WHITE PAPER

APRIL 2015

HEAVY-DUTY VEHICLE FUEL-EFFICIENCY SIMULATION:

A COMPARISON OF US AND EU TOOLS

Vicente Franco, Oscar Delgado and Rachel Muncrief

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

www.theicct.org

communications@theicct.org

BERLIN | BRUSSELS | SAN FRANCISCO | WASHINGTON

ACKNOWLEDGEMENTS

This work was generously funded by ClimateWorks Foundation. The authors are grateful for this and other funding sources, which allow us to fulfill our mission of improving the environmental performance of vehicles in the transport sector. Special thanks go to our colleagues at the US Environmental Protection Agency and at the European Commission–DG Joint Research Centre who provided feedback on an earlier draft of this work.

For additional information:

International Council on Clean Transportation
1225 I Street NW, Suite 900
Washington DC 20005 USA

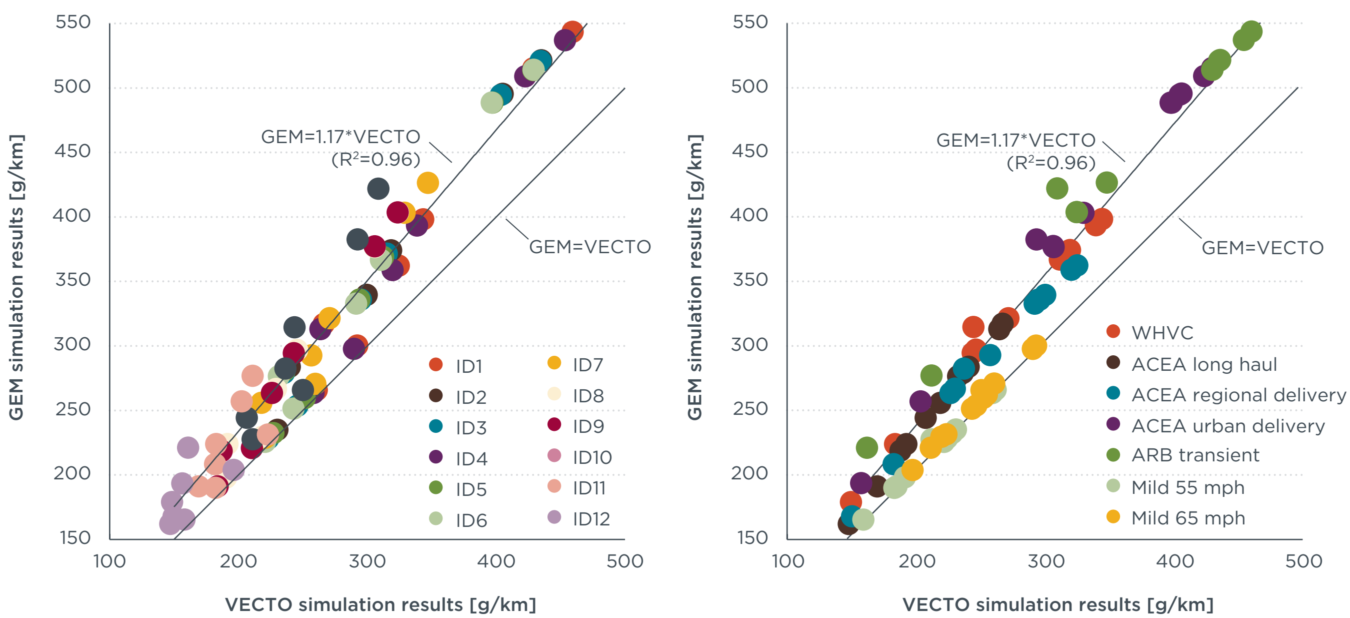
communications@theicct.org | www.theicct.org

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Vehicle simulation tools can enable a reliable estimation of the fuel efficiency of HDVs while eliminating undesirable sources of variation such as driver behavior or the influence of ambient conditions. This report discusses the use of simulation tools to certify the whole-vehicle efficiency of heavy-duty vehicles (HDVs), and presents a comparison of the tools used for the regulatory quantification of CO_2 emissions from HDVs in the US (GEM v2.0, used for HDV GHG/FE Phase 1 regulation) and the EU (VECTO v2.0.3 beta; not yet used in a regulatory context). The comparison covers both the software implementation and methodological aspects, and is intended to explore the differences between two tools that are intended for similar uses but were developed independently.

Both GEM and VECTO were reviewed based on the available documentation and source code, and the different parameters of the models were aligned to the extent possible. Twelve HDVs were simulated in both models under seven different duty cycles, using both tools. For one of the simulated cycles, a simple **"one-at-a-time" sensitivity analysis** was performed by controlled variation of selected parameters in both simulation environments.



The results of the simulations show important differences that can be attributed to the model components (e.g., driver model, gearshift strategy) that differed most significantly between the two models. For most parameters, the sensitivity analysis confirms the expected linear behavior of the models within moderate ranges of parameter variation.

Computer simulation offers regulators and OEM manufacturers exciting prospects for the certification of HDV efficiency and CO_2 emissions. Whole-vehicle simulation techniques have the potential to reduce vehicle testing efforts worldwide and improve the quality and availability of much-needed HDV efficiency data.

1 INTRODUCTION

Unlike light-duty vehicles, HDVs are sold with many possible combinations of engines, transmissions, and body styles. To type-approve all the possible combinations would be expensive and impractical, so **engine dynamometer** testing has historically been the preferred method for criteria pollutant emissions type-approval tests of heavy-duty engines. However, engine dynamometer testing is not suitable for measuring fuel economy or CO_2 emissions because the emissions of the complete HDV are not reflected by engine testing alone.[1] This test procedure would, therefore, if used for efficiency type-approval, incentivize energy efficiency improvements at the engine level only.

Chassis dynamometer testing (placing the entire HDV on a roller bench and measuring its efficiency while driving it over a standard test cycle) is an ideal way of assessing the emission behavior of HDVs, as this technique inherently considers the entire vehicle (Sharpe and Lowell, 2012). The main disadvantage of this measurement technique is the high cost of individual test runs and the high operating costs of HDV chassis dynamometer laboratories. In order to counterbalance these increased costs, **vehicle simulation** is becoming an increasingly important tool for regulators. Vehicle simulation software can be used for the prediction of fuel consumption and CO_2 emissions from HDVs under various operating conditions, as long as sufficiently detailed models are provided and the necessary input data and parameters are available.

Vehicle simulation is useful for both policy analysis and monitoring. Given the fast rate of development of technologies associated with road transport and the pressure to reach demanding targets, vehicle simulation models can provide a relatively inexpensive and valuable source of information, particularly in cases where experimenting becomes impractical (Kousoulidou et al., 2013, Franco et al., 2015). Using vehicle simulation in a regulatory environment has several advantages for both regulators and HDV manufacturers:

» A large number of simulation runs can be performed with a very small marginal cost.

» The influence of the whole vehicle is captured (both individual components and interactions between them).

» Results can capture energy efficiency/fuel saving improvements.

» Simulation models/procedures are flexible and can be adjusted with reasonable costs.

» Regulations can be aligned with the practices of industry, which already employs computer simulations for whole-vehicle efficiency assessment.

1 This is generally true, although modern engine test benches can be made to run any real-world engine load test cycle by simulating the vehicle to get torque and engine speed curves, either offline or as hardware-in-the-loop simulation (HILS). If this method were used for certification, it would create the issue (mentioned previously) of having to run a large number of physical tests.

2 DESCRIPTION OF THE MODELS

VECTO and GEM are similar tools used and developed for similar purposes. Both models comprise the following main elements:

1. A user interface for data input.
2. A default database of vehicle configurations, driving cycles, engine maps, and default values for component data.
3. A core physical model that performs the simulation of vehicle operation and predicts the corresponding fuel consumption and CO_2 emissions from engine maps.
4. Post-processing routines for generating aggregated results.[2]

In the sections that follow, both models are briefly described, with a focus on the characteristics that set each model apart from the other.

2.1 GENERAL ARCHITECTURE

VECTO (Vehicle Energy Consumption Calculation Tool) is a software tool developed for the simulation of fuel consumption and CO_2 emissions from HDVs. It is based on **component test data** (Hausberger et al., 2012). VECTO is built upon the calculation routines initially developed by the Technical University of Graz in Austria, and is an ongoing development.[3] VECTO is written in Visual Basic.NET, a multi-purpose, object-oriented computer programming language created by Microsoft that is suitable for general software development.

For our comparison exercise, no access to the source code of VECTO was possible. However, the tool was provided to ICCT in "proof of concept" mode, which allows the user to access a large number of model parameters, which are for the most part stored as editable comma-separated list files (see Table 1). When VECTO is released in final version mode, it is foreseen that most input data (e.g., driving cycles, driver behavior) will be fixed according to certification regulations. The software will thus run under "declaration mode."

2 In this comparison exercise, we aligned the elements of 2) whenever possible and focused on 3).

3 In all likelihood, VECTO will be a key part of the forthcoming EU scheme for the monitoring of CO_2 emissions from HDVs (Franco et al., 2015).

Table 1. Main auxiliary files of VECTO*

Auxiliary file extension **Hierarchical dependency:** **Orange** ***Blue*** **Purple**	**Contents**
.vecto	Master "job" file that contains the description of the simulation run via appropriate references to the rest of the auxiliary files for ***drive cycle(s), vehicle, engine, gearbox, auxiliaries*** and ***driver definitions.***
.vdri	*Drive cycle* definition (time-based or distance-based). Road grade and power consumption from auxiliaries is defined here.
.vveh	*Vehicle* definition. This file includes general vehicle parameters such as mass or frontal area, plus references to the **cross-wind correction file vcdv** (see section 2.4.2).
.veng	*Engine* definition. This file includes general engine parameters such as cylinder capacity, inertia, or rated power, plus references to the following auxiliary files: **.vmap:** fuel consumption map **.vfld:** engine full-load and drag torque curve
.vgbx	*Gearbox* definition. This file includes general gearbox parameters such as number of gears and gear ratios/efficiencies, plus a reference to an auxiliary file that defines the shifting strategy for the gearbox **(.vgbs;** see Section 2.3.6).
.vaux	*Auxiliaries* definition (power demand curves as a function of engine speed).
.vmod, .vres	Files where simulation results (modal or summary values) are stored (see Section 2.2.2).
.vacc	Table with the maximum allowable instantaneous acceleration and deceleration (mimics the behavior of a human driver).

* These are editable (as .csv files) in spreadsheet software

GEM (Greenhouse Gas Emissions Model) was developed by US EPA as a means for determining compliance with EPA's GHG emissions and NHTSA's fuel efficiency standards (US EPA, 2011a), for Class 7 and 8 combination tractors and Class 2b-8 vocational vehicles. The GEM v2.0 model itself is a part of the final regulation, and is distributed as a freely available desktop computer application. The model consists of a graphical user interface (GUI) and the underlying model. Both are written in MATLAB/Simulink, which is the most widespread block diagram environment for modeling dynamic systems. A new version of GEM (v3.0) is currently under development as part of the next phase of HDV GHG/FE standards, which are due to be finalized in 2016.

Under normal circumstances, users of GEM are only allowed to input a very limited number of simulation parameters, and the model uses its built-in library of vehicle definitions to run. For this comparison exercise, the ICCT was granted access to the source code of GEM. This allowed access to the built-in vehicle definitions, as well as the modification of simulation parameters that would have otherwise been inaccessible from the GUI version that is publicly distributed by EPA (see Table 2).

Table 2. Access to model parameters for the purposes of comparison exercise

	Regular user access	ICCT access
VECTO 2.0.3 beta	"Declaration mode:" Only a limited number of parameters can be input from the GUI.	"Proof-of-concept mode": Source code is not available, but many simulation parameters are editable files.
GEM 2.0	Limited number of parameters from GUI.	Access to all simulation parameters and vehicle definitions.

