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TECHNOLOGY VERIFICATION TOOL FOR GREEN FREIGHT PROGRAMS

APPLICATION OF VEHICLE SIMULATION TOOLS TO ACCELERATE TECHNOLOGY UPTAKE

Oscar Delgado, Felipe Rodríguez, Cristiano Façanha

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

www.theicct.org

communications@theicct.org

BEIJING | BERLIN | BRUSSELS | SAN FRANCISCO | WASHINGTON

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

communications@theicct.org | www.theicct.org | @TheICCT

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EXECUTIVE SUMMARY

This study presents the application of existing vehicle simulation tools to streamline technology verification and accelerate technology uptake in green freight programs. The applied tool, referred to here as the Technology Verification Tool (TVT), can be used by fleet or green freight program managers to estimate the potential fuel savings of truck technologies without extensive real-world testing.

Improving the efficiency of heavy-duty vehicles (HDVs) is an effective strategy for emissions control. On-road HDVs represent less than 5% of the global vehicle fleet but consume 40% of on-road fuel. Improving HDV efficiency is an effective way to reduce greenhouse gas (GHG) emissions and decrease operating costs for truck operators. Countries have implemented a variety of policy tools to improve truck efficiency, including regulations, market-based approaches, and fiscal instruments. As part of HDV efficiency regulations, the United States developed the Greenhouse Gas Emissions Model (GEM), and Europe created the Vehicle Energy Consumption Calculation Tool (VECTO) as certification and compliance tools. Both software tools simulate vehicle fuel consumption and GHG emissions under inputs obtained through standardized component testing. This study applies these tools to verify the effects of aerodynamic devices and low rolling-resistance tires on fuel consumption under a representative set of duty cycles.

One example of a market-based approach is green freight programs, which provide information and promote fuel-saving technologies and strategies while rewarding the best carriers and shippers. Technology verification is the process by which a green freight program tests the validity of fuel savings claimed by efficiency technology suppliers, providing confidence to interested parties. Currently, the SmartWay program of the U.S. Environmental Protection Agency (U.S. EPA, 2018e) is the only green freight program with a comprehensive technology verification program. Technology verification can be resource intensive with the agency providing extensive technical oversight or, at an even greater expense, operating their own test facilities using specialized equipment. Since the EPA's technology verification program may prove difficult to replicate in nascent green freight programs in countries with fewer resources, an alternative is to complement real-world tests with vehicle simulation. The underlying idea is that the benefits of technologies verified elsewhere via real-world tests can be estimated for a different market or application through vehicle simulation.

This study uses tools based on GEM and VECTO to estimate the potential fuel-saving benefits of aerodynamic devices and low rolling-resistance tires of typical Latin American tractor-trailers, as well as the effects of different duty cycles. The analysis compares the results for a generic tractor-trailer with those for 100 vehicle variants meant to represent a diverse range of fleets. The simplified tools allow carriers interested in quantifying the effects of such technologies to estimate fuel-consumption reductions using a vehicle model that is similar but not identical to their actual vehicles.

Simulation results indicate a relatively narrow range in efficiency improvements with variation of truck parameters. In other words, different trucks within the same truck category should experience similar efficiency improvements when using the same technology. On the other hand, the variation in efficiency improvements is much wider when changing duty cycles, in particular for aerodynamic devices whose effectiveness varies significantly with vehicle speed. This supports the use of a TVT to greatly expand

the range of driving conditions that can be cost-effectively evaluated and obtain a more representative range of efficiency improvements for a given carrier's operations.

The study concludes that it is feasible to use an existing and publicly available vehicle simulation tool to develop the TVT and simulate fuel-consumption reduction with reasonable accuracy. Both GEM and VECTO are suitable candidates for adaptation and show consistent results under a similar set of input parameters. At the moment, VECTO offers greater flexibility for adaptation for technology-verification purposes, mainly because driving cycles are editable and not hard-coded in the tool.

There are multiple benefits from using a TVT under a green freight program. First, carriers could justify technology investments without extensive real-world testing. Second, technology suppliers could test products once and use simulation to estimate the technology benefits over a wider range of truck profiles and driving cycles. Third, the tool could benefit green freight programs by building credibility for technologies and awareness with carriers. Finally, adoption of similar tools worldwide could make technology verification synergetic across regions, reducing costs.

