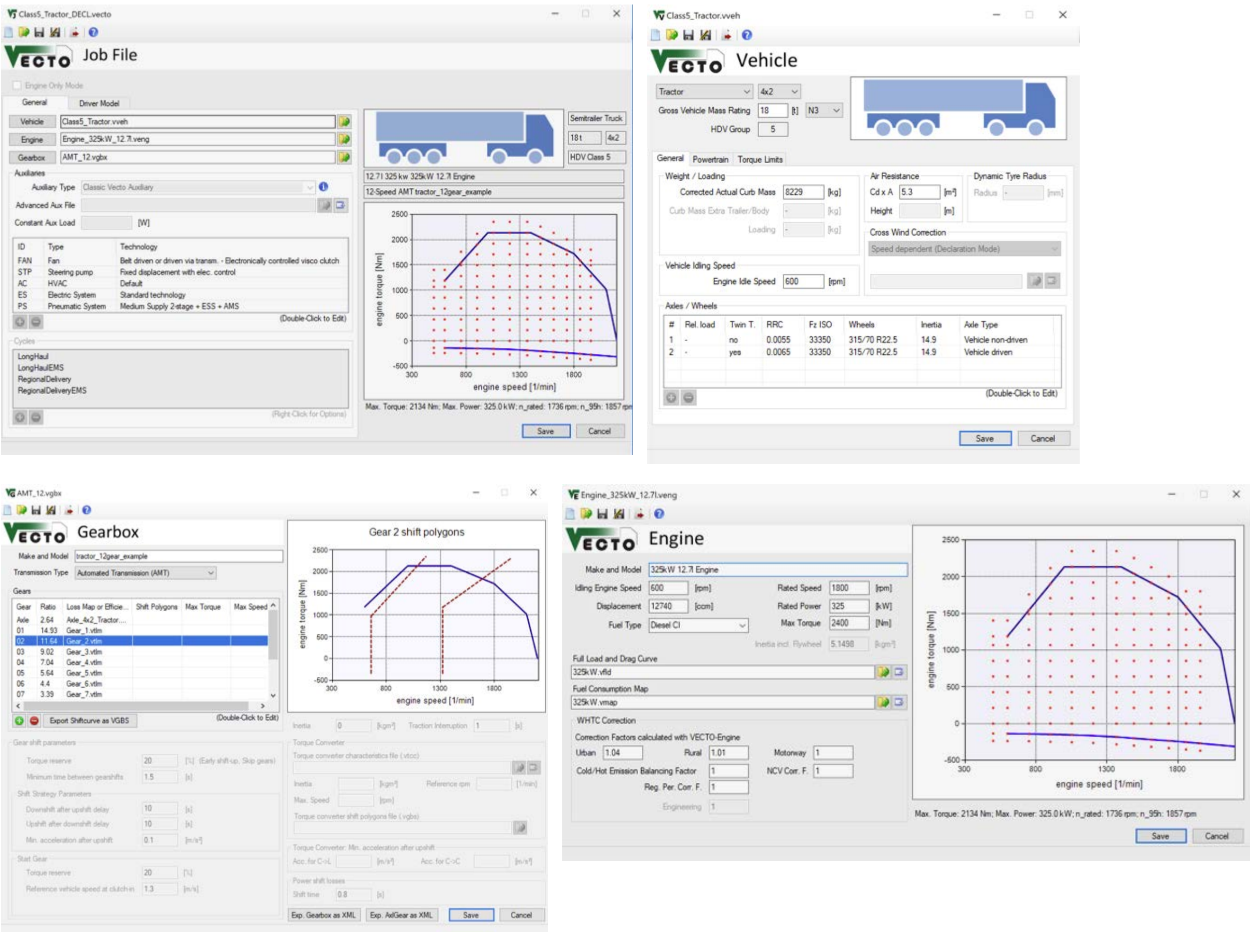

Figure 2. VECTO input graphical user interfaces.

VECTO uses the input data to create mathematical models of the various HDV components; these models simulate the vehicle's energy flow and fuel consumption over different payloads and driving cycles.[3] Five different driving cycles, or mission profiles, are defined in VECTO: Urban Delivery, Regional Delivery, Long Haul, Municipal Utility, and Construction. These cycles are distance-based cycles with grade. That is, they are defined as a target speed over distance, and the driver module in VECTO tries to achieve and maintain the targeted speed. The inclination of the road as a function of distance is also defined in the mission profile. Figure 3 shows the target speed and grade of the five VECTO cycles as a function of distance, as defined in version 3.2.1.1054 of VECTO. The Regional Delivery and Long Haul cycles have recently been revised, and it is possible that the remaining three cycles will also receive modifications before the beginning of the mandatory CO_2 declaration of new HDVs in January 2019.

The VECTO output consists of two types of files. The summary file contains the cumulative vehicle energy use at different locations in the powertrain, the fuel consumption, and other performance metrics of the vehicle for the different simulation runs. The modal files, one per simulation run, contain the time-resolved data of the power flows at different locations in the powertrain and the resulting fuel consumption rates. For each vehicle simulation run (i.e., a payload–driving cycle combination), VECTO outputs the fuel consumption and CO_2 emissions. The results are presented in three forms: by distance (gCO_2/km, l/100 km), payload-specific (gCO_2/tonne-km, l/tonne-km), and volume-specific (gCO_2/m^3-km, l/m^3-km).

3 The standard payload and the applicable driving cycles are a function of the vehicle segment.

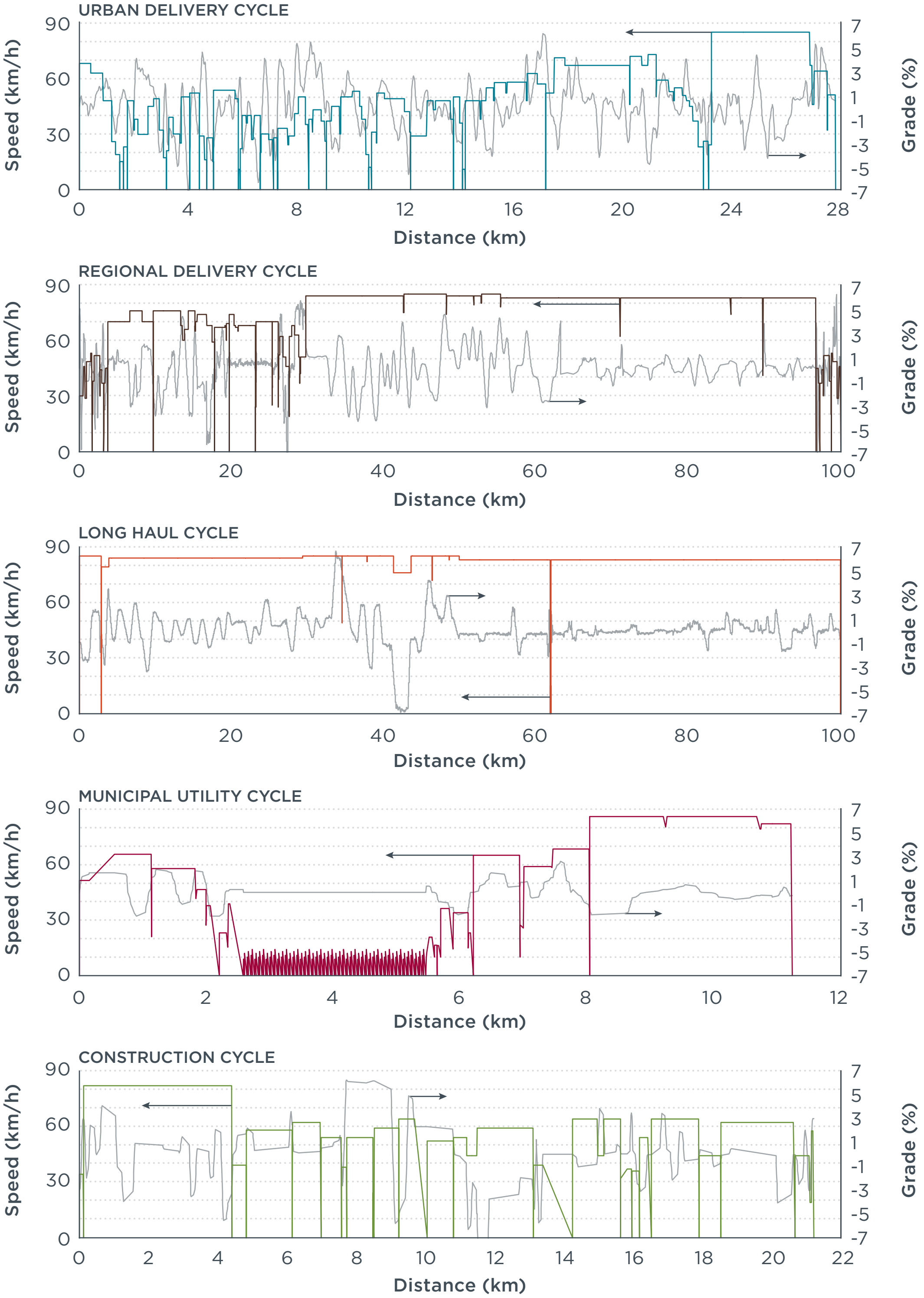

Figure 3. Mission profiles included in VECTO 3.2.1.1054.