2.1.1 Backward/forward model operation

Both GEM and VECTO are **longitudinal vehicle dynamics block** models. This means that they simulate the dynamic behavior (and the associated instantaneous fuel consumption and CO_2 emissions, via built-in engine maps) of a vehicle that moves along its longitudinal axis. When the vehicle is in motion, it is assumed that the engine speed is equal to the speed at the wheels, scaled by the current gear and final axle drive ratio. With this type of model, lateral forces involved during steering and cornering are ignored. This is an acceptable approach because lateral forces are much smaller than longitudinal forces during cruising.

An important difference between GEM and VECTO is that the former has a so-called forward-looking architecture, whereas the latter is a backward-looking model. This distinction is related to the internal "point of view" or mode of operation of the model:

» Forward-looking (or simply "forward") models predict operation states (the simulation is run "from accelerator pedal to wheel"). In forward simulations, the vehicle operation (course of vehicle speed, gearshifts, operation of vehicle components) is a result of the interaction of algorithms in the simulation model (the driver model and different control algorithms for particular vehicle components[4]) with set targets, such as a course of target vehicle speed over distance. This more complex method of simulation is applied in case the specific vehicle operation is not available as model input.

» In backward simulations, the required load to be delivered by the internal combustion engine is calculated based on the driving resistance, the power losses in the drivetrain, and the power consumption of the auxiliary systems (the simulation is run "from wheels to engine"). Engine speed is determined from a gearshift model, the gear ratios, and the wheel diameter, and fuel consumption/CO_2 emissions are then interpolated from a fuel map.

One key difference between the two architectures is that, while backward models take the driving cycle as the actual vehicle speed, forward models take the driving cycle as the target vehicle speed and use a control loop, or "driver model," to provide a throttle signal input to the powertrain. In this sense, forward-looking models are generally regarded as being more suitable for technology analysis, control strategy development and for the simulation of complex powertrain architectures. Backward models, on the other hand, allow for quick analyses when limited input information is available, or when the target is to reproduce specific tests and operating conditions. For equal model complexity, there are no significant differences in the time required to run the

4 The methodology for the characterization of individual vehicle components is being developed in collaboration with European HDV manufacturers.

simulations.[5] From a software development perspective, it is also possible to turn a backward model into a forward one, but the effort required for this is unknown.[6] A summary of the differences between the forward and backward simulation approaches is given in Table 3.

Table 3. Comparison of forward and backward modeling approaches

	Advantages	Disadvantages
Forward modeling (GEM)	Transient oscillation in vehicle speed possible, more closely resembles actual driving. Easier to implement advanced control strategies, can accommodate "black box" subsystems.	The driver models is more complex, has greater influence on simulation results.
Backward modeling (VECTO)	Driver model easier to implement. Sufficient if no differentiation between control and vehicle physics is required.	Only possible if all input signals of all subsystems are known at beginning of each simulation time step (efficiency maps dependent on input torque cannot be used) "Black box" systems cannot be integrated (this would require explicit definition of control strategies, for instance to simulate hybrid systems). Cannot predict vehicle performance parameters such as acceleration and is unsuited to component-limited operation simulations.

2.2 INPUT AND OUTPUT DATA

The differences between the input data required by each model and the simulation outputs they provide are briefly discussed in this section.

2.2.1 Model input data

Although VECTO and GEM work internally with roughly the same parameters, most input data in GEM (e.g., tractor frontal area, weight, gear box, FC maps) are predefined and cannot be modified by the user unless access to the source code is granted. From the GUI, the main user inputs are the rolling resistance of the tires (input separately for steer and drive tires) and the coefficient of aerodynamic drag (see Figure 1). The remaining parameters of the simulation are determined internally based on the regulatory subcategory of the vehicle.

5 The backward approach is generally faster because it does not need higher order integration routines to simulate the controller-plant interaction. Backward models allow the use of larger time steps and simpler integration routines, but these differences only become noticeable when a large number of simulations are run.

6 There is also the possibility to combine pseudo-forward elements into backward-looking models. This is being contemplated for future development of VECTO (see Kies et al., 2013).

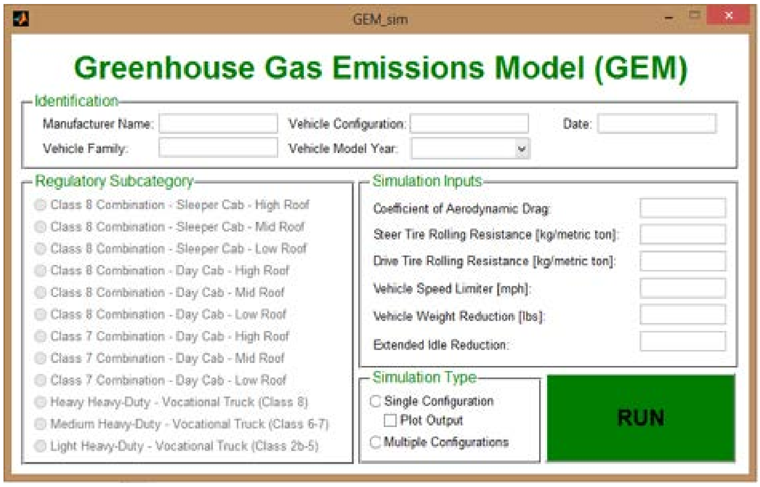


Figure 1. User interface of GEM 2.0

VECTO, on the other hand, allows many more simulation parameters to be input by the user (Figure 2). The differences between the input data methods of both models are summarized in Table 4.

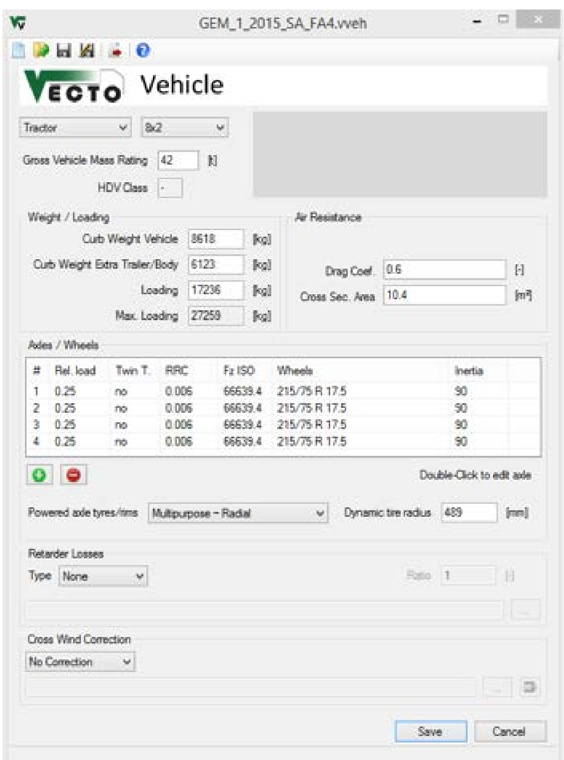


Figure 2. VECTO dialog for vehicle parameter input*

**Similar windows exist for the gearbox and the engine*

Table 4. Main input data for simulations on both models

Input data	VECTO	GEM
Vehicle		
Frontal area	User-defined	Built-in, generic values for different HDV categories
Air drag coefficient	User-defined	User-defined
Vehicle and trailer mass	User-defined	Built-in, generic values for different HDV categories
Payload	User-defined	Built-in, generic values for different HDV categories
Tire characteristics	Tire radius is user-defined, rolling resistance is user-defined for each axle	Built-in, generic values for tire radius; rolling resistance is user-defined, separate values for steer and drive tires
Engine		
Rated power & displacement	User-defined	Built-in, generic values for different HDV categories (four different engine power/ displacements)
Steady-state fuel consumption map	User-defined, generic map provided for one vehicle	Built-in, generic maps available for different HDV categories
Full load curve	User-defined, generic map provided for one vehicle	Built-in, generic values for different HDV categories
Transmission		
Number of gears, gear ratios and efficiency maps	User-defined	Built-in, generic values (four different gearboxes)
Gearshift strategy	User-defined “shift polygons” defined by engine speed/torque points for upshifts/downshift	Built-in, generic upshift/downshift points based on vehicle velocity for each gearbox
Full load curve	User-defined (generic map provided for “demo” vehicle)	Built-in, generic values for different HDV categories
Simulation environment		
Ambient conditions	User-defined	Built-in, generic values (four different gearboxes)
Fuel characteristics	Density and carbon content are user-defined	Built-in, generic values (common for all vehicles)
Test cycles	Can run any user-defined *time-based* or *distance-based cycles*. Simulation of road grade is possible	Three built-in *time-based* cycles; additional cycles can be run with access to source code. Simulation of road gradient is possible, but road gradient is not included in the built-in cycles.

2.2.2 Simulation outputs

As far as **simulation outputs** are concerned, GEM produces **single, cycle-weighted** grams CO_2/ton-mile and gallons/1,000 ton-mile results. Every time a simulation is run, GEM will simulate the three built-in drive cycles: ARB transient cycle, 55 mph steady state cruise, and 65 mph steady state cruise cycle (see Section 2.3.7). It will then calculate aggregate results by applying different weights to the results of each drive cycle.[7] GEM converts the mile per gallon result into a ton-mile result by using a predefined payload for each regulatory class. Modal data are internally computed, but these results are not reported and cannot be viewed without source code access. On the other hand, VECTO provides the user with both aggregate and modal results for several emissions and vehicle dynamics signals, as well as engine and transmission states (see Table 5).

Table 5. Output data for both models

Output data	VECTO	GEM
Fuel consumption (FC)/CO_2 emissions		
Aggregated FC/CO_2	Overall value for any simulated test cycle. Absolute (in grams) or distance-based values (in grams per kilometer)	Weighted average of the three built-in cycles (in grams of CO_2 per ton-mile, calculated from the category-specific payload)
Instantaneous FC/CO_2 emissions	Reported at 1 Hz	Not reported in GUI-only version, accessible only if running source code
Speed and acceleration		
Instantaneous speed	Both target and simulated values reported at 1 Hz	Reported at 1 Hz (only as plot), accessible only if running source code
Instantaneous acceleration	Both target and simulated values reported at 1 Hz	Not reported in GUI-only version, accessible if running source code
Engine/transmission states		
Gear number	Reported at 1 Hz	Not reported in GUI-only version, accessible if running source code
Instantaneous engine speed	Reported at 1 Hz	Not reported in GUI-only version, accessible if running source code
Instantaneous power	Reported at 1 Hz (total power at the wheels and individual driving resistances and losses)	Not reported in GUI-only version, accessible if running source code

2.3 MODEL ELEMENTS

The simulations run in VECTO and GEM as a result of the interaction of several model elements or subsystems (e.g., engine, transmission, driver or test cycle). In the following sections, we briefly describe what each of these elements does and whatever differences may exist in their implementation in either model.

2.3.1 Ambient

This subsystem defines ambient conditions under which vehicle operations are simulated: ambient temperature, pressure, and air density. The latter is the only real relevant parameter for the simulations, as it can be calculated from the other two via the ideal gas law. Air drag is directly proportional to ambient air density.

The ambient conditions in GEM are hard-coded into the model (and are therefore not user-accessible) with values in accordance with standard SAE practices (ambient

7 These weights vary with the regulatory subcategory. They are meant to represent how each type of vehicle is used. For example, for Class 8 sleeper-cab tractors, the weights are 86% for 65mph cruise, 9% for 55 mph cruise, and 5% for ARB transient cycle.

temperature of 25°C and ambient pressure of 101.325 kPa). These result in a calculated air density of 1.18 kg/m³. VECTO, on the other hand, allows air density to be freely selected via the user interface.