Next steps for future research include the development of representative duty cycles and reference vehicles for specific regions, which requires a freight assessment, supporting literature review, and the collection of telematics data. The TVT will also need to rely on some real-world testing to calibrate the tool and better approximate modeled to real-world results.

1. INTRODUCTION

1.1 BACKGROUND

Freight transportation plays a crucial role in the development of global economies and is expected to outpace the growth of passenger transportation activity in coming decades (Façanha, Blumberg, & Miller, 2012). On-road heavy-duty vehicles (HDVs) represent more than 60% of energy consumption and fuel use in freight transportation globally, reaching as much as 80% in some regions (see Figure 1). Within the on-road sector, HDVs account for less than 5% of the global vehicle fleet but 40% of energy consumption. Within diesel road transport, HDVs account for less than 25% of diesel vehicle sales and stock but represent 75% or more of the fuel use and black carbon emissions that worsen urban air quality and human health impacts (Miller & Jin, 2018). These disproportionate contributions make HDVs an effective target for fuel consumption and emissions control, contributing to the reduction of climate impacts and costs for truck operators.

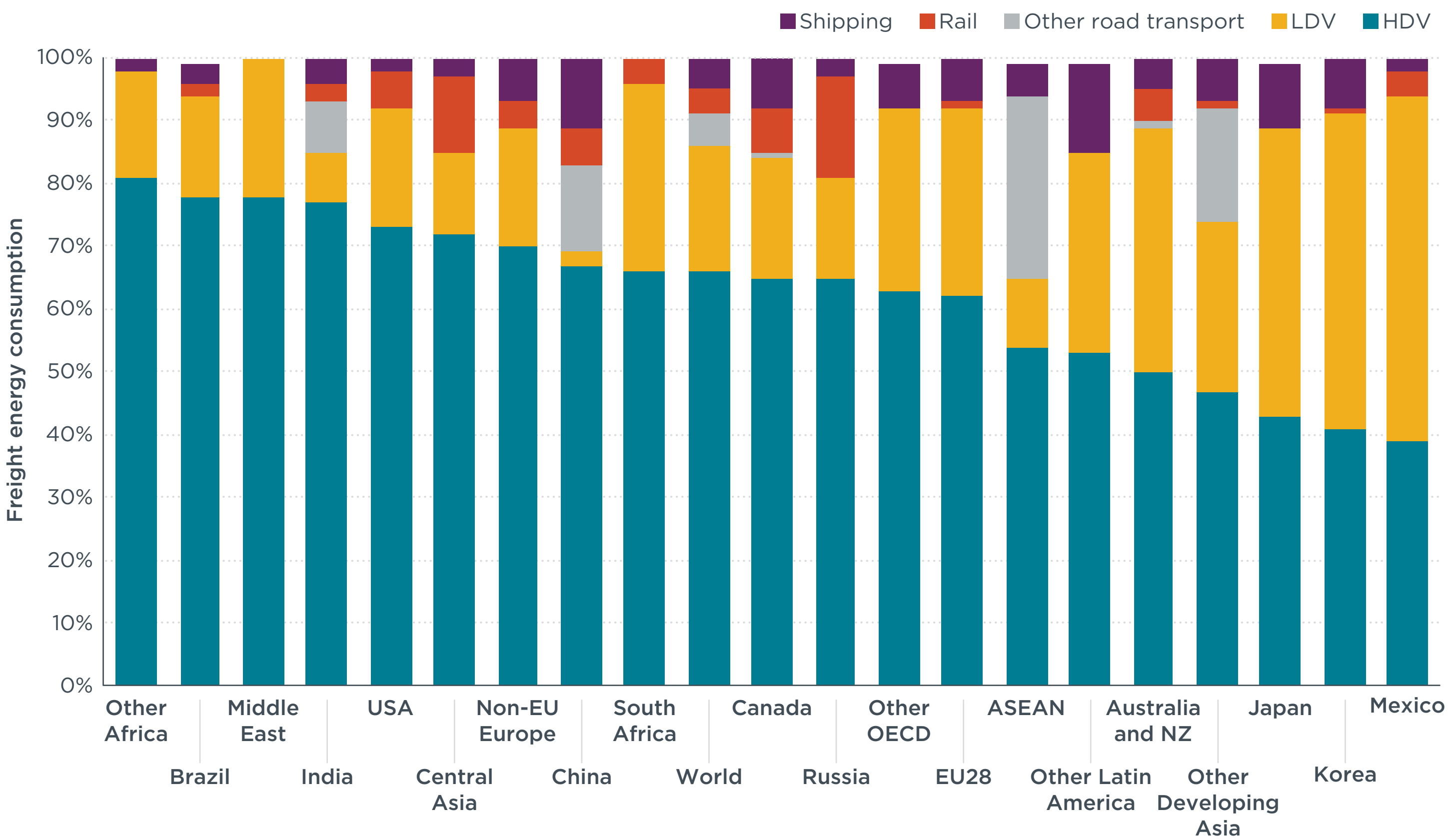

Figure 1. Share of freight energy consumption by mode in 2015 (excludes international shipping)

Note: Based on IEA data from the Mobility Model ETP 2017 Version © OECD/IEA 2017, www.iea.org/statistics. License: www.iea.org/t&c; as modified by the ICCT.

One pathway for reducing HDV fuel consumption and emissions is to accelerate the uptake of efficient truck technologies through a combination of regulations, such as fuel-efficiency and GHG standards; market-based approaches, such as voluntary green freight programs and labeling; and fiscal instruments, such as fuel and CO_2 taxes. In the past decade, key vehicle markets have regulated efficiency of new HDVs—the United

States, Canada, China, and Japan—or are in the process of doing so—India and the European Union. As testing the many potential HDV configurations is impractical and costly, most of these programs use vehicle simulation software as a certification and compliance tool to quantify HDV fuel consumption. Representative examples of these tools are the Greenhouse Gas Emissions Model (GEM) in the United States and the Vehicle Energy Consumption Calculation Tool (VECTO) in the European Union.

In addition to improving the efficiency of new vehicles through regulations, some countries have developed voluntary green freight programs, which are generally market-based, public-private partnerships, that promote fuel-saving technologies and strategies while providing information, recognition and other incentives for efficient carriers and shippers. SmartWay, the world's first green freight program, was established by the U.S. Environmental Protection Agency (EPA) in 2004 (U.S. EPA, 2018a). Subsequently, similar programs in North America were implemented in Canada with FleetSmart Canada, since merged into a single SmartWay program with the United States, and Mexico with Transporte Limpio. Programs in China and other regions are in different stages of implementation (Baker et al., 2015).