VECTO'S MODEL ARCHITECTURE

To calculate the vehicle fuel consumption, it is necessary to convert the information contained in the driving cycle into operating points in the engine map (i.e., speed-torque pairs) under the constraints of the simulated payload and the characteristics of the vehicle components. This is achieved by VECTO through a backward-looking simulation approach.[4] In VECTO's backward-looking model structure, the simulation flow occurs in the opposite direction to the way it takes place in the actual vehicle. In real-world operation, the driver, through the accelerator pedal, gives a command to the engine to provide enough power to bring the vehicle to a desired speed. The energy flow starts with the conversion of the fuel's energy into work by the engine. The engine work continues through the clutch, gearbox, driveshaft, and drive axle to be ultimately converted into tractive work at the wheels.

In VECTO's backward-looking architecture, the Driver module converts the drive cycle information[5]—that is, the desired vehicle speed given a road gradient—into an acceleration request. The information is passed to the Vehicle module, which, on the basis of total vehicle mass, drag coefficient, and rolling resistance, converts the acceleration request into a force request. The Wheel module converts the force request into a torque request at the wheel hub and adds the torque from wheel inertias. The torque request is forwarded to the Brakes[6] and Axle modules. The latter accounts for the respective axle torque losses and sends a torque request to the Transmission module.[7]

The Transmission module contains two submodules, one containing the torque loss maps for all the gears in the gearbox, the other containing the gearshift strategy.[8] On the basis of the selected gear, the Transmission module accounts for the respective torque losses and defines an engine operating speed. The Engine module receives the torque request from the transmission and from the Auxiliaries module, and locates the speed-torque operating point on the engine map. If the resulting engine operating point falls within the boundaries established by the full-load torque curve and motoring drag curve of the engine, the Engine module returns a success message and the simulation advances to the next time interval. If this is not the case, the Engine module returns an error message to the Driver module, which in return reduces the acceleration request if the requested engine torque was above the full-load torque curve.[9] This process is repeated until the Engine module returns a success message. Figure 4 shows the model architecture and the simulation flow.

Once a valid engine operating point has been found, the fuel consumption reading from the steady-state engine fuel map is corrected to account for the effects of transient operation, cold engine operation, aftertreatment system regeneration, and the fuel's heating value. The transient correction factor is determined by comparing the fuel consumption of the engine over the World Harmonized Transient Cycle (WHTC), as measured during engine testing, to the simulated WHTC consumption obtained through interpolation from the steady-state fuel map.[10] The cold-start correction accounts for the fuel consumption over the WHTC in cold conditions, and eliminates the perverse incentive of optimizing hot-WHTC fuel consumption at the expense of the cold-start WHTC performance.[11] The aftertreatment correction factor takes into account the increased fuel consumption during periodic regeneration of the diesel particulate filter.

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4 A previous ICCT white paper on simulation tool comparison (Franco, Delgado, & Muncrief, 2015) provides further information on the concepts of backward-looking and forward-looking simulation.

5 The driving cycles are distance-based (i.e., the road grade and target speed are a function of distance). The simulation, however, advances in the time domain. To achieve the conversion, the cycle is divided in distance steps that cover approximately 0.5 s. With the distance step fixed, the Driver module computes the resulting time step based on its acceleration request. From this point onward, the simulation runs in the time domain.

6 This is relevant only in the case of a higher deceleration than the one resulting from the road load forces.

7 Depending on the equipment, two extra modules can be present: the Angle-drive and the Retarder. The Retarder module does not provide any braking power and only accounts for torque losses during retarder idling.

8 See Franco et al. (2015) for further information on the gearshift strategy.

9 The Engine module can also return an error message if the requested negative torque was below the drag curve. In this case, the driver model operates the vehicle's brakes.

10 The WHTC has three distinct operating regimes: urban, rural, and motorway. The transient correction factor in VECTO weights these three regimes differently according to the driving cycle.

11 The cold-hot balancing factor (BF) is a number greater than 1 that uses the cold and hot specific fuel consumption (SFC) values. It is defined as follows: $BF = 1 + [0.1 \times (SFC_{cold} - SFC_{hot}) / SFC_{hot}]$.

Lastly, the fuel's heating value correction factor accounts for any possible differences between the energy content of the fuel used during engine fuel mapping and the standard fuel used by VECTO in its calculations. The CO_2 emissions are calculated from the corrected fuel consumption values and the carbon content of the standard fuel used in VECTO. Further details can be found in the adopted declaration regulation (European Commission, 2017c).

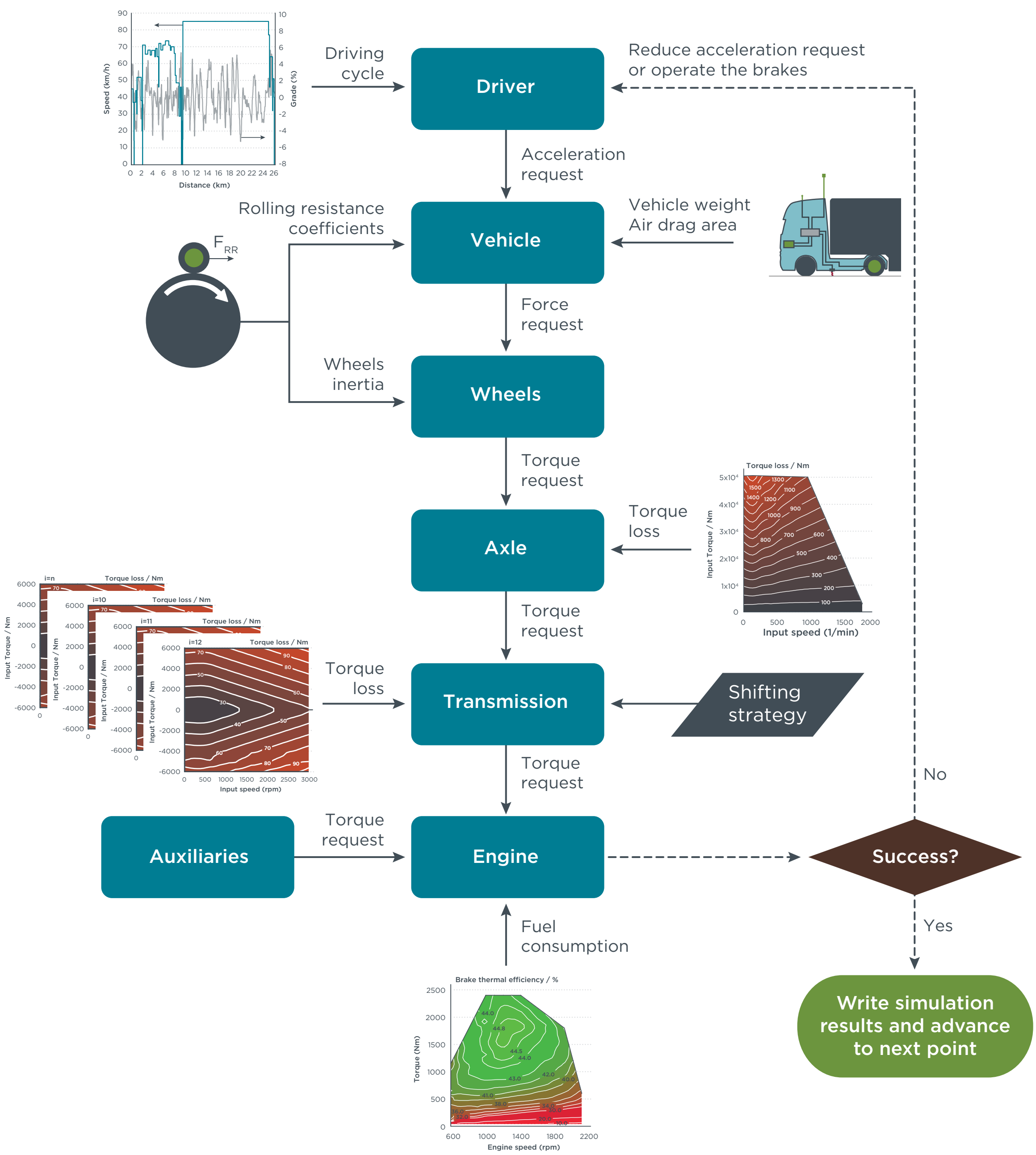

Figure 4. VECTO backward-looking simulation flow. For simplicity, the Brakes, Angle-drive, and Retarder modules are not shown.