2.3.2 Driver

The driver model in GEM uses the target driving speed to estimate vehicle torque demand at any given time, and then the power required to drive the vehicle is derived to estimate the required accelerator and braking pedal positions. If the driver misses the vehicle speed target, a speed correction logic controlled by a **proportional-integral-derivative (PID) controller** is applied to adjust necessary accelerator and braking pedal positions in order to try to match the target vehicle speed at every simulation time step. This is a forward-looking approach (see Section 2.1.1) that cannot be emulated by VECTO, which instead uses the engine **full-load curve** of the simulated vehicle, which is complemented by an internal lookup table of maximum allowable instantaneous acceleration and deceleration values for given velocity points (Table 6). This is a simple control strategy that effectively translates into a realistic driver behavior (i.e., it doesn't slam the brakes or floor the accelerator, even if doing so would help meet the required speed).

Table 6. Example of lookup table governing driver behavior in VECTO

Velocity [km/h]	Maximum acceleration [m/s²]	Maximum deceleration [m/s²]
0	1.75	-0.25
10	1.42	-0.74
...	...	...
100	0.22	-0.25

2.3.3 Vehicle

The vehicle system models the "outer shell" of the vehicle, including the tires. The drag coefficient, frontal area, mass of the vehicle, and other parameters are housed in this component. VECTO and GEM have very similar model subsystems. A significant difference between them is that VECTO allows the specification of individual coefficients of rolling resistance for each axle, whereas GEM distinguishes between drive and steer axles.

2.3.4 Auxiliaries

The power demand of engine auxiliaries, such as the oil pump, the coolant pump, or the fuel delivery pump, is covered by the FC map, so there is no need for a separate model. To depict the remaining auxiliaries (the cooling fan, steering pump, air compressor, alternator, and air conditioner), an additional model is necessary in order to put the HDV CO_2 test procedure in a position to set incentives to improve these components.

GEM models electrical auxiliary systems (e.g., alternator, starter, electrical accessories, etc.) as a single electric load with a constant power demand placed on the engine. The value of this electric load varies for the different vehicle categories, ranging from 300 to 350W. Mechanical auxiliary systems such as coolant or air conditioning pumps are also modeled as a constant load of 1kW on the engine, for all vehicle categories.

In VECTO, auxiliaries are modeled with a more realistic approach.[8] For each auxiliary, a “work cycle” (electric power to be provided by the alternator, which has its own efficiency map) and an efficiency map for the auxiliary can be programmed. The details on how auxiliaries will be modeled in the declaration mode of VECTO are still undecided, but a probable first solution will be to adopt standard constant mean values and generic power demand curves (dependent on engine speed) for individual auxiliaries. These constant values and curves will be sourced from OEMs and main suppliers, ad hoc testing and expert views.

2.3.5 Engine

The engine subsystem in GEM is based on a steady-state fuel map covering all engine speed and torque conditions and torque curves at wide open throttle (full load) and closed throttle (no load). The engine fuel map is a matrix of fuel injection rates covering pre-specified engine speed and torque intervals from which the simulated values are interpolated. This map is adjusted automatically by taking into account three different driving modes: acceleration, braking, and coasting. The fuel map, torque curves, and the different driving modes are pre-programmed into GEM for three different default engines.

VECTO also adopts user-defined, simple steady-state fuel consumption maps. This means that there may not be consistency between the simulated results and the measured results over a transient cycle (WHTC) since transient effects cannot be simulated with a steady-state map. It is foreseen that a whole-cycle transient **correction factor** will be applied. The details on the calculation and application of this correction are still under discussion.

2.3.6 Transmission

GEM uses a simple gearbox model for manual transmissions. The transmission inertia, number of gears and gear ratios are predefined in GEM, as is the efficiency for each gear. One 6-speed and two 10-speed manual gearboxes are thus defined, and each vehicle category is assigned a specific gearbox for the simulations.

VECTO uses a similar parameterization of the manual gearboxes, but the user is free to select the number of gears, gear ratios, and efficiency tables. Automated manual and automatic transmissions (with torque converter) can also be parameterized.

As far as **gearshift strategies** are concerned, there are substantial differences between the implementations in VECTO and GEM. To determine when upshifts and downshifts take place, GEM uses a simple table of fixed points based on vehicle speed. VECTO uses a more realistic approach whereby upshift and downshifts happen whenever the engine speed crosses the upshift or downshift line defined by a “shift polygon” (Figure 3). This gearshift behavior is closer to that of a real driver that seeks to operate the engine around peak torque. The user can choose to allow upshifts to happen inside the polygon area for automatic-manual transmissions (as long as the higher gear provides a minimum torque reserve and the new rpm value is above the downshift value), or to allow the transmission to skip gears.

8 There is an ongoing discussion regarding the final modeling approach in VECTO. This is one of several model development areas with open issues. The version provided to ICCT included the module for a generic alternator drawing from 0.07 to 5.13 kW as a function of engine speed, plus a generic auxiliary drawing from 0 to 6.67 kW of instantaneous power. For the purposes of the comparison, auxiliaries were deactivated for either model (see Section 3.3).

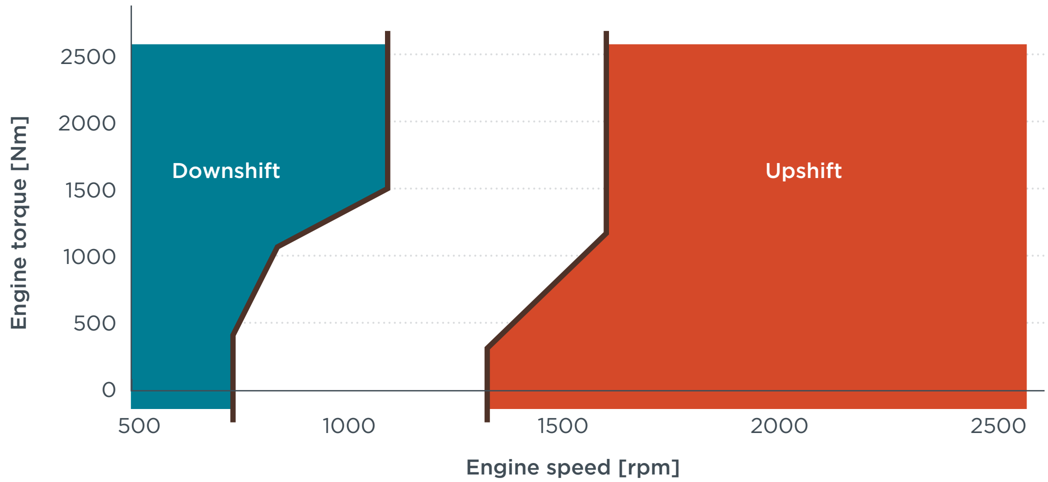


Figure 3: Illustration of VECTO's "shift polygons"
Source: VECTO user manual

2.3.7 Test cycles

The aim of HDV simulation tools is to estimate realistic fuel consumption values. VECTO and GEM have substantially different approaches regarding the implementation of test cycles.

For every simulation run, GEM runs the three time-based driving cycles (in which the target speed is defined for each time step) and applies different weightings to the results, depending on vehicle category, to produce a single efficiency value (see Section 2.2.2). These built-in cycles are pictured in Figure 4. These are three short cycles (two steady-state, one transient) with no road gradient.[9]

VECTO, on the other hand, allows the simulation of any duty cycle input as a .vdri auxiliary file. VECTO accepts both time-based and distance-based time cycles. The rationale behind using distance-based cycles *(i.e.,* cycles where target speeds are defined for every unit of distance) is that, unlike their time-based counterparts, these cycles define a mission: When distance-based are used, all vehicles perform the same duty and run for the same distance regardless of their specific power. When using distance-based cycles, there are two important points that need to be considered. The first is that the actual average speed during the simulation depends on the specific power of the vehicle (lighter, more powerful trucks will reach the target speeds earlier), and this could create variation in the equivalent time-based cycles. Therefore, it is important to assess both efficiency and average speed results when looking at the results of this type of simulation. The distance-based cycles used in the comparison of the models (developed by the European association of car manufacturers, ACEA) are shown in Figure 5.

9 The capability of simulating variable road gradients (slopes) is however built into GEM, and it is used in the model comparison exercise described in Section 3.