The SmartWay program relies on data collection, performance benchmarking and reporting, technology verification, and commitments from partners to better environmental performance. Technology verification is a key element because it tests the validity of fuel-consumption reductions claimed by suppliers of efficiency technologies, providing confidence to interested parties. Technology verification testing requires standardized procedures and can be resource intensive, with the agency providing extensive technical oversight of available independent engineering firms, or, at an even greater expense, operating their own test facilities using specialized equipment. Because of these constraints, testing is usually done under a limited set of driving cycles, which might not represent accurately the wide range of real-world operations that carriers typically experience.

There are clear synergies among technology verification, green freight programs, and HDV efficiency regulations. Green freight programs and efficiency regulations drive the adoption of fuel-saving technologies for trucks. Technology verification in green freight programs can accelerate the adoption of cost-effective technologies in fleets by removing information barriers and increasing carrier confidence to invest in retrofits. As more carriers adopt fuel-saving retrofit technologies, resulting in measurable reductions in total cost of ownership, the demand for new trucks with standard fuel-efficiency technologies also increases. In addition, the resulting fuel-consumption reduction and technology adoption data inform the regulatory design of HDV fuel-efficiency standards.

This study assesses the feasibility of adapting existing vehicle simulation tools to develop a simplified tool, which we name the Technology Verification Tool (TVT), to streamline technology verification for nascent green freight programs with limited resources for extensive real-world testing[1]. The remainder of Chapter 1 provides background on green freight programs, technology verification, and vehicle simulation tools. Chapter 2 presents the methodology to develop the simplified tools and describes three case studies on the effects of aerodynamic devices, low rolling-resistance tires,

1 Technology verification organizations usually refer to "full-scale testing", meaning that a real truck or component is tested. These are usually tested under narrowly controlled conditions that might not be representative of all driving conditions observed in the real world. In this paper, "real-world testing" includes "full-scale testing" and is used more generally to differentiate between the realms of simulation and physical testing.

and duty cycles. Chapter 3 shows the results and analysis for the case studies. Chapter 4 summarizes conclusions, and Chapter 5 suggests potential next steps.