VECTO'S LIMITATIONS

VECTO is a sophisticated vehicle simulation tool that has been developed over several years as a joint effort of the European Commission and Graz University of Technology. However, VECTO does not fully capture all of the fuel-saving technologies that are currently in the market or are projected to be commercialized in the coming years. Consequently, any future regulatory measure, such as mandatory CO_2 emissions standards for HDVs, would fail to incentivize the development and adoption of a large number of fuel-saving technologies.

A recent report by the Joint Research Centre (JRC) of the European Commission assessed VECTO's capabilities and limitations through consultation with various stakeholders (Zacharof & Fontaras, 2016). The responses to the survey indicate that several technologies are not fully covered by VECTO or the corresponding declaration procedure. Table 2 lists the technologies identified by the European Automobile Manufacturers' Association (ACEA) that are not fully covered by the declaration procedure.[12]

Table 2. Relevant technologies not fully covered by the HDV CO_2 declaration procedure. Source: Zacharof and Fontaras (2016).

Engine	Electric turbochargers Waste heat recovery Powertrain deep integration Alternator
Aerodynamics	Trailer road-load technologies Adjustable fifth wheel
Tires	Wide-base single tires Tire pressure monitoring Automatic tire inflation
Axles and transmissions	Dual-clutch transmission (DCT)
Hybrids	Hydraulic hybrids Full/mild electric hybrids Flywheel hybrids
Auxiliaries	A/C efficiency
Energy management	Predictive cruise control Advanced driver assistance systems Vehicle speed limiter

Of the 17 technologies[13] that were identified as not fully covered in JRC's survey, seven do not require any modifications in VECTO. Although these technologies can be captured with the current modeling capabilities of VECTO, the HDV CO_2 declaration regulation does not contemplate their impact in component or vehicle certification. These seven technologies are:

» **Alternator:** The alternator is modeled as an engine auxiliary load in VECTO. Currently, a fixed alternator efficiency of 70% is used for the calculation of the engine parasitic power consumption as a function of the vehicle's electrical power consumption. The inclusion of alternators with higher efficiencies is possible without modifying VECTO's architecture.

» **Trailer road-load technologies:** The HDV CO_2 declaration regulation uses pre-defined standard trailers for vehicle declaration; therefore, trailer road-load technologies (i.e., aerodynamic drag, rolling resistance, and mass reduction) are not accounted for. The certification of trailer fuel efficiency technologies will not require any modification in VECTO, as only the trailer-specific input data would change. Trailer technologies have a large impact on a vehicle's CO_2 emissions and can be easily implemented in the existing CO_2 declaration regulation. Because of

12 Other stakeholders were also consulted as part of the JRC survey, with some of the replies being contradictory. ACEA's reply was the most comprehensive and was analyzed separately in JRC's report.

13 This analysis does not consider four technologies reported as "not fully covered" in JRC's report: continuously variable transmissions, auxiliary power units, neutral idling, and external grille shutters. The first two are not as relevant in the EU as they are in the United States. Neutral idling was included in the VECTO release from July 2017. Active flow devices in the tractor, such as external grille shutters, are covered by the adopted declaration regulation (if the devices are always activated and are able to reduce air drag at vehicle speeds over 60 km/hour).

the importance of trailers in curbing CO_2 emissions from road freight, the regulatory options for incentivizing improvements in this area are covered separately in an upcoming publication.

- **Adjustable fifth wheel:** This technology allows the adjustment of the gap between a semi-trailer and the towing tractor, influencing the aerodynamic drag of the tractor-trailer combination. The technology is not widely available in the EU and is not considered in air drag constant-speed testing. However, contrary to the opinion of JRC's survey respondents, the technology's effect can be quantified within the framework of the current CO_2 declaration regulation.
- **Wide-base single tires:** The rolling resistance effect of wide-base single tires can be simulated in the current VECTO model. However, because of the low market penetration of these tires in the fleet and the absence of wide-base single tires as OEM-fitted equipment, they were not included in the tire dimension option in VECTO. The rolling resistance of wide-base single tires can be measured by the same test as for regular tires, ISO 28580.
- **Dual-clutch transmission:** VECTO includes transmission models for four types of transmissions: manual, automated manual, power split automatic transmissions, and serial automatic transmissions. The operating principles of dual-clutch transmissions are similar to those of manual and automated manual transmissions. However, there are differences in shifting logic and traction interruption during shifting. VECTO is capable of modeling these transmissions, although the differences in shifting behavior need to be further studied in order to select the corresponding component and shifting parameters in VECTO. Nonetheless, depending on the level of integration between the engine and transmission, a shifting strategy specific for dual-clutch transmissions could still fail to accurately model the fuel consumption benefits of this technology.
- **A/C efficiency:** A/C systems are modeled in VECTO as a constant auxiliary load on the engine. High-efficiency A/C systems can be captured by the current VECTO model by extending the corresponding auxiliary list. Currently, two A/C options exist: none or default. The inclusion of high-efficiency A/C systems will require a component certification test to determine the system efficiency.
- **Vehicle speed limiter:** Speed limiters can be easily implemented without major modifications to VECTO's model architecture.

Capturing the fuel efficiency benefits of the remaining technologies would require the inclusion of separate modules that capture the main characteristics of the technology and their interaction with the rest of the vehicle. However, the accurate modeling of some of these technologies (e.g., predictive cruise control and hybrid powertrains) would require significant changes in VECTO's model. This is resource- and time-intensive, as it demands a major redesign of VECTO. However, simpler options for the inclusion of these technologies exist. The options for the integration of some of these technologies into the current CO_2 declaration regulation, using the current VECTO model as backbone, are discussed in an upcoming publication.

COMPARISON OF EU AND US VEHICLE SIMULATION TOOLS

The CO_2 declaration methodologies for HDVs in the EU and the United States are similar, insofar as they both use a combination of component testing and vehicle simulation for the declaration of the fuel consumption and CO_2 emissions. In the United States, the vehicle simulation tool, called GEM, was created by the Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) during the development and implementation of the Phase 1 (U.S. EPA & U.S. DOT, 2011) and Phase 2 (U.S. EPA & U.S. DOT, 2016) GHG standards for HDVs. This section provides a description of GEM and highlights the parallels and differences between GEM and VECTO.

GEM'S MODEL ARCHITECTURE

Like VECTO, GEM is a physics-based model that simulates the longitudinal dynamics of HDVs. The simulation of the fuel consumption and CO_2 emissions is based on a series of user-defined and built-in parameters. Table 3 summarizes the user-defined inputs for the definition of the vehicle to be simulated. GEM does not feature a graphical user interface; the inputs are defined in a comma-separated value file with appropriate column formatting.

Table 3. Main GEM inputs.

Component	GEM input
Engine	Displacement, idle speed, fuel consumption map, full-load torque curve, motoring friction curve, fuel consumption over the ARB Transient Drive Cycle for eight or nine different vehicle configurations
Transmission	Transmission type, gear ratios, and maximum torque per gear Optional: Power loss map as a function of torque and speed for each gear
Axle	Axle ratio Optional: Power loss map as a function of torque and speed
Aerodynamic drag	Air drag area as determined by coast-down methodology; standard trailers are used for tractor modeling
Tires	Rolling resistance coefficient (C_{rr}) for each axle; drive tire revolutions per mile
Off-cycle technologies	Improvements through application of speed limiter, neutral idle, intelligent controls, accessory load reduction, extended idle reduction, tire pressure system, and other technologies
Vehicle	Vehicle weight reduction (sum of standardized weight reductions per component), vehicle regulatory subcategory (e.g., Class 8, sleeper cabin, high roof), and axle configuration

The user-defined vehicle parameters are used to simulate the fuel consumption and CO_2 emissions over three specific driving cycles at a specified payload. The output from GEM's simulations consists of the fuel consumption (gal/1000 ton-mile) and CO_2 emissions (gCO_2/ton-mile) over a specific combination of the three regulatory drive cycles. The weighting of the different cycles on the declared fuel consumption and CO_2 emissions is dependent on the vehicle regulatory subcategory (U.S. EPA, 2016). The three drive cycles are ARB Transient, 55 mph with grade, and 65 mph with grade. The ARB Transient drive cycle is a time-based cycle with no grade, whereas the 55- and 65-mph cycles are distance-based cycles with constant target speed and include grade. Figure 5 shows the speed and grade traces for the three GEM cycles used in the Phase 2 GHG standards for HDVs in the United States.