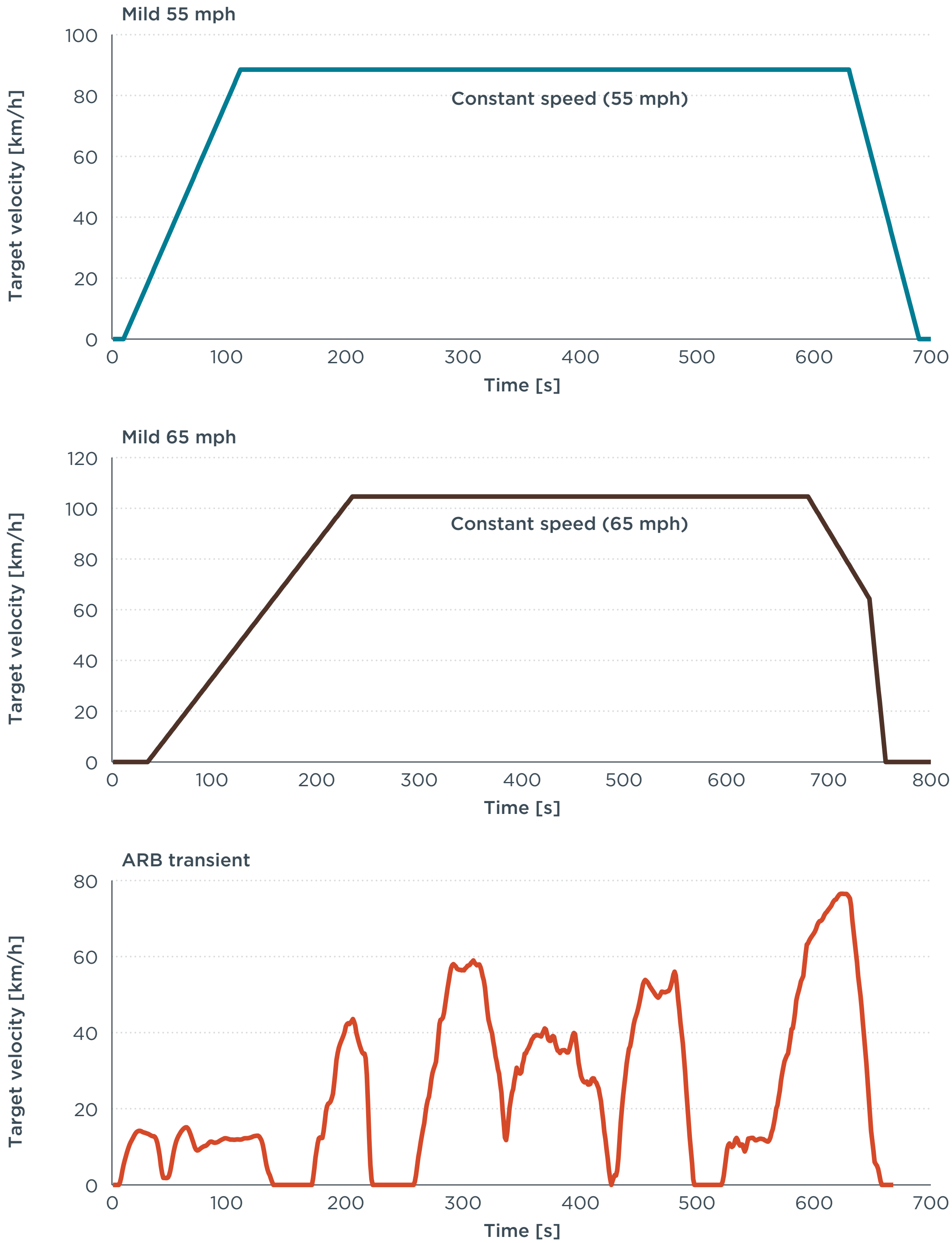


Figure 4: Built-in test cycles of GEM

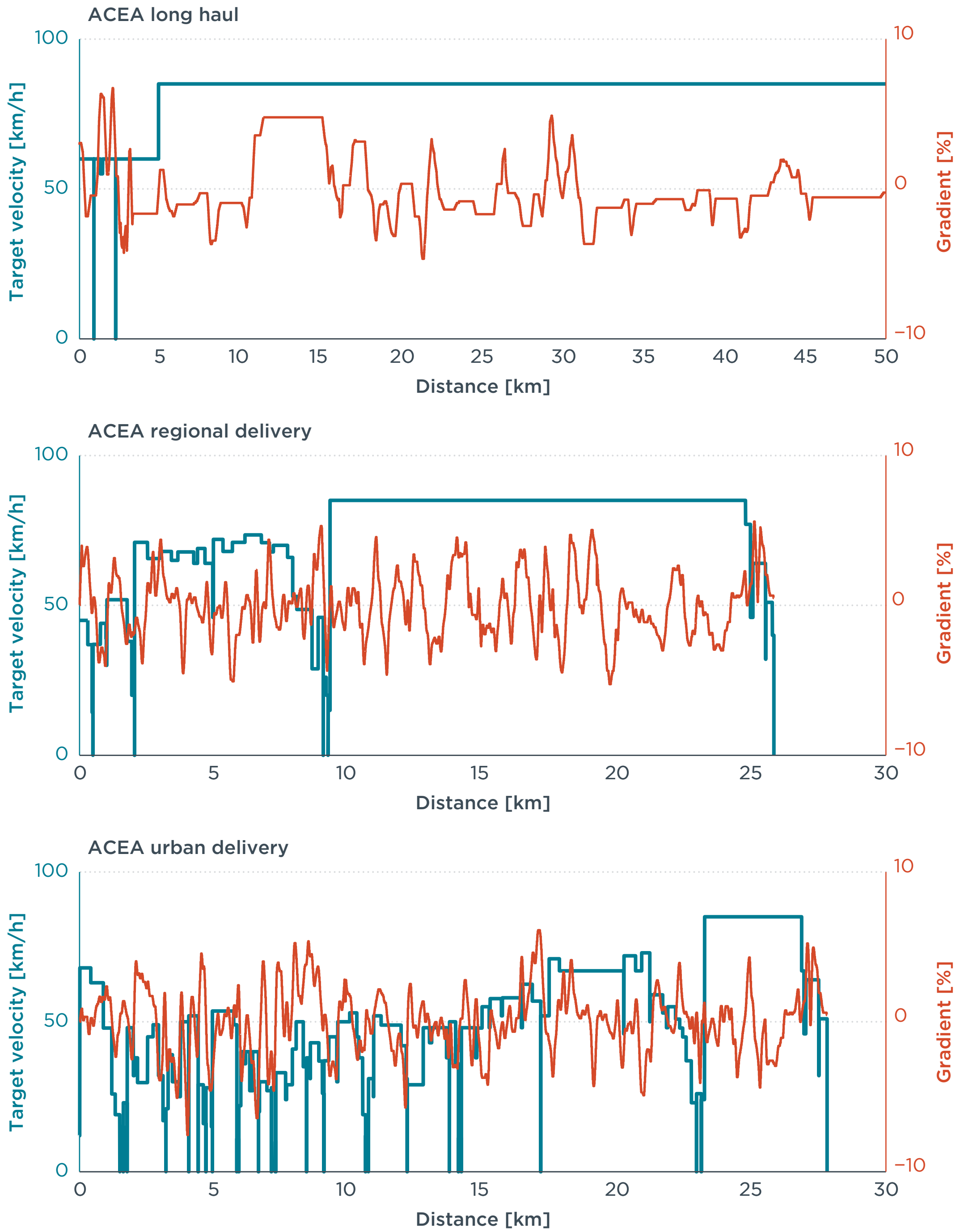


Figure 5. ACEA distance-based test cycles

2.4 MODEL SPECIAL FEATURES

Outside from the basic shared functionalities, each model has special features. In general, these remained deactivated for the comparison exercise, but they are briefly commented on in the next sections.

2.4.1 GEM

Vehicle speed limiter: GEM has the possibility of simulating a vehicle speed limiter for combination tractors. It does so simply by substituting the instantaneous target speeds in the cycles by a user-specified speed limit.

Vehicle weight reduction: If a combination tractor features lighter-weight wheels or tires, or other lighter components described in the regulations, then the user can input the sum of the weight reductions prescribed by the weight bins.

Extended idle reduction: If a sleeper cab combination tractor contains an extended idle reduction technology and a five-minute automatic engine shutoff, then the user can select a 5 g CO_2/ton-mile[10] reduction, which is applied in the post-processing of the simulation results.

2.4.2 VECTO

Crosswind correction: VECTO allows the influence of crosswind to be incorporated into the simulation. This effect is modeled through a characteristic curve of variations in the air drag coefficient C_d as a function of yaw angle (i.e., the angle between air inflow and the direction of travel) or vehicle speed (assuming a constant crosswind; see Figure 6).[11]

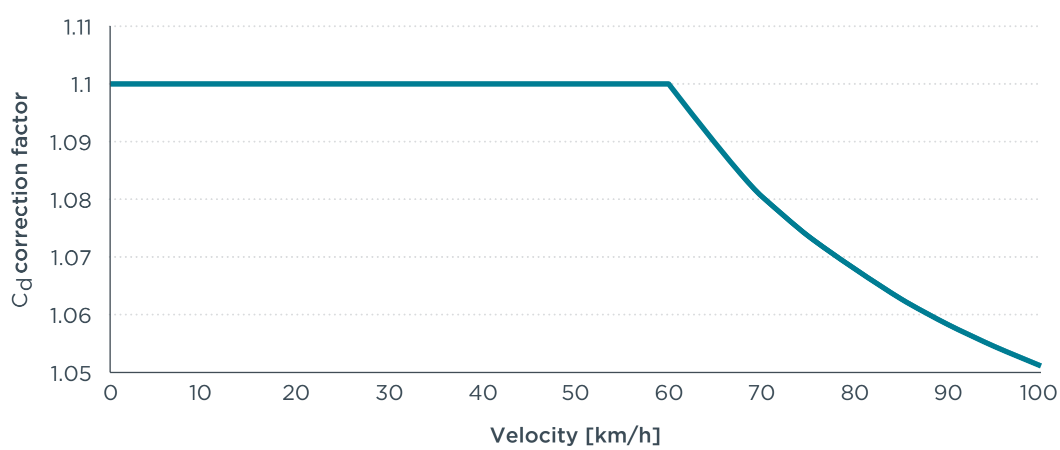


Figure 6. Demo curve for crosswind correction as a function of speed

Engine start-stop: a simple implementation of a start-stop system is included in VECTO. When enabled, the engine will be turned off whenever power demand (excluding auxiliaries) becomes zero provided that the vehicle speed is below a (user-defined) maximum speed and that the engine was previously running for a (user-defined) minimum period of time.

10 Short tons; 1 ton ≃ 0.907 metric tons.

11 This characteristic curve can be input as an additional auxiliary file (.vcdv).

Overspeed/Eco-roll: in situations where the power at the wheels is negative (downhill coasting), VECTO can allow the vehicle to coast *without* applying the brakes as long as the instantaneous speed is lower than the target speed plus a certain allowance of (user-defined) "overspeed." A variation of this "overspeed mode" is the eco-roll mode, whereby the HDV will go to neutral gear (engine idling) during downhill driving and apply the brakes only if the target speed plus an overspeed is reached. Additionally, the vehicle switches to normal driving as soon as the target speed minus an allowed "underspeed" is reached. These features simulate advanced cruise control systems.

Look-ahead coasting: This feature simulates the behavior of a "smart" driver who allows the HDV to coast briefly in anticipation of a deceleration phase. Coasting will begin before the new lower target speed depending on the user-defined **look-ahead deceleration** $a_{lookahead}$ (see Figure 7).

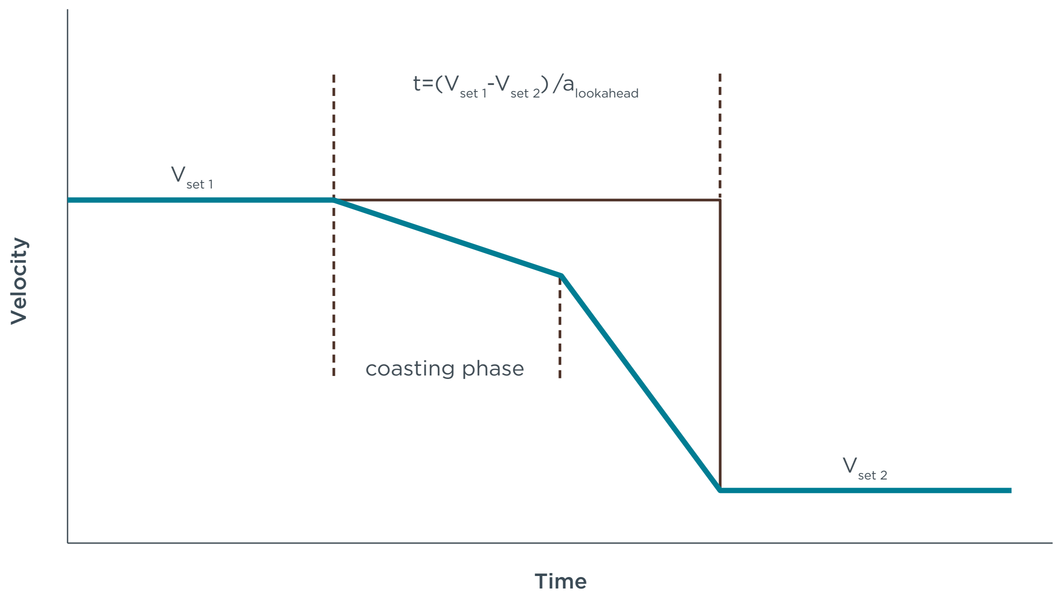


Figure 7. Illustration of VECTO's look-ahead feature
Source: VECTO user manual

Engine-only mode: This mode is used to calculate fuel consumption from a given load cycle (engine speed and torque), simulating an engine dynamometer test (in this case, the load cycle is given in terms of required engine speed/torque; results are output in g/kWh). Under this mode, vehicle (.vveh), gearbox (.vgbx) and auxiliary (.vaux) files are not required.

3 MODEL COMPARISON METHODOLOGY

The comparison exercise was structured in four phases, briefly explained in Sections 3.1 to 3.4.

3.1 REVIEW OF MODELS AND DEFINITION OF SIMULATION SCENARIOS

The aim of the exercise was to perform a comparison in which all input data and model parameters (user-accessible or otherwise) were brought in line in both models through the definition of common simulation scenarios, including common engine fuel consumption maps. In doing so, the differences in the simulated results may then be attributed to differences in the software implementations and/or the methodological choices made for each model.

"Core" source code (i.e., the source code in VECTO, or the Simulink model in GEM) was not manipulated so as not to deviate from the intended final use of the models, which deliberately limit user access to vehicle parameters and simulation options. The differences in the simulated results include the influence of the different methodological aspects, such as the driver model or the gearshift strategies.

3.2 DEFINITION OF BASELINE VEHICLES

A number of baseline vehicles had to be defined before performing the simulations. The procedure chosen was to take the (explicit) **default vehicle definitions** built into GEM (see Tables 7 and 8) such as payload, frontal area, rolling resistances and so forth, and use them as input parameters for VECTO, taking advantage of the fact that the proof of concept version of VECTO allows the definition of many simulation parameters, either directly from its GUI or by editing the various auxiliary files.