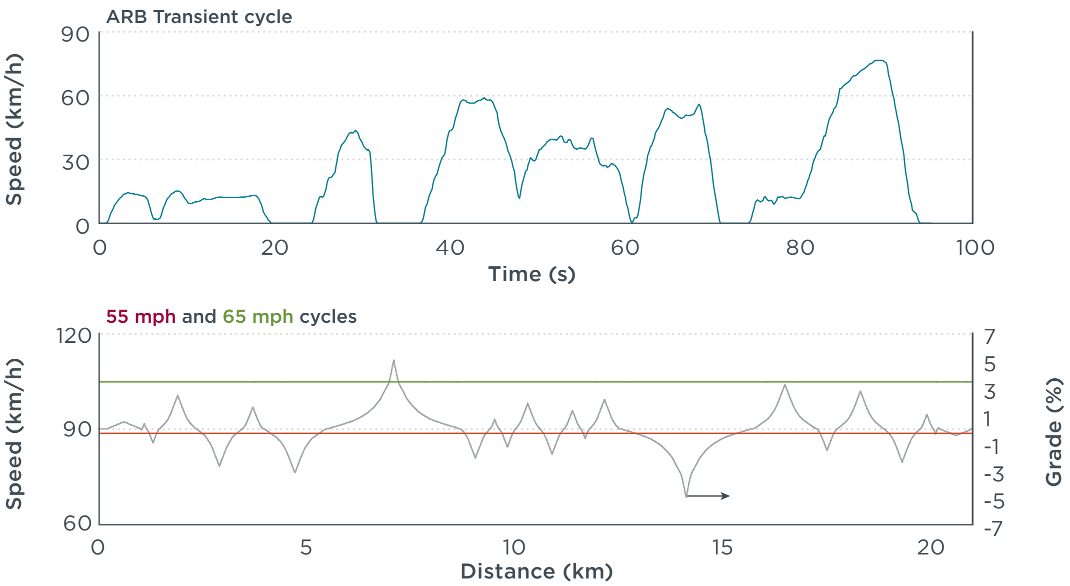

Figure 5. Driving cycles included in GEM Phase 2.

GEM was developed in Matlab Simulink, which is a graphical programming environment for modeling, simulating, and analyzing dynamic systems. Unlike VECTO, GEM is a forward-looking model in which the simulation is run in the same direction as the energy and information flow—that is, from the accelerator pedal to the wheels. The GEM architecture comprises four main modules: Powertrain, Vehicle, Driver, and Ambient (Figure 6). The vehicle speed and acceleration are the result of the interaction of the Driver, Powertrain, and Vehicle modules through a network of feedback loops. The Powertrain module is the core component of GEM and consists of the Engine, Transmission, Driveline, and Accessories submodules and the interactions between them. The Engine submodule receives the accelerator pedal position signal from the Driver module and translates it into a torque request. The torque request is then limited by a torque response submodule that uses the engine displacement and the maximum torque curve of the engine to estimate the engine's response. The result of this process is the torque output at the engine's crankshaft, which in turn is used to calculate the fuel flow by interpolation of the steady-state fuel consumption map defined by the user.

The engine's output torque is fed into the Transmission submodule, which contains the transmission controller and the mechanical model of the transmission, and executes the preprogrammed shifting strategy. The shifting strategy attempts to select the gear that allows minimum fuel consumption after applying constraints on engine speed and torque reserve. It also allows downshifts due to high driver demand. The resulting torque at the transmission's output shaft is transferred to the driveline. In the Driveline submodule, the torque flows from the driveshaft to the axle to the tires. In each step, the mechanical models of each of these components adjust the torque signal to account for the rotational inertia, the mechanical losses, and the tires' rolling resistance.

The output of the Driveline submodule is a net thrust force at the wheel hub. This signal is transferred to the Vehicle module, which calculates the vehicle dynamics based on vehicle mass, aerodynamic drag coefficient, and road grade. The output of the Vehicle module is the resulting vehicle speed at the end of the simulation time interval, along with the new position of the vehicle with respect to the driving cycle. The vehicle speed and powertrain response are fed back into the Driver module so that it can update the accelerator pedal position, effectively closing the loop of GEM's forward-looking architecture. The closed-loop Driver module is a proportional-integral-derivative controller that looks ahead in the drive cycle to anticipate its response. The Driver module allows the vehicle to exceed the target speed by 3 mph before the brakes are applied.

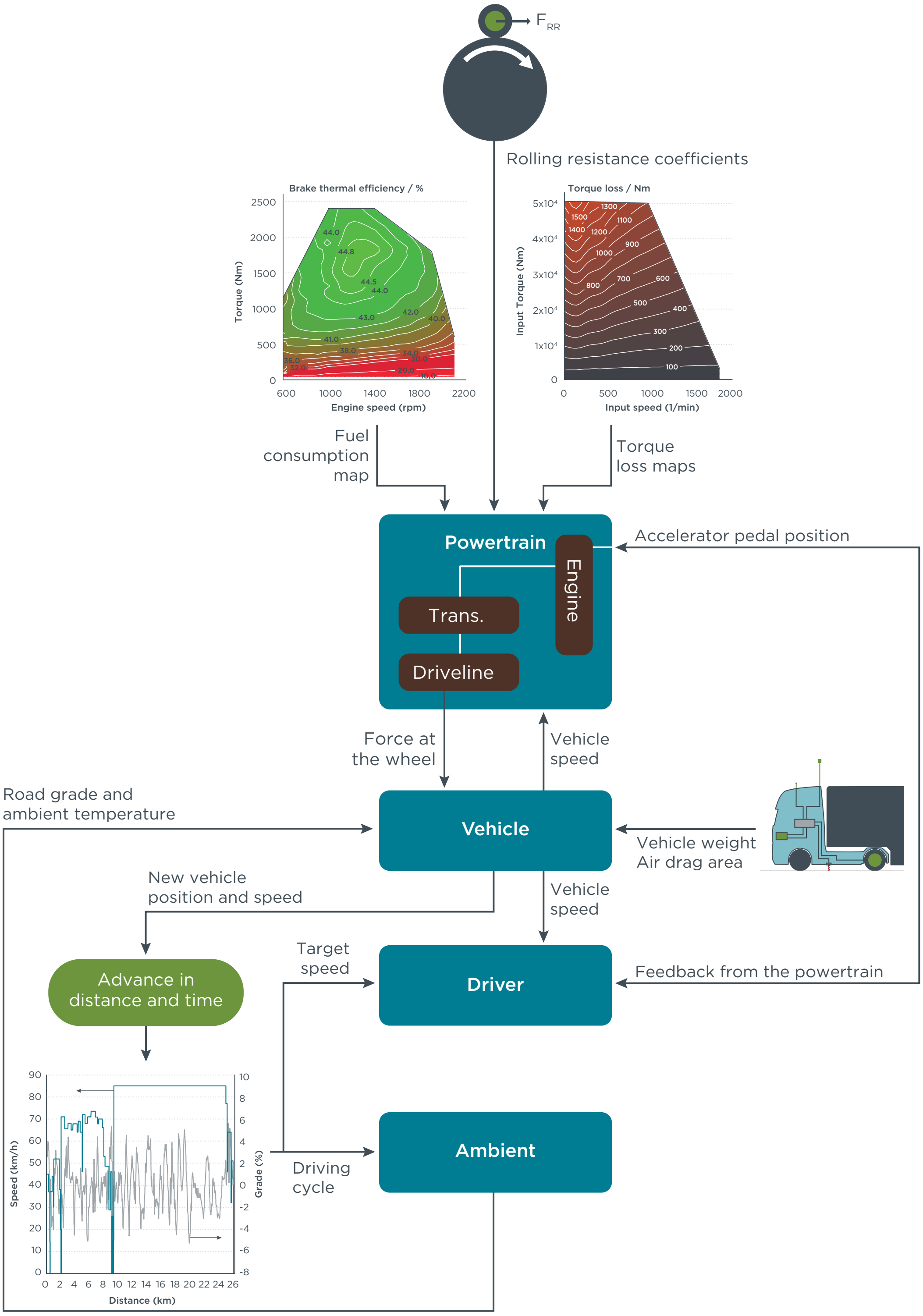

Figure 6. GEM forward-looking model architecture. For simplicity, only the key modules and features of GEM's architecture are shown.

PARALLELS AND DIFFERENCES BETWEEN VECTO AND GEM

Both VECTO and GEM are physics-based models that simulate the longitudinal dynamics of HDVs. However, the simulation of fuel consumption follows different approaches in each tool. VECTO uses a backward-looking architecture, in which the simulation flow occurs in the opposite direction of the actual energy and torque flows. GEM, on the other hand, uses a forward-looking architecture in which the driver interacts directly with the vehicle through the accelerator pedal. The simulation proceeds in the same direction as the energy and torque flows.

This section addresses the differences and similarities between VECTO and GEM that go beyond the underlying difference in the model architecture. In particular, we discuss the differences in the built-in simulation parameters and in the processing of the user inputs.

Engine fuel map

Although both tools use stationary engine fuel consumption maps, there are some subtle differences in the corrections done to these maps before they are used in the simulation. For both regions, the fuel consumption mapping procedure is based on existing engine testing regulations.[14] In the EU, the fuel map must be corrected to account for variations in the fuel heating value, and correction factors are used to account for the periodic regeneration of the diesel particulate filter, and the cold start fuel consumption. In the United States, the fuel map is corrected to account only for variations in the fuel heating value.

Both simulation tools use transient correction factors to account for the transient performance when interpolating the fuel flow from the steady-state fuel consumption map. For a given engine in the United States, the engine must be tested over eight or nine different speed-torque traces that correspond to the engine operating points of different vehicle configurations over the ARB Transient cycle. GEM uses this information to account for transient operation, the so-called "cycle-average engine fuel maps" (Zhang et al., 2016, U.S. EPA & U.S. DOT, 2016, § 1036.540). Manufacturers also have the option of using the cycle averaging procedure for the 55 mph and 65 mph constant speed cycles.[15]

In the EU, the engine must be tested over the WHTC. The transient correction factor is determined by comparing the fuel consumption of the engine over the WHTC, as measured during engine testing, to the simulated WHTC fuel consumption obtained through interpolation from the steady-state fuel map. Three individual correction factors corresponding to the three distinct operating regimes of the WHTC (i.e., urban, rural, and motorway) are provided to VECTO. For a given driving cycle, VECTO calculates the overall transient correction by an appropriate weighting of the three individual correction factors.

Transmission and axle efficiency

Both models use torque loss maps as a function of input speed and torque for determining the energy losses of the transmission and the drive axles. In VECTO, the user input of the torque loss maps is mandatory. In GEM, the user can choose GEM's predefined spinning losses and efficiency values, or can provide detailed power loss maps.

Tire rolling resistance

Tire rolling resistance coefficients (C_{rr}) are one of the key parameters for determining a vehicle's fuel consumption. In both regions, tire rolling resistance is measured using the test procedure defined by the standard ISO 28580.[16] GEM assumes that tire rolling resistance remains constant with load, and uses the rolling resistance coefficients

14 United States: Regulation 40 CFR parts 86, 1036, and 1065. EU: UN/ECE Regulation 49 Rev.06, Annex 4.

15 This paragraph was revised on March 7, 2018 to clarify the US cycle-average test procedure.

16 In the EU, the regulation defining the rolling resistance testing is UN/ECE Regulation R117. However, the provisions established in UN/ECE R117 are equivalent to those in the standard ISO 28580.

measured during testing directly without applying any correction factor. VECTO, on the other hand, assumes that the rolling resistance coefficient decreases slightly with increasing vertical load, and corrects the input values to capture this effect (Graz University of Technology & Joint Research Centre, 2017). Given the default payloads used by VECTO's declaration mode, the actual vertical loads observed by the tires during simulation are usually lower than those specified in the standard testing procedure, which are established at 85% of their maximum load capacity in the ISO 28580 standard. As shown in Figure 7, the net result of the correction is a higher rolling resistance coefficient during the VECTO simulation than the one measured in the ISO 28580 test.

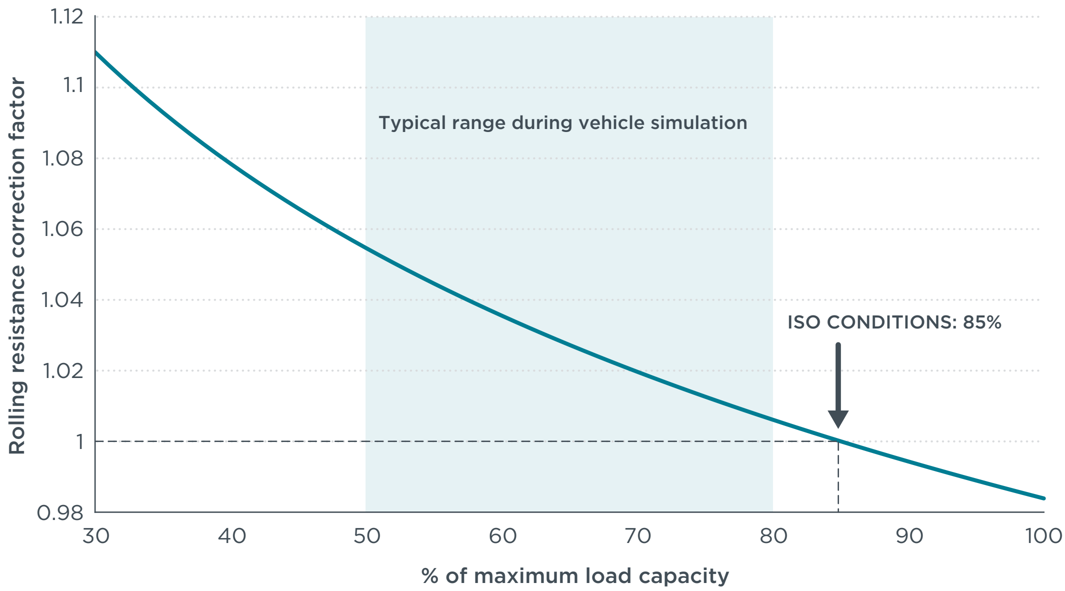

Figure 7. Correction factor applied by VECTO to the rolling resistance as a function of the tire load factor

Vehicle air drag

The United States and the EU use different testing procedures for the determination of the air drag area. The US air drag test is based on a coastdown procedure. In the EU, a constant-speed methodology is used. Both methodologies measure the air drag area (C_dA),[17] which is then input into the simulation tools. Because the simulated fuel consumption is sensitive to the aerodynamic resistance, it is important that the simulation tools use realistic wind conditions, particularly accounting for crosswind conditions. In the United States, the C_dA measured in the coastdown procedure is adjusted to reflect the wind-averaged conditions. The latter are defined as constant crosswinds with an air direction of 4.5° with respect to the vehicle's longitudinal axis—that is, a yaw angle of 4.5°. This corrected value serves as GEM's input. The simulation tool does not apply any further correction.

In the EU, the crosswind correction is done directly by VECTO. The constant-speed test results are corrected to represent the C_dA at 0° yaw angle. This value is directly used in the simulation tool. VECTO's correction of the declared C_dA value at 0° yaw angle is a function of vehicle speed and assumes a wind speed of 3 m/s at 4 m above the ground, blowing from all directions with a uniform distribution. VECTO's air drag correction also takes into account that wind speed is a function of vertical distance to the ground, assuming a parabolic shape for the air speed profile as a function of height.

17 The air drag area is the product of the air drag coefficient (C_d) and the vehicle's frontal area (A).

Vehicle mass and payload

The treatment of the vehicle mass and payload differs between the two simulation tools. For each vehicle type, GEM uses a predefined vehicle mass that is adjusted downward by the standard weight reduction from the use of lightweight materials, such as aluminum, high-strength steel, and thermoplastics. The preapproved lightweighting technologies are listed in the Phase 2 HDV GHG regulation (U.S. EPA & U.S. DOT, 2016, § 1037.520). The resulting total weight reduction affects the total vehicle mass used in the simulation run, as well as the corresponding applied payload. GEM adjusts the payload used during simulation upward to account for the higher carrying capacity obtained through the lightweighting technologies. The payload is increased by one-third of the total weight reduction; as a result, the total reduction in vehicle mass during simulation is two-thirds of the total weight reduction. In VECTO, the vehicle mass and payload are treated more straightforwardly: The curb mass of the vehicle forms part of the VECTO inputs, and the simulated payload is a function of the vehicle group and corresponding driving cycle.

To account for the rotational inertia of the wheels during transient operation, GEM adjusts the vehicle mass by adding 125 pounds for each tire present in the vehicle. The resulting mass, called dynamic mass, affects only the inertial forces (i.e., forces due to acceleration) and has no impact on the gravitational forces (i.e., does not affect the other components of the road load forces). In VECTO, the rotational inertia of the wheels is accounted for directly; VECTO assumes a wheel inertia that is a function of the tire dimensions.

SIMULATION COMPARISON BETWEEN VECTO AND GEM

In 2015, ICCT conducted a study (Franco et al., 2015) comparing the simulation results of VECTO and GEM. Since then, both tools have been substantially updated, warranting a new comparison of their simulation results.

For this comparison exercise, VECTO 3.2.1.1054 and Phase 2 GEM were used; they correspond to the latest available versions of the simulation tools. The analysis was performed on the executable, publicly available versions of the tools to prevent unintentional modifications to the models. Given the great flexibility provided in VECTO's engineering mode, access to the source code was not necessary for detailed modification of the simulation boundary conditions. GEM, on the other hand, does not provide the same flexibility, as many parameters use the built-in default inputs and cannot be modified by the user. This resulted in specific constraints for the selection of the simulation scenarios (i.e., vehicle definitions, test cycles, and payloads).