Table 7. Classification of simulated vehicles (US regulatory categories)

Vehicle ID	US regulatory class	Regulatory Subcategory
1	Class 8	Sleeper cab, high roof
2	Class 8	Sleeper cab, mid roof
3	Class 8	Sleeper cab, low roof
4	Class 8	Day cab, high roof
5	Class 8	Day cab, mid roof
6	Class 8	Day cab, low roof
7	Class 7	Day cab, high roof
8	Class 7	Day cab, mid roof
9	Class 7	Day cab, low roof
10	Heavy heavy-duty	Vocational truck (class 8)
11	Medium heavy-duty	Vocational truck (class 6-7)
12	Light heavy-duty	Vocational truck (class 2b-5)

Table 8. Main characteristics of the vehicles used in the simulation

	Sleeper cabs			Day cabs						Vocational trucks		
Vehicle ID	1	2	3	4	5	6	7	8	9	10	11	12
Engine power [kW]	339	339	339	339	339	339	261	261	261	339	201	149
Engine inertia [kg·m²]	4.16	4.16	4.16	4.16	4.16	4.16	3.36	3.36	3.36	4.16	2.79	2.79
Engine idle speed [rpm]	600	600	600	600	600	600	600	600	600	600	750	750
Rated engine speed [rpm]	2200	2200	2200	2200	2200	2200	2600	2600	2600	2200	2600	2600
Engine displacement [cc]	15000	15000	15000	15000	15000	15000	11000	11000	11000	15000	7000	7000
Transmission inertia [kg·m²]	5	5	5	5	5	5	5	5	5	5	0.5	0.5
Number of gears	10	10	10	10	10	10	10	10	10	10	6	6
Drive shaft inertia [kg·m²]	1	1	1	1	1	1	1	1	1	1	0.3	0.2
Differential inertia [kg·m²]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.1	0.15
All axle inertia [kg·m²]	360	360	360	360	360	360	233.4	233.4	233.4	200	60	60
Final drive ratio	2.64	2.64	2.64	2.64	2.64	2.64	3.73	3.73	3.73	2.64	3.36	2.85
Weight tractor [kg]	8618	8505	8391	7938	7756	7711	5216	5035	4990	12247	6328	4672
Weight trailer [kg]	6123	4536	4763	6123	4536	4763	6123	4536	4763	0	0	0
Payload [kg]	17237	17237	17237	17237	17237	17237	11340	11340	11340	6804	5080	2585
Total weight [kg]	31978	30277	30391	31298	29529	29710	22680	20911	21092	19051	11408	7257
Number of axles	5	5	5	5	5	5	4	4	4	3	2	2
Loaded tire radius [m]	0.489	0.489	0.489	0.489	0.489	0.489	0.489	0.489	0.489	0.489	0.389	0.378
Tire rolling resistance [kg/kg]	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Frontal area of vehicle [m²]	10.4	7.7	6.9	10.4	7.7	6.9	10.4	7.7	6.9	9.8	9	9
Coefficient of aerodynamic drag	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.6	0.6

Source: GEM built-in vehicle definitions (US EPA 2011b)

3.3 TRANSLATION OF SIMULATION SCENARIOS

In order to perform the comparison of the models, the simulation scenarios (i.e., the vehicle definitions, ambient conditions, tests cycles and so forth) had to be ported or translated from one simulation environment to the other. In many cases, the translation of the parameters was straightforward (e.g., for simple parameters such as the frontal area of the vehicles, the rolling resistance of the tires or the rated power of the engines, which require at most a change of units). In other cases, some adaptations had to be performed. The process of translation of the simulation scenarios is briefly described in the sections that follow.

3.3.1 Adaptation of test cycles

VECTO can simulate any driving cycle defined by the user, and is capable of working with both **distance-based cycles (**in which the target speed is defined for every unit of distance cover, and therefore the total distance covered during the test is fixed) and **time-based cycles** (where the target speed is defined for each second of the test, and the total duration of the test is fixed). On the other hand, the GUI version of GEM can only run its three built-in, time-based cycles (see Section 2.3.7). The original source code of GEM was slightly modified in order to run other test cycles in addition to the built-in ones.

For the comparison exercise, all the time-based test cycles listed in Table 9 were run for each baseline vehicle in both models. These include the built-in GEM cycles, WHVC (World Harmonized Vehicle Cycle; a standard transient chassis dynamometer cycle pictured in Figure 8), and a modification of the ACEA distance-based cycles. Because GEM can only run time-based cycles, and in order to make sure that both models ran the exact same cycles, the ACEA cycles were run in VECTO for Vehicle 1, and VECTO's translation of the cycle was used to generate time-based cycles for GEM.

Table 9. Test cycles used in the comparison exercise

Test cycle	Description	Duration [s]
WHVC (time-based cycle)	World harmonized test cycle (chassis dynamometer translation of transient engine dynamometer cycle WHTC; no road gradient variations).	1800
ACEA long haul (distance-based cycle, time-based adaptation used in GEM)	Delivery to national and international sites (mainly highway operation and a small share of regional roads; *includes road gradient variations*).	2623
ACEA regional (distance-based cycle, time-based adaptation used in GEM)	Regional delivery of consumer goods from a central warehouse to local stores (inner city, suburban, regional and also mountain roads; *includes road gradient variations*).	1682
ACEA urban (distance-based cycle, time-based adaptation used in GEM)	Urban delivery of consumer goods from a central store to selling points (inner city and partly suburban roads; *includes road gradient variations*).	3387
Mild 55 mph (time-based cycle)	Steady-state cycle with 55 mph top speed, with mild acceleration and deceleration ramps (no road gradient variations). GEM standard cycle.	700
Mild 65 mph (time-based cycle)	Steady-state cycle with 55 mph top speed, with mild acceleration and deceleration ramps (no road gradient variations). GEM standard cycle.	800
ARB Transient (time-based cycle)	Short, transient cycle. GEM standard cycle.	668

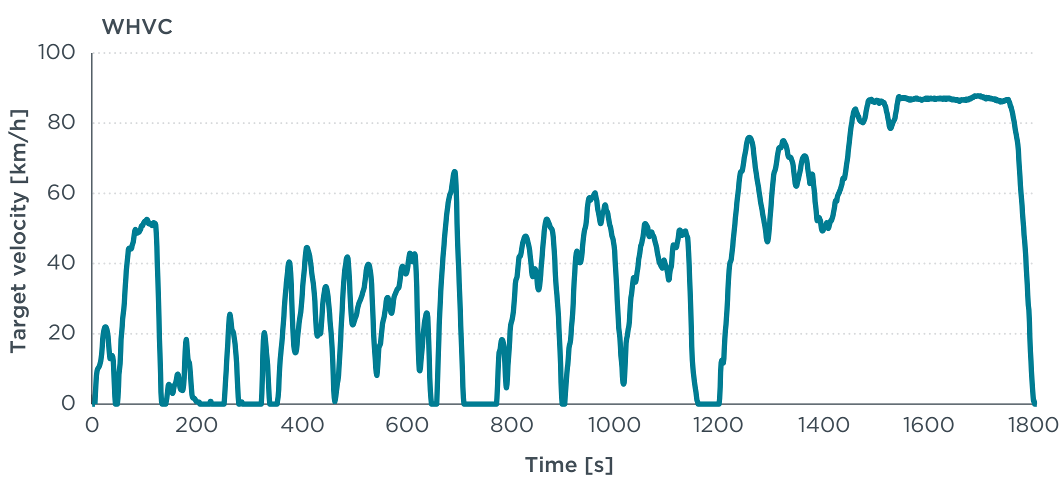


Figure 8. Time-speed profile of the WHVC cycle

3.3.2 Driver model

The driver behaviors of both models could not be brought in line and were left unmodified. This is due to the fundamental difference, as mentioned earlier, in the model architectures of VECTO and GEM: The latter is a forward-looking model, whereas the former is backward-looking.[12]

3.3.3 Gearshift strategy

Because gearshift strategies are fundamentally different between the two models (velocity-based in GEM, torque-based in VECTO), they cannot be directly ported between models. They cannot be left as they are, either, because the distribution of VECTO made available to ICCT only included the model of a six-speed gearbox corresponding to the "demo" vehicle. The modeling approach was thus to take the gearshift strategy included in VECTO and scale it by the ratios of rated torques and rated engine speeds (i.e., the ratios of the rated torques and engine speeds of each GEM engine to the corresponding parameters of the single VECTO demo engine, thus preserving the original shape of the original polygon). To generate the required 10-speed gearbox models, the gearshift points were generated through interpolation by assuming equal spacing of shifting points across the rpm range.

12 Backward-looking models such as VECTO do not require a driver model operating the throttle: if the vehicle is able to match the target speed at any given point in time, it will do so perfectly. VECTO incorporates a pseudomodel for behavior of a human driver by limiting the acceleration and deceleration capabilities of the simulated vehicle.

3.3.4 Summary

Table 10 is a summary of how input data and other model elements were adapted from GEM to VECTO to make the comparison possible.

Table 10. Summary of the adaptation of models

<table>
<tr><td>Elements that were directly ported</td><td>Boundary/ambient conditions: air density, temperature
“Simple” engine parameters: power, cylinder capacity
“Simple” vehicle parameters: total vehicle mass, frontal area, tire radius, rolling friction coefficients, aerodynamic drag coefficient.
Parameterization of mechanical and electrical auxiliaries (the simple parameterization of GEM was adopted)</td></tr>
<tr><td>Elements that were ported with some adaptations (minor loss of fidelity)</td><td>Driving cycles: GEM uses time-speed traces, while VECTO takes distance-speed traces as input. The following cycles were ported as required, are available for both models:
ARB transient, mild 55 mph, mild 65 mph (GEM default)
Time-based translations of ACEA regional delivery, ACEA urban delivery, ACEA long haul (VECTO default, variable road grade)
WHVC
Engine
FC maps: VECTO takes three-column maps as input ([Torque][Engine rpm][FC value]]; GEM takes N x M matrices of FC values. Unlike GEM, VECTO requires FC values for negative torque (engine motoring), so these are added to the adapted maps (with an FC value of 0, thus assuming fuel cut-off).
Full-load and drag torque curves: full-load curves can be adapted directly. VECTO requires a drag torque curve (not modeled in GEM). The modeling approach was thus to take the drag torque curve included in the “demo” engine model in VECTO and scale it by the ratios of rated torques (GEM torque to VECTO demo torque) and rated engine speeds.
Gearboxes
Gear ratios from GEM can be easily ported to VECTO; they only need to be divided by the final drive ratio specified for each GEM vehicle type. Transmission efficiencies can be directly ported.
The gearshift strategy of the “demo” gearbox in VECTO was scaled to produce equivalent 10-speed gearboxes.</td></tr>
<tr><td>Elements that were not ported</td><td>Driver behavior (adaptation is not possible due to different model architectures (forward-looking in GEM and backward-looking in VECTO).
Auxiliaries (they were deactivated for both models).</td></tr>
</table>

3.4 SIMULATION RUNS

Once the simulation scenarios were ready in both environments, the third phase of the exercise comprised the performance of the simulation experiments. This was straightforward because the simulations are not computationally intensive (individual cycle simulations run in well under one minute on a personal computer).

3.4.1 Sensitivity analysis

In order to perform a sensitivity analysis of key simulation parameters, vehicle 1 was repeatedly simulated under the ACEA long haul cycle. For each of the simulation runs, each one of the parameters listed in Table 11 were varied by plus/minus 10-20-30% from their baseline values, while the others remained constant. This is “one-at-a-time” sensitivity analysis to assess the influence of individual parameters upon results. This simple approach is deemed appropriate considering that the underlying physical equations that govern the simulations are linear, and that no interaction among the different parameters is expected.

Table 11. Variation of parameters for the sensitivity analysis

Parameter	Baseline value	Sensitivity analysis values
Frontal area [m²]	10.4	7.28, 8.32, 9.36, *10.4*, 11.44, 12.48, 13.52
C_d	0.6	0.42,0.48, 0.54, *0.6*, 0.66, 0.72, 0.78
Tire rolling resistance [kg/ton]	6	4.2, 4.8, 5.4, *6*, 6.6, 7.2, 7.8
Final drive ratio	2.64	1.85, 2.11, 2.38, *2.64*, 2.90, 3.17, 3.43
Road grade [%]	Time-dependent	Fixed values added to the original values: -0.3, -0.2, -0.1,0, +0.1, +0.2, +0.3

4 RESULTS

The results of the simulations for both models (in grams of fuel per kilometer) are plotted in Figure 9. The fuel consumption values of GEM simulations were generally higher than those of VECTO (by about 17% according to a simple linear regression). The results of the less transient cycles (mild 55 mph, mild 65 mph) are very similar for both models. This is to be expected, because these simple cycles consist mostly of a steady-state section in which the engine should run at the same operating point for both models. In practice, some differences arise, which can be attributed to different behaviors during the acceleration and deceleration phases.