Vehicle definition

For comparison of the tools, it was necessary to define a number of base vehicles. The definition of the vehicle in GEM is done through the inputs shown in Table 3. The total simulation weight, number of axles, and payload are defined according to the vehicle regulatory subcategory. Furthermore, GEM includes a number of predefined modeling parameters that are used for all tractor-trailers. These include the gearbox mechanical efficiency, axle mechanical efficiency, electric and mechanical accessory power consumption, trailer rolling resistance, and weight distribution over the axles. VECTO's engineering mode allows for the modification of all the user-defined and built-in parameters used by GEM. Therefore, the vehicles were defined using GEM's standard vehicles as a starting point. Great care was taken to generate a set of inputs for VECTO that matched the exact parameters defined in GEM.

Two main base vehicle types were studied: (1) a 4x2 day cab, mid-roof tractor-trailer equipped with a 262 kW engine and a 10-speed automated manual transmission (AMT), and (2) a 6x2 sleeper cab, high-roof tractor-trailer with a 340 kW engine and the same 10-speed AMT (see Table 4 and Figure 9 to 11). For each vehicle type, values for the axle ratio, air drag area, steering axle rolling resistance, drive/tandem axle rolling resistance, and vehicle weight reduction were randomly selected using a uniform distribution in the ranges shown in Table 4. A total of 500 unique vehicle configurations were randomly generated for each of the two vehicle types. As an example, Figure 8 shows the distribution of the values of the aforementioned parameters for the 500 different 6x2 tractor-trailers simulated.

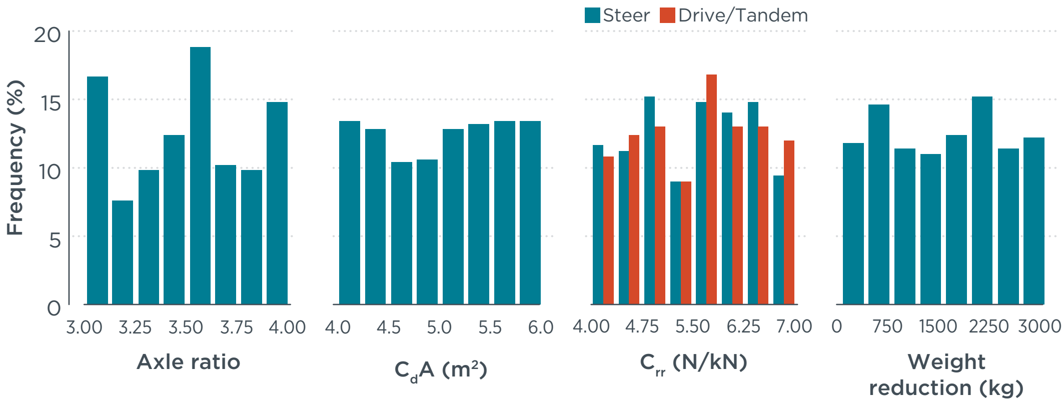

Figure 8. Distribution of the input parameters for the 6x2 tractor-trailer simulation.

Table 4. Vehicle specifications used in the GEM and VECTO simulations.

Component	Parameter	4x2 tractor-trailer	6x2 tractor-trailer
Engine	Displacement	11.0 liters	15.0 liters
	Idle speed	650 rpm	600 rpm
	Power	262 kW @ 1715 rpm	340 kW @ 1726 rpm
	Fuel consumption map	See Figure 9	
	Transient correction	None	
Transmission	Transmission type	AMT	
	Gear ratios	12.8; 9.25; 6.76; 4.9; 3.58; 2.61; 1.89; 1.38; 1; 0.73	
	Torque loss map	See Figure 10	
Axle	Axle ratio	Between 3:1 and 4:1	
	Torque loss map	See Figure 11	
Aerodynamic drag	C_dA	Between 4 and 6 m²	
	Crosswind correction	None	
Tires	C_{rr} steering axle	Between 4 and 7 N/kN	
	C_{rr} drive/tandem axles	Between 4 and 7 N/kN	
	C_{rr} trailer axles	6 N/kN	
	Tire dynamic radius	512 mm	
Accessories	Accessory power	3500 W (constant)	
	Accessory load reduction	None	
Vehicle	Base vehicle mass	9570 kg	14741 kg
	Base payload	11340 kg	17237 kg
	Vehicle weight reduction	Up to 2000 kg	Up to 3000 kg
	Max. vehicle overspeed	4.8 km/h	
	Total number of axles	4	5

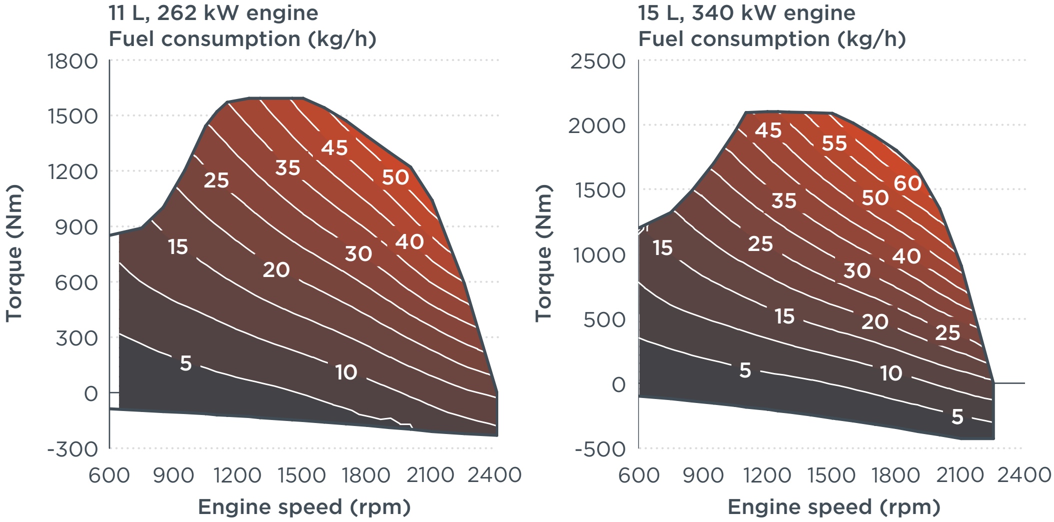

Figure 9. Engine fuel maps used for the simulated 4x2 and 6x2 tractor-trailers.