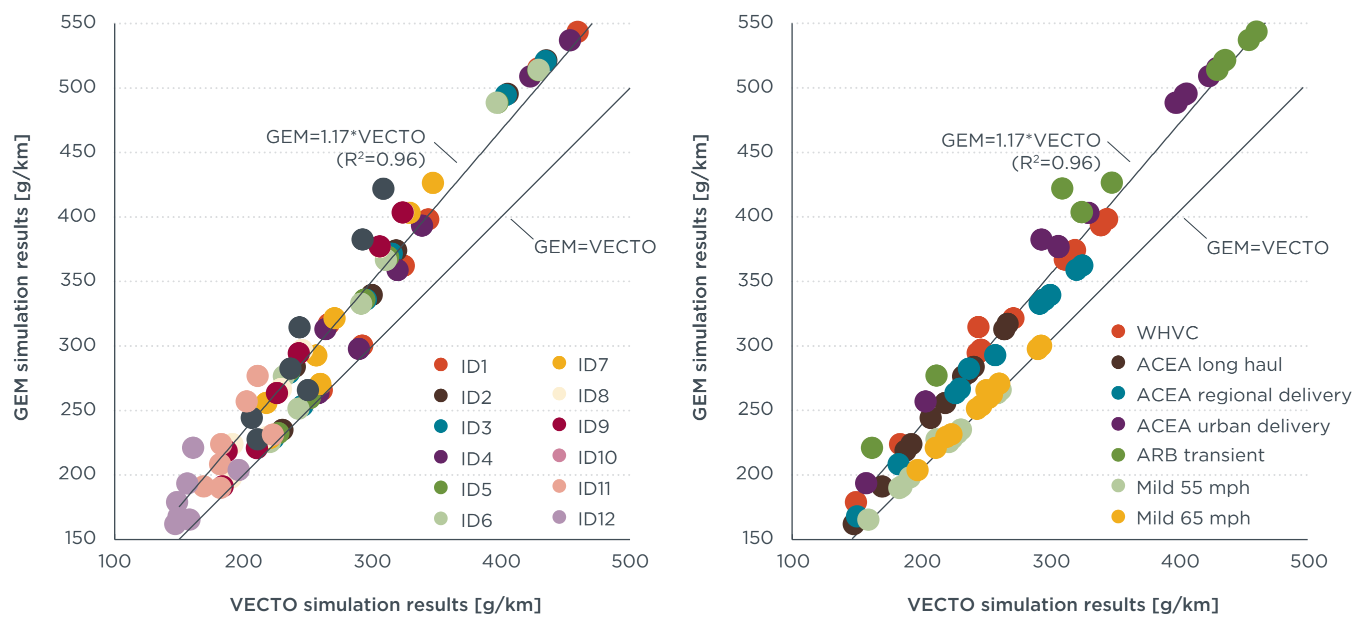


Figure 9. Scatterplots of simulation results

4.1 COMPARISON OF MODEL RESULTS BY DUTY CYCLE

In Figures 10a and 10b, the results of the simulations are provided by duty cycle. Both figures present the same data, but the level of aggregation is different in order to highlight the general trend across vehicles (Figure 10a) and the specific behavior of the models for a given duty cycle (Figure 10b).

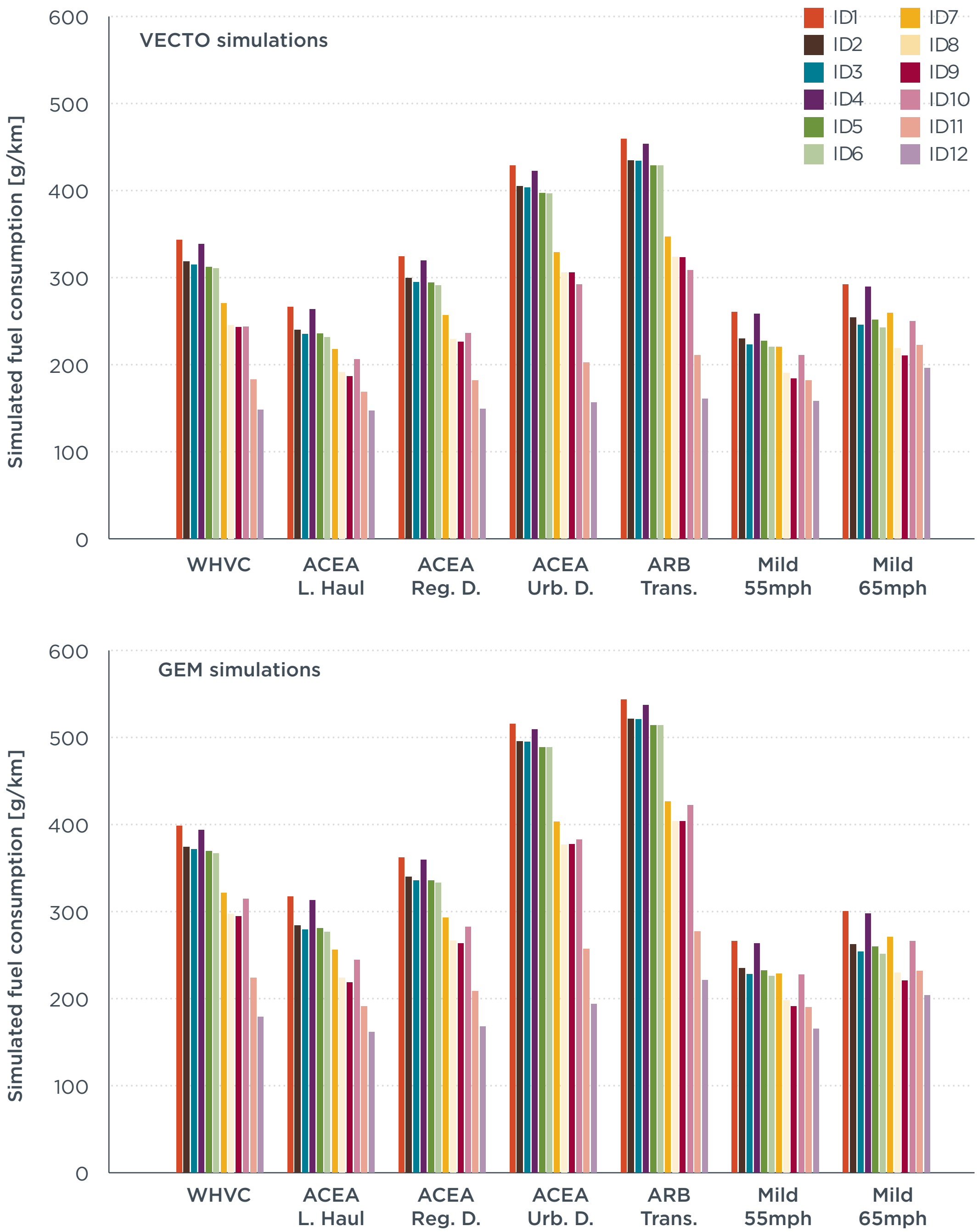


Figure 10a. Simulation results for all vehicles, by model and duty cycle

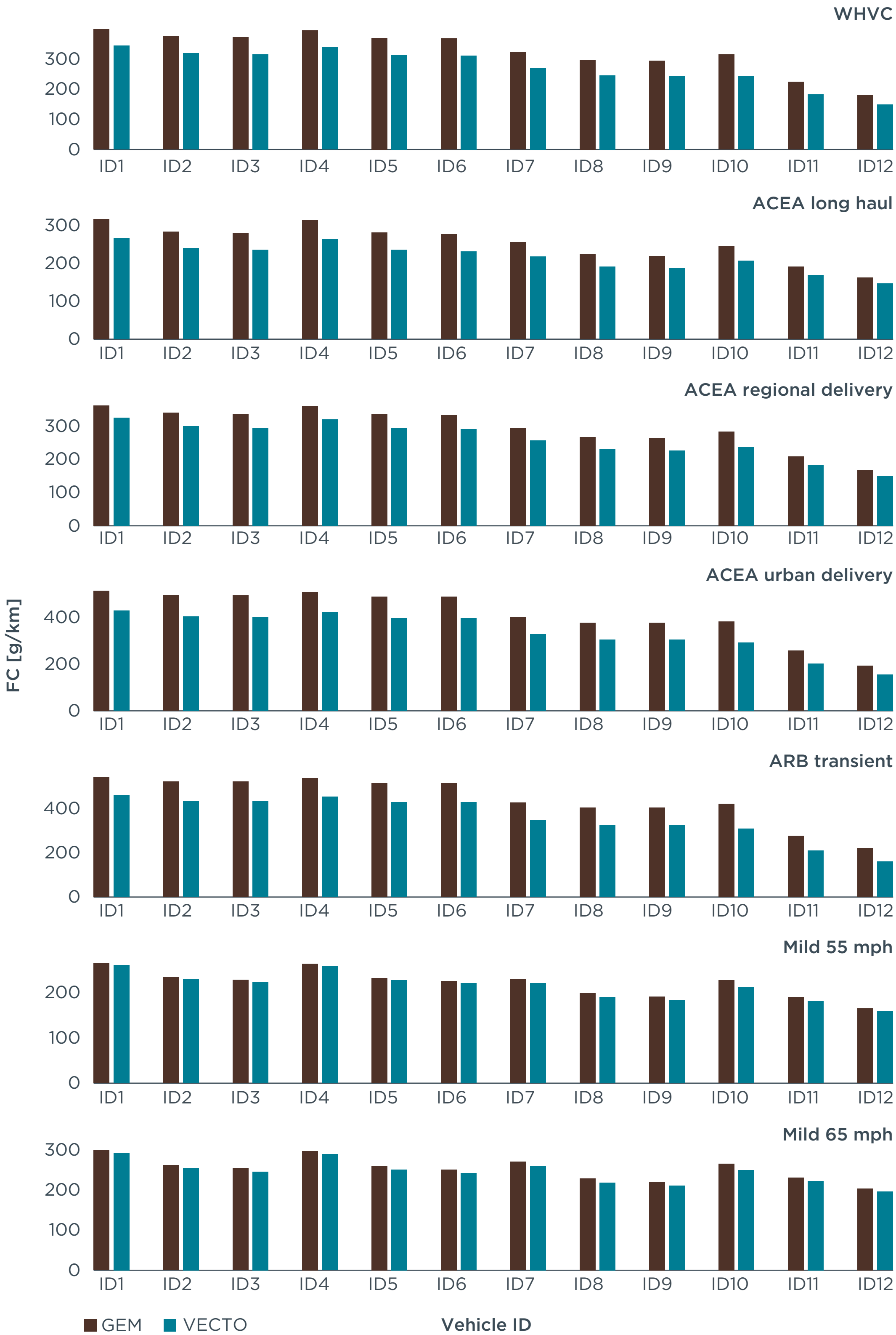


Figure 10b. Simulation results for all vehicles, by model and duty cycle

4.2 COMPARISON OF NORMALIZED MODEL RESULTS BY VEHICLE

Figure 11 shows the results of the simulations after an internal normalization to the results of the WHVC cycle (i.e., the results of each model for the different vehicles are divided by the corresponding result for WHVC; hence the fixed unit results for this cycle). The purpose of this normalization is to remove the differences due to the fact that the two models have distinctly different gearshift and driver models, which react differently to road gradient and transient operation during the simulations. In general terms, and excluding the effects of road gradient, the (normalized) behavior of both models is similar.