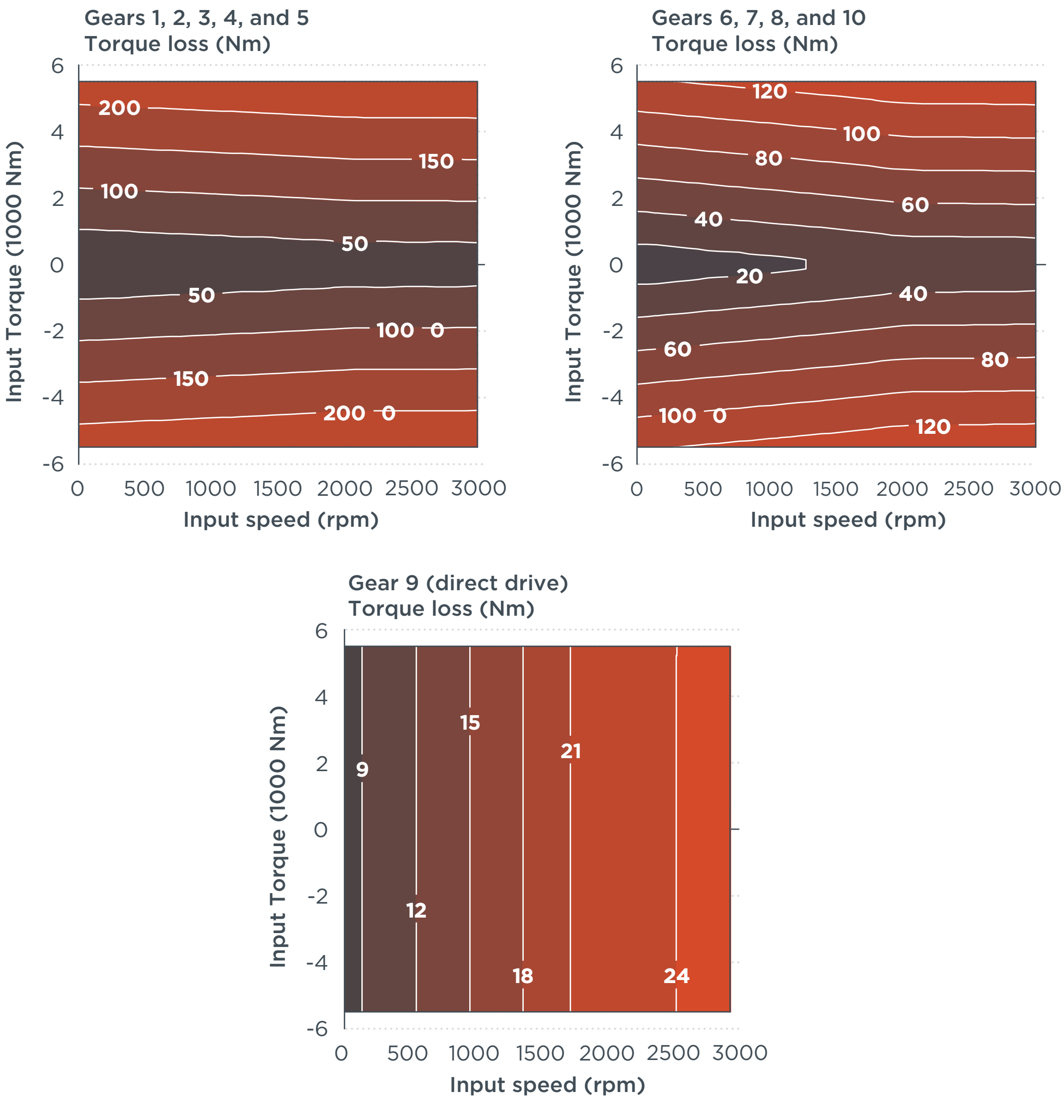

Figure 10. Torque loss maps for the 10-speed AMT transmission.

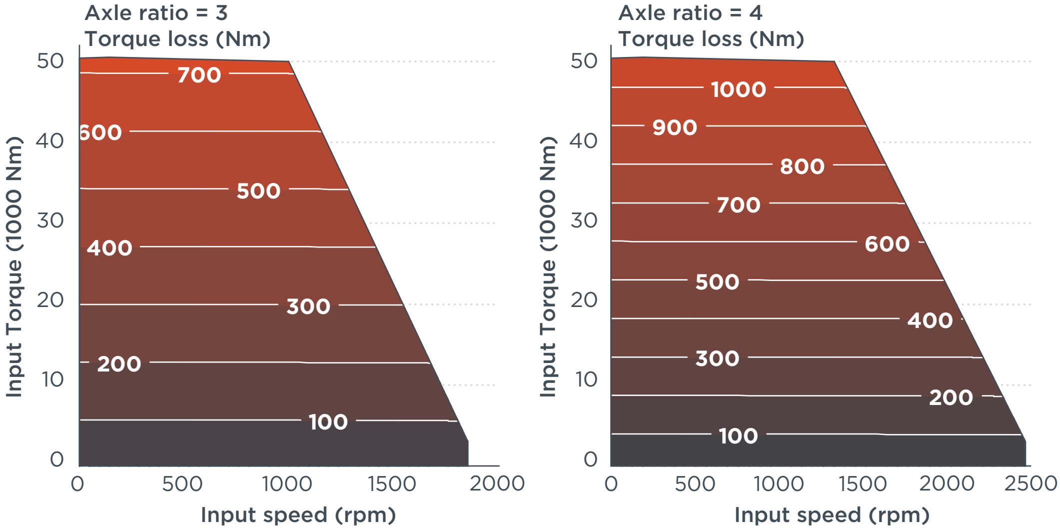

Figure 11. Torque loss maps for the drive axle for ratios 3 and 4. The torque loss maps were determined as a function of the axle ratio according to GEM's built-in procedure. The torque loss maps of the other axle ratios used fall between these two extremes.

Duty cycle, payload, and boundary condition adaptations

GEM does not allow the use of user-defined driving cycles. Therefore, the comparison analysis was performed using the three built-in cycles in Phase 2 GEM: ARB Transient, 55 mph with grade, and 65 mph with grade. These cycles are shown in Figure 5. The ARB Transient cycle is a time-based cycle with no grade, whereas the 55- and 65-mph cycles are distance-based cycles with constant target speed and grade. Because VECTO allows for both time- and distance-based simulations, no adaptation of the GEM test cycles was required. VECTO was then run in time mode simulation for the ARB Transient cycle, and in distance mode simulation for the other two cycles.

VECTO and GEM include methodologies to account for the transient correction of the steady-state fuel maps. These correction approaches were deactivated in each tool to eliminate the influence of transient correction on the comparison exercise. In VECTO, the transient correction can be directly eliminated by setting the WHTC correction factor to 1. In GEM, however, the transient correction takes place through a cycle-averaged methodology. In this approach, the engine must be physically tested on an engine dynamometer over nine ARB Transient cycles corresponding to nine predetermined vehicle configurations. For each vehicle configuration, the corresponding engine speed-torque points are generated using GEM's cycle generation tool. To eliminate the transient correction in GEM, it was necessary to use GEM's cycle generation tool to generate the speed-torque points for these nine transient cycles. The resulting engine cycles were used to simulate the fuel consumption and engine work in VECTO's engine-only mode. VECTO's engine-only mode directly interpolates the steady-state engine map without applying any transient correction. The results were provided to GEM as the required cycle-averaged input. This approach eliminates the transient correction while satisfying GEM's input requirements (see Table 3).

As discussed above, GEM adjusts the payload used during simulation upward to account for the higher carrying capacity obtained through weight reduction. This approach affects both the total vehicle mass used in the simulation run and the corresponding payload. As a result, the base payload shown in Table 4 corresponds to the case of no weight reduction. For tractor-trailers, if lightweighting technologies are used, the payload is increased by one-third of the total weight reduction. VECTO's payload was adjusted consistently to capture this payload correction performed by GEM.

Care was also taken to ensure that the internal corrections performed by VECTO on the air drag area and the rolling resistance were not active, so that the input values are used directly in the simulation. For the air drag resistance, VECTO's engineering mode allows for direct deactivation of the crosswind and boundary layer corrections. In the case of the rolling resistance, VECTO's internal adjustment was deactivated by matching the vertical loads during simulation and the load assumed to be applied during the rolling resistance test.

Lastly, the dynamic mass correction performed by GEM to account for the rotational inertia of the wheels during speed transients (i.e., acceleration and braking) was accounted for in VECTO by setting the wheel inertia to a negligible value and increasing the vehicle curb mass during the simulation of the ARB Transient cycle. Because this cycle does not have grade, there was no impact of the added mass on the gravitational component of the road load. The effect of this additional vehicle mass on the rolling resistance proved to be negligible and was not corrected for. Because the 55- and 65-mph cycles are constant-speed cycles, GEM's dynamic mass correction has no measurable effect, and no additional correction was necessary for the VECTO input.

Simulation results

A total of 6000 simulations were run corresponding to the two simulation tools (GEM and VECTO), three drive cycles (ARB Transient, 55 mph, and 65 mph), two vehicle types (4x2 and 6x2 tractor-trailers), and 500 individual parameter combinations for each vehicle type. Two key simulation output metrics were used to compare GEM and VECTO over the three different driving cycles: the engine crankshaft work (kWh) and the payload specific fuel consumption per kilometer (g/tonne-km). VECTO and GEM exhibited similar simulation durations. Although VECTO's backward-looking model results in shorter computation times, the reading and verification of the input files can be time-consuming. GEM's forward-looking model results in longer computation times; however, given GEM's simple input format (as a .csv file), the reading of the input data requires relatively little time.

The engine work metric is useful to gauge the agreement between VECTO and GEM in the energy flows observed by the engine. As discussed above, the simulated engine work is dependent on the combined influences of aerodynamic drag, rolling resistance, inertial forces, and gravitational forces applied to the vehicle over the driving cycle, as well as on the energy losses originating in the axle and transmission (see Figure 4 and Figure 5). Because the component inputs were carefully matched between the simulation tools, the differences observed in simulated engine work between VECTO and GEM would stem mainly from the driver model (ability to follow a target drive cycle) and the model architecture (forward- versus backward-looking models).

The fuel consumption metric is useful way to measure the impact of the shifting strategies built into VECTO and GEM. For a given value of engine work, the shifting strategy determines the regions of the engine map (see Figure 9) used to provide the required engine power. Differences between VECTO and GEM for a given value of engine work can be attributed to differences in shifting strategies.

Figure 12 shows the results from the comparison exercise between VECTO (*x* axes) and GEM (*y* axes). The results are displayed according to vehicle type, driving cycle (transient without grade; constant speed with grade), and output metric (fuel consumption; engine work). For each set of data, a simple linear regression model with forced intercept at the origin was fit to the results to assess the agreement between VECTO and GEM. The regression coefficients and the coefficients of determination (R^2) were used to quantify the agreement between VECTO and GEM.

The results show that despite the differences in model architecture (forward- versus backward-looking), driver model, and shifting strategy, VECTO and GEM produce similar results in terms of engine work and fuel consumption. Over the ARB Transient cycle (Figure 12, top), the results show that GEM slightly overpredicts fuel consumption with respect to VECTO, by 1% and 3% for the 6x2 and 4x2 vehicle types, respectively. The simulated engine work, on the other hand, shows a smaller disagreement between the models, with a difference below 1%.

Over the 55- and 65-mph cycles with grade (Figure 12, bottom), the regression coefficient and R^2 are closer to unity for both the fuel consumption and the engine work. The results show that over the constant-speed cycles with grade, GEM simulates a fuel consumption that is up to 1% higher than that simulated by VECTO. Because fewer gear shifts are required to follow these drive cycles, the influence of the shifting strategy on the GEM-VECTO correlation is reduced. Note, however, that despite the constant-speed character of the cycle, the presence of road grade results in torque excursions and some speed transient events when gear shifting is required to cope with the cycle's grade. Thus, the influence of gear shifting is not completely eliminated in these cycles.

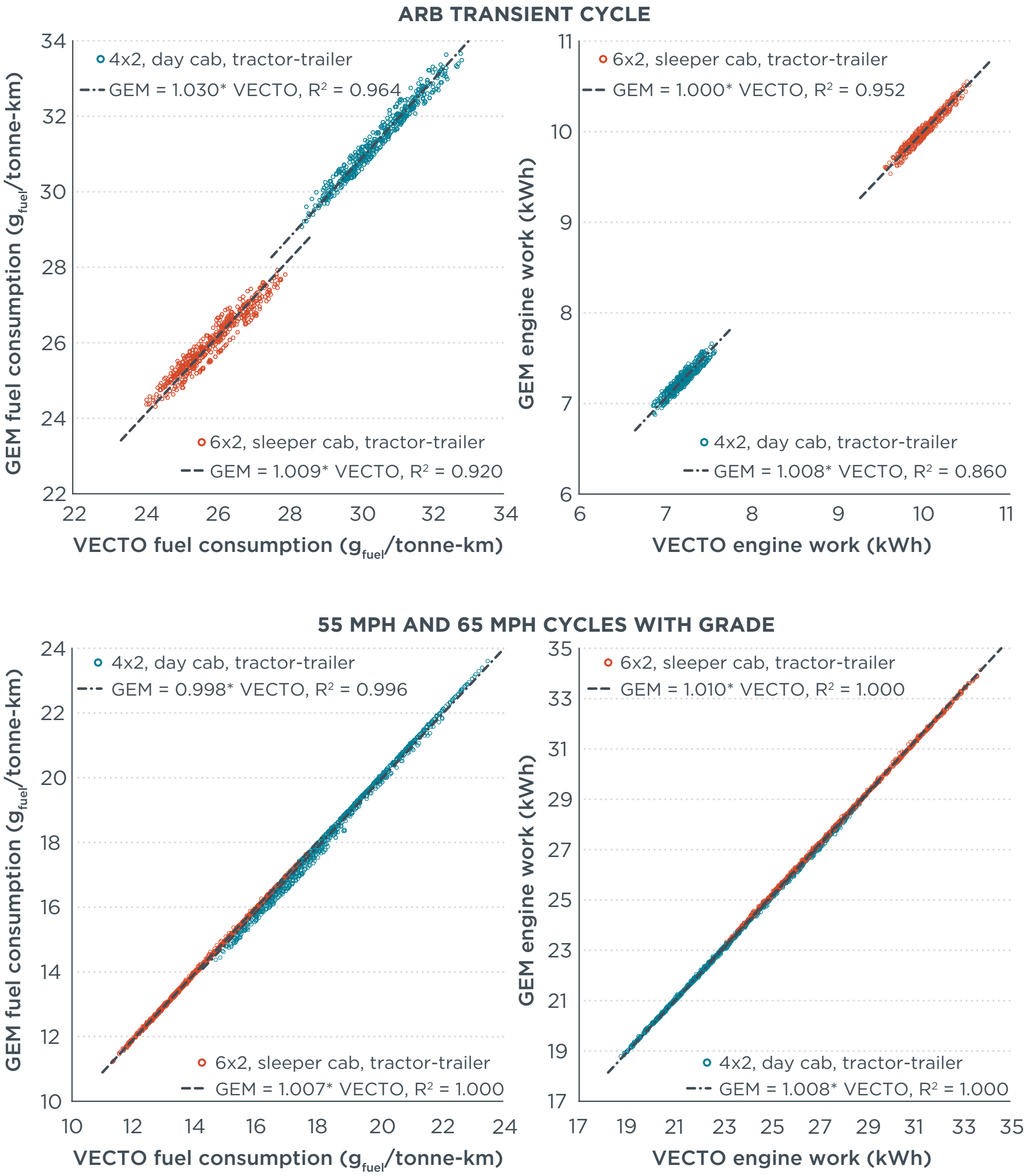

Figure 12. Comparison of the fuel consumption and engine work as simulated with VECTO and GEM.

In summary, the differences in model architecture do not seem to have a measurable impact on the performance of the studied models. Despite the fundamental differences posed by the use of backward-looking simulation in VECTO and forward-looking simulation in GEM, the comparison exercise shows very good agreement between the simulation tools. The small disagreements observed between GEM and VECTO, and the moderate unaccounted variability (R^2 ranging from 0.86 to 1) of the VECTO-GEM correlation models, can be attributed to the differences in shifting strategies used by each tool. It can be concluded that for a given technology improvement, the two models simulate similar CO_2 emissions and fuel consumption reduction in relative and absolute terms.

In the case of VECTO, the transition from backward-looking to forward-looking simulations would require major modifications to the current modeling architecture. The results of the present analysis suggest that the modeling methodology is highly sensitive to the component input information but less sensitive to the underlying model architecture. It is therefore advisable to maintain the current VECTO backward-looking architecture for the future implementation of advanced fuel efficiency technologies and for the respective manufacturer-specific control strategies.

CONCLUSIONS

Vehicle simulation is the backbone of the certification procedure for CO_2 emissions of heavy-duty vehicles around the world. The simulation tools for the modeling of the longitudinal dynamics of HDVs use simple force balances to estimate the energy use at different points of a vehicle's powertrain, as a function of internal driveline losses, aerodynamic drag, rolling resistance, and inertial and gravitational forces. The accuracy of the simulation results depends on a detailed characterization of the vehicle components through component testing.

Examination of the model structures of VECTO and GEM, the regulatory simulation tools in the EU and the United States, reveals fundamental differences in their architectures. Yet the comparison of the simulation results from both tools, over a large set of identical input data, shows that the differences in model architecture and driver modeling result in minor differences in simulated fuel consumption.

The success of a vehicle simulation approach to capture the real CO_2 emissions of heavy-duty vehicles is strongly reliant on the accuracy of the component input data, on the internal preprocessing of these data by the simulation tool, and on the range of technologies simulated. The impact of the model architecture, driver modeling, and shifting strategy on the simulated fuel consumption is evidently less important.

A number of current and future fuel efficiency technologies are not captured by VECTO and the corresponding CO_2 declaration procedure. Most notably, the current declaration procedure does not capture improvements in the aerodynamics, rolling resistance, and mass reduction (i.e., road-load technology improvements) from trailers. The long-haul fuel consumption reduction potential stemming from road-load technology improvements in the trailer alone is estimated at 15% (Delgado, Rodríguez, & Muncrief, 2017). The trailer technologies required to achieve this sharp fuel consumption reduction are currently available in the market, although adoption rates are low. To incentivize the rapid adoption of fuel-saving trailer technologies, it is essential for trailers to be included in the ongoing regulatory efforts to address the CO_2 emissions of HDVs, and thus for trailers to be included in the CO_2 declaration regulation. This inclusion does not require any major modifications to the simulation tool, nor to the technical provisions of the declaration regulation. Detailed recommendations to achieve this will be described in an upcoming publication.

Other key technologies that are not captured by the CO_2 declaration procedure include electric powertrains, hybrid powertrains, powertrain deep integration, and waste heat recovery systems. Although these technologies are not yet commercially available or have negligible market penetration, they have been in development in recent years and their potential for reducing fuel consumption has been demonstrated. The market uptake of these technologies can be positively influenced by regulatory measures aimed at improving the fuel efficiency of HDVs. However, this would require their effect to be captured by the CO_2 declaration procedure.

The European Commission has set an ambitious timeline for the introduction and implementation of regulations aimed at curbing HDV CO_2 emissions. Experience with the development of VECTO indicates that developing and implementing additional models into the simulation tool would require a substantial commitment of time and resources. It is thus advisable that policymakers address the current limitations of VECTO without disrupting the adopted CO_2 declaration procedure. The available options to achieve this will be outlined in an upcoming publication.

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