To make sure that the differences in gearshift behavior were affecting the results of the simulations, we derived a simple metric to evaluate how similar the gear choices of either model were: we compared the second-by-second gear choice of either model, and computed the number of seconds that the gear choice for one model was higher, lower or equal to the gear choice of the other model. When the gear discrepancy was higher than one gear, we multiplied the number of seconds by the absolute difference in gears. Finally, the results are normalized by the total duration of the simulation cycle to derive a “gear discrepancy” indicator (as a percentage of total time of the cycle spent in a higher, lower, or same gear). This provides a simple evaluation of the differences in gearshift behavior between the two models, which is applied to Vehicles 1 and 12 for all cycles in Figure 12. In this figure, we observe that the more transient cycles (WHVC, ARB transient, ACEA urban delivery) are the ones that exhibit the highest gearshift behavior discrepancy between the models. At the same time, these are also the cycles with the highest absolute discrepancies in the simulation results.

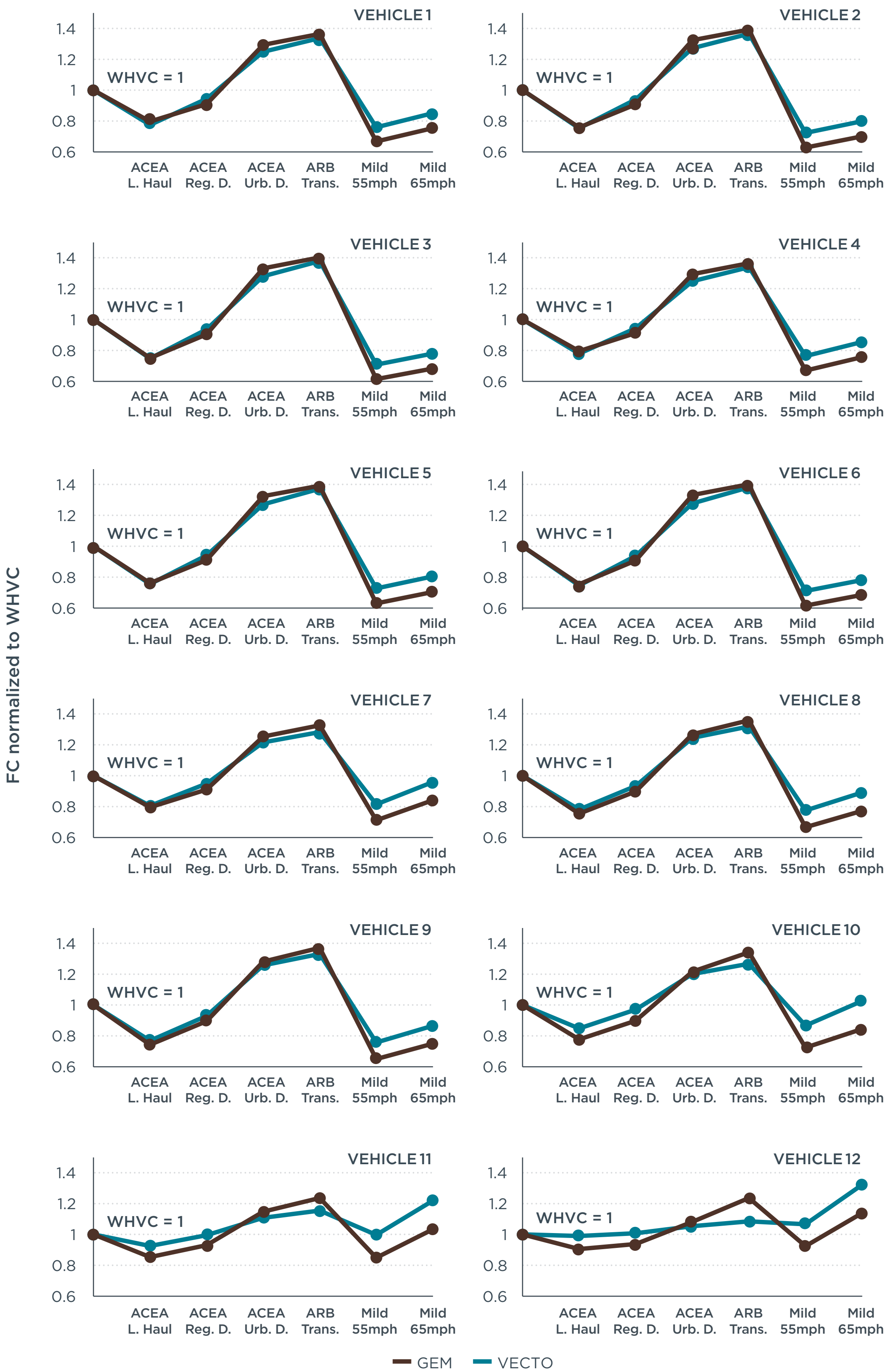


Figure 11. Simulation results by vehicle, normalized to WHVC

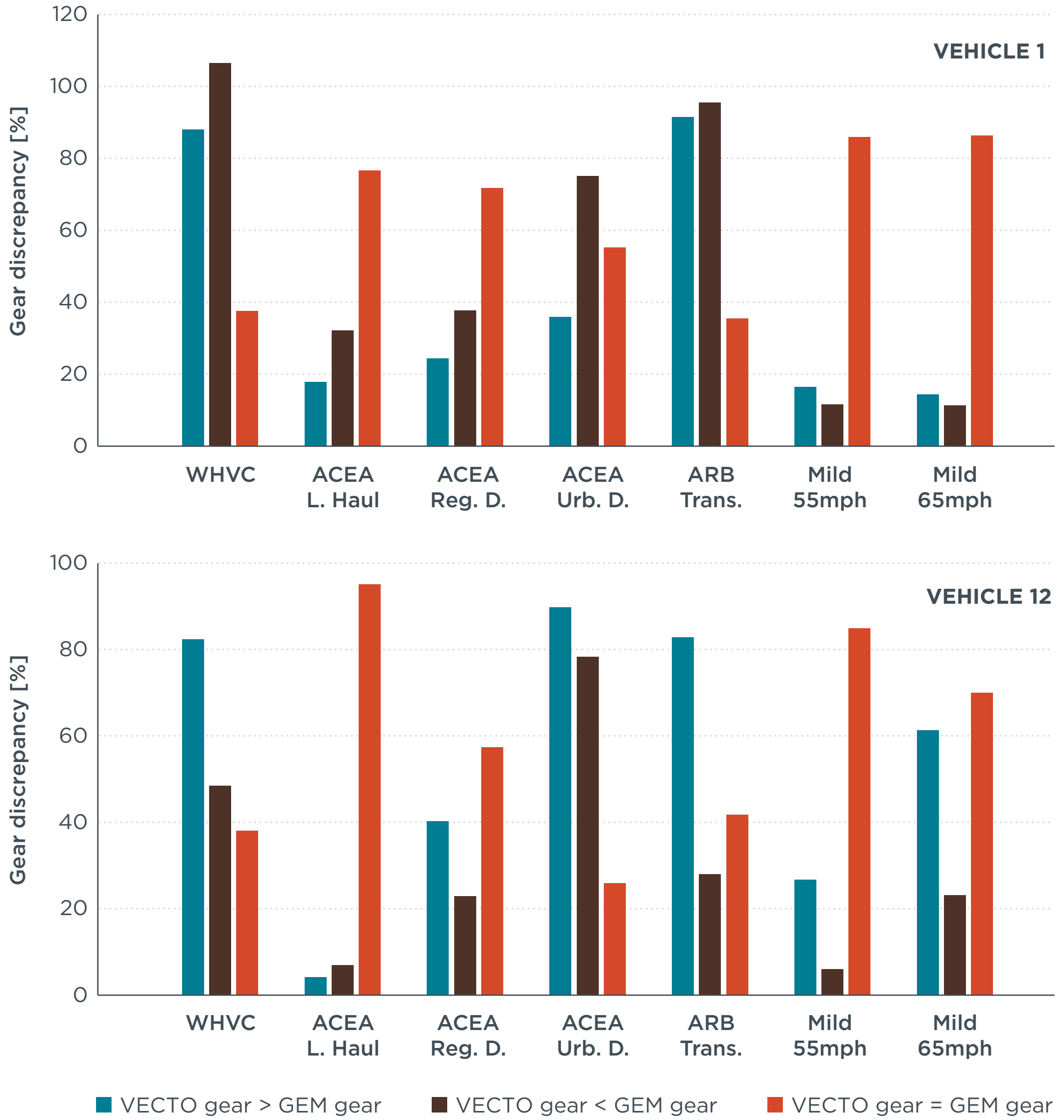


Figure 12. Evaluation of gear selection discrepancy for Vehicles 1 and 12 (all cycles)

4.3 RESULTS OF THE SENSITIVITY ANALYSIS

The results of the sensitivity analysis are presented in Figure 13. In most cases, the influence of parameters is linear or quasi-linear for the ranges of variation studied.

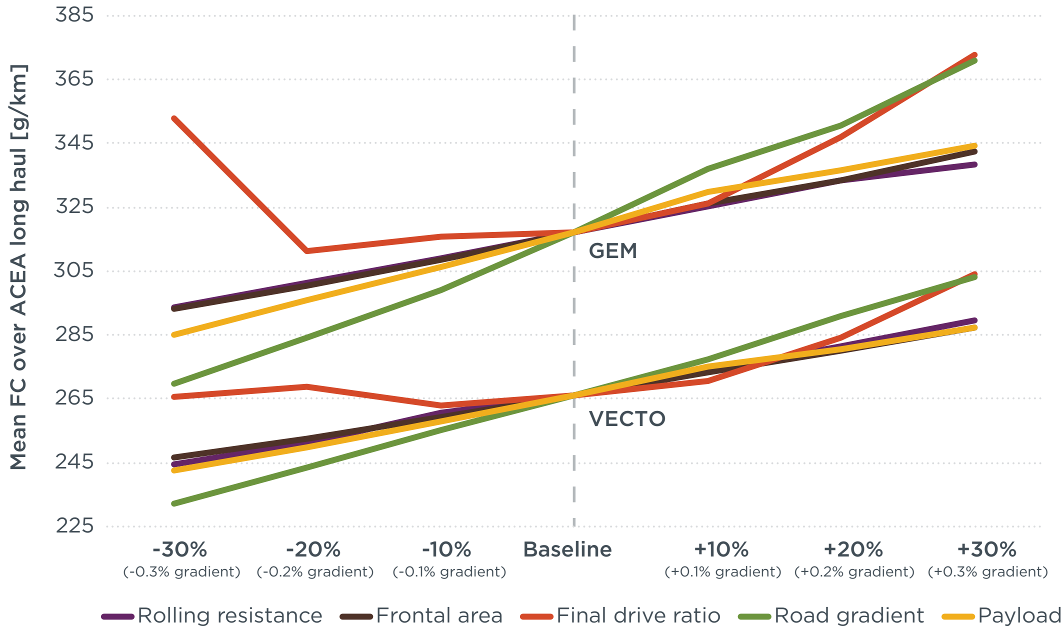


Figure 13. Results of the sensitivity analysis for GEM and VECTO

An interesting result is the influence of the final drive ratio (FDR). By changing this parameter, the operating points for a given vehicle speed also vary, and so do the results of GEM (which has a shifting strategy based on fixed vehicle velocity points). VECTO, on the other hand, has a more realistic gearshift strategy based on torque and it is able to compensate for the more extreme variations in the final drive ratio by changing the gearshift pattern (hence the lower sensitivity of the results to this parameter). When we ran the "gear discrepancy" analysis on FDR and payload (Figure 14), we observed that variations in FDR had a much larger influence in the gearshift pattern than variations in payload, which would be consistent with the nonlinearity observed for FDR during the sensitivity analysis.

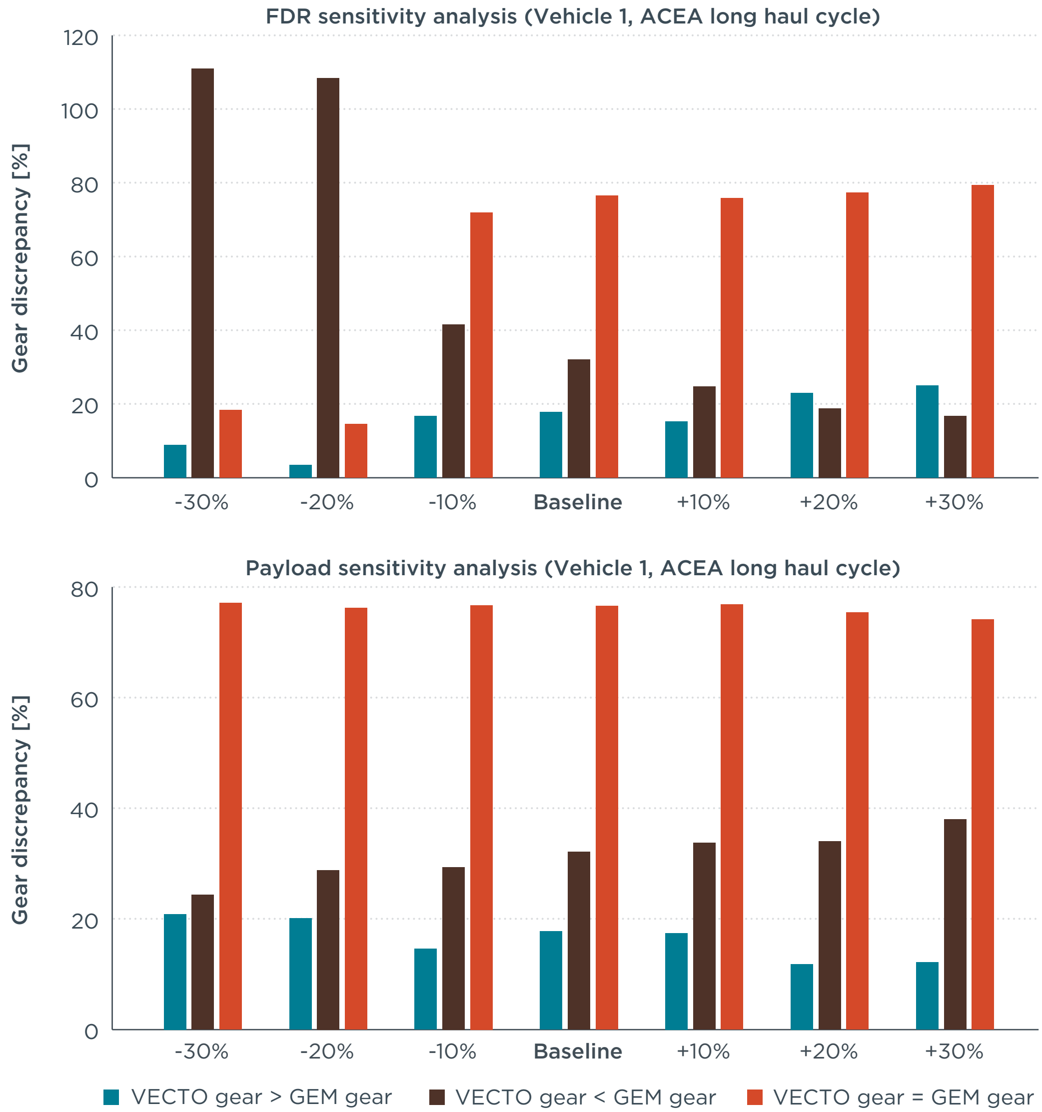


Figure 14. Evaluation of gear selection discrepancy for the sensitivity analysis simulations of FDR and payload

5 DISCUSSION

HDV efficiency certification test procedures use a combination of simulation and component testing. In this new regulatory environment, the quality of input data such as vehicle parameters, engine maps, and gearshift strategies could matter more than the operation of the simulation tools themselves, which perform relatively simple calculations based on well-known physical principles.

Regulators developing their own simulation tools for standards' compliance face a number of important challenges. First, they need to determine the appropriate level of detail for their models, as there is a tradeoff between complexity and accuracy. Second, they need to decide how to standardize component testing protocols and simulation procedures. Finally, they need to decide on data reporting procedures, balancing the need for transparency with the protection of the confidential business information of vehicle and component manufacturers.

5.1 SIMULATION TOOLS IN THE REGULATORY ENVIRONMENT

Using whole-vehicle efficiency simulation makes good technical and economic sense. Unlike engine dynamometer tests, simulation can capture the influence of individual components upon whole-vehicle efficiency, and unlike whole-vehicle dynamometer testing, simulation makes it possible to test a high number of vehicle types and subtypes with small marginal costs.

Simulation tools have been used internally by OEMs for some years now, both for powertrain development and for efficiency assessment purposes. These are usually proprietary tools such as Autonomie or AVL Cruise, which are not applied for regulatory uses due to their complexity and to third-party ownership of the source code. On the other hand, regulators seek to have tight control over the models, so they are willing to sacrifice some accuracy to keep the models less complex and more manageable. Their approach has thus been to develop their own tools from scratch, sometimes in collaboration with OEMs. Finally, operators of HDV fleets will likely have an interest in using HDV efficiency simulation tools to guide their vehicle purchases. In this sense, the ability to use user-defined duty cycles and to reliably assess the effect of changes in inputs upon efficiency would greatly increase the usefulness of the simulation tools beyond certification.

5.2 MODEL COMPARISON EXERCISE

The comparison exercise between VECTO and GEM shows a few interesting results. First of all, it shows that the correspondence of parameters and model elements is not always straightforward. In some cases, the alignment of model parameters requires a simple change of units (e.g., for the tire rolling resistance coefficients), but in other cases some further adaptations need to be performed. Whenever significant departures in modeling choices exist, it may not be possible to produce a perfect adaptation of the models, leading to losses of model fidelity and ultimately to discrepancies in the simulated results. Examples of this are the driver model and the gearshift strategies of VECTO and GEM, which are conceptually different and could not be effectively aligned.

Secondly, the comparison shows that both models are “internally consistent,” in the sense that similar relative patterns are observed for each vehicle and sequence of cycles (see Figures 10a and 10b), and that they exhibit similar sensitivities to variations in key parameters. This means that the models are adequate for assessing the influence of variations in simulation parameters, which is the intended use of the current version of GEM, but perhaps less so for accurately predicting actual fuel consumption values (unless the models are calibrated with measured data, as is being done in the case of VECTO).

5.3 OPPORTUNITIES FOR ALIGNMENT AND HARMONIZATION

Despite the current fragmentation of the regulatory simulation tools—GEM in the US, VECTO in Europe, MLIT’s model in Japan, and CATARC’s model in China—these have a large number of common principles. This leaves an open door to alignment based on a set of best practices that are beginning to emerge. Current opportunities for alignment lie mostly in component testing procedures (e.g., how the efficiency of a transmission is determined) and modeling (e.g., how a gearbox should be modeled and whether the model is forward or backward looking). The cycle “concept” (e.g., whether it is distance- or time-based) could also be aligned, but the cycles themselves should be adapted to reflect region-specific operation patterns. The benefit of aligning models around a mutually agreed-upon set of best practices would be that certification values from different countries could be more easily comparable, while at the same time regulators could still maintain full development control of their model.

In the foreseeable future, and in view of the significant technical advantages of the technique, other world regions will likely seek to incorporate HDV efficiency simulation to their legislation. In our view, these regions would benefit from adapting the simulation methods developed elsewhere instead of “reinventing the wheel”. In this scenario, the openness and transparency of simulation tools could be the key to their widespread adoption.

In the long run, a global, harmonized HDV simulation tool could conceivably be developed. A harmonized approach should be able to handle region-specific configurations, which is in fact one of the main strengths of HDV efficiency simulation techniques. A harmonized HDV simulation tool would reduce global development and maintenance costs, but there remain some hurdles to its development. These hurdles are likely more political than technical in nature.

6 CONCLUSIONS AND FUTURE WORK

Computer simulation offers regulators and OEM manufacturers exciting prospects for the certification of HDV efficiency and CO_2 emissions. Whole-vehicle simulation techniques have the potential to reduce vehicle testing efforts worldwide and improve the quality and availability of much-needed HDV efficiency data (Sharpe and Muncrief, 2015). This will be accomplished by placing the focus on individual component testing and modeling to feed the simulation tools rather than on measurements at the dynamometer test bench. The quality of these input data is just as important to the accuracy of the results provided by these tools as the operation of the tools themselves.

The simulation tools used in regulatory environments are simpler than the proprietary tools that OEMs have been using for powertrain development, but they are being further developed (sometimes in collaboration with OEMs) to include more technologies with fuel-saving potential (e.g., advanced transmissions or intelligent management of auxiliaries). The final equilibrium point between simplicity and comprehensiveness is still uncertain: regulators favor transparency and simplicity, but OEMs require more sophisticated models to be able to demonstrate the benefits of advanced control systems and powertrain configurations (for example hybrid vehicles, which are not fully covered by simple models such as GEM or VECTO). At the same time, OEMs are wary of fully disclosing the details of these (even to regulators) to protect their commercial interest.

A global, harmonized tool for HDV efficiency simulations would be desirable, but it seems unlikely in the near future. The hurdles to harmonization are less technical than they are political and administrative—intellectual property rights, data ownership and confidentiality issues. A stepping stone to a full globally harmonized tool would be for countries to align their tools around a set of mutually agreed upon best practices. For now, VECTO and GEM will continue to be developed independently. We expect the new version of GEM (Phase 2 GEM, to be released in 2016) to reach a level of sophistication on par with VECTO. Conversely, we expect VECTO to make it past beta stage and start being used for the certification and reporting of CO_2 emissions from European HDVs.

7 REFERENCES

Franco, V., Hammer, J., Tietge, U., Muncrief, R., Vermeulen, R. and Verbeek, R. (2015). *Cost-benefit analysis of options for certification, validation, monitoring and reporting of heavy-duty vehicle fuel consumption and CO_2 emissions.* TNO report performed for the European Commission (DG CLIMA) under framework contract CLIMA.C.2/FRA/2013/0007. Delft, the Netherlands.

Hausberger, S., A. Kies, et al. (2012). *Reduction and testing of GHG emissions from heavy-duty vehicles—Lot 2: Development and testing of a certification procedure for CO_2 emissions and fuel consumption of HDV.* Graz, Austria: Graz University of Technology.

Kies, A.; Rexeis, M., Silberholz, G., Luz, R., Hausberger, S. (2013). *Options to consider future advanced fuel-saving technologies in the CO_2 test procedure for HDV.* Graz, Austria: Technical University of Graz Report no. FVT -104/13/ Rex Em 06/13-6790 of 19.12.2013. Retrieved from http://www.theicct.org/implementing-fuel-saving-technologies-vecto-options-and-estimated-gains.

Kousoulidou, M.; Fontaras, G.; Lonza, L.; Dilara, P. (2013). *Review and evaluation of emission models and vehicle simulation tools.* European Commission Joint Research Centre Technical Report EUR 25716 EN. Publications Office of the European Union; pp. 1–72.

Sharpe, B. and Lowell, D. (2012). *Certification procedures for advanced technology heavy-duty vehicles. Evaluating test methods and opportunities for global alignment.* ICCT White Paper No. 16. Washington, DC: ICCT.

Sharpe, B. and Muncrief, R. (2015). *Literature review: real-world fuel consumption of heavy-duty vehicles in the United States, China, and the European Union.* ICCT White Paper. Washington, DC: ICCT.

US EPA. (2011a). Final Rulemaking to Establish Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles, pp. 1–553.

US EPA (2011b). Greenhouse Gas Emissions Model (GEM) User Guide. Report EPA-420-B-11-019; 2011b; pp. 1–16.