1.2 GREEN FREIGHT PROGRAMS AND TECHNOLOGY VERIFICATION

Green freight programs are typically voluntary partnerships between government and industry aimed at improving freight efficiency by removing information, technology, and financial barriers for fuel-saving technologies and operational measures, while also leveraging market mechanisms to accelerate technology uptake. Green freight programs include the following key elements (Sharpe, 2015):

a) **Data collection and benchmarking**. Green freight programs collect fuel consumption and other key data from carrier partners across different modes of freight transportation, allowing them to track and report their progress while benchmarking performance against peers. Performance reporting supports green procurement and corporate carbon reduction and carbon social responsibility efforts.

b) **Guidance for technologies and operational best practices**. Green freight programs collect, evaluate, and share industry best practices to help program partners including carriers, logistics operators, and shippers to make better-informed decisions about fuel-saving technologies and operational strategies.

c) **Branding**. Technology suppliers and fleets are able to publicize technology advances and enhanced performance levels due to their participation in the green freight program, increasing market visibility and giving stakeholders incentives to participate. Branding can take various forms, including public-facing labels of certified performance.

d) **Technology verification**. Technology verification accelerates the adoption of cost-effective technologies by providing objective and reliable information on technology performance and cost savings and ultimately removing market and information barriers. Green freight programs conduct independent testing of technologies using industry standard test procedures. Fleet operators benefit by using proven technologies, vetted by independent entities. Technology suppliers demonstrate the effectiveness of their technologies and gain market share.

Figure 2 provides an overview of the technology verification process within a green freight program. Suppliers submit applications for their technologies to be verified and provide either (1) equipment for testing or (2) results from manufacturer conducted testing. After validating eligibility, the green freight program conducts tests or reviews testing performed by an independent agency. These tests should follow standardized test protocols established and made available by the green freight program. Approval for inclusion on the list of verified technologies is based on set criteria for individual technologies. Once approved, each technology is listed in the database or website for access by the carrier, providing fuel consumption or emission-reduction values and recommendations to users. Then, based on their needs, carriers decide which technologies to adopt. A feedback loop, not illustrated in the figure, may happen once the carriers test technologies and share their experiences with the green freight program.

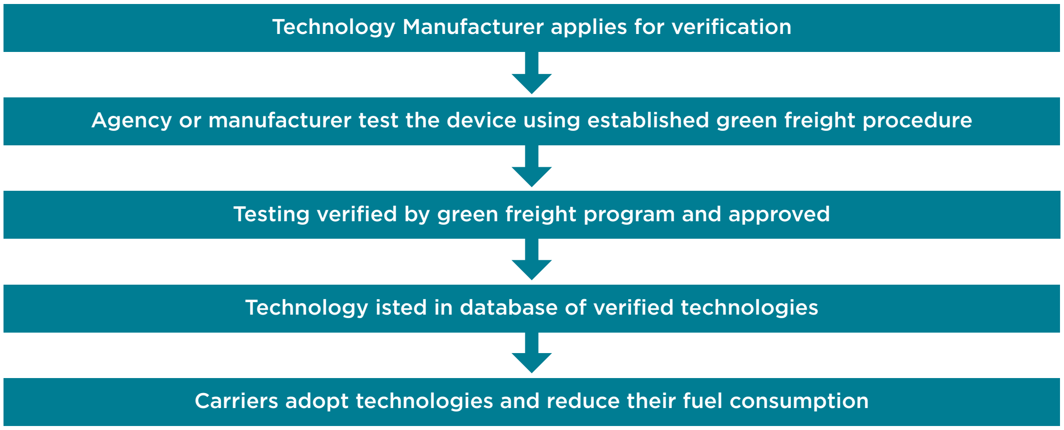

Figure 2. Overview of technology verification within a green freight program. Adapted from U.S. EPA SmartWay (2018d).

1.3 SMARTWAY PROGRAM TECHNOLOGY VERIFICATION

The SmartWay program is the only green freight program that has a comprehensive technology verification program (Sharpe, 2015). The EPA has adopted a suite of testing protocols that technology suppliers can use to measure the effectiveness of their products in three key areas: aerodynamic technologies, low rolling-resistance tires, and idle-reduction technologies (see Figure 3). Typically, technologies must meet a certain threshold to be added to the "SmartWay Verified Technologies" list (U.S. EPA SmartWay, 2018e). Each technology verification process is discussed below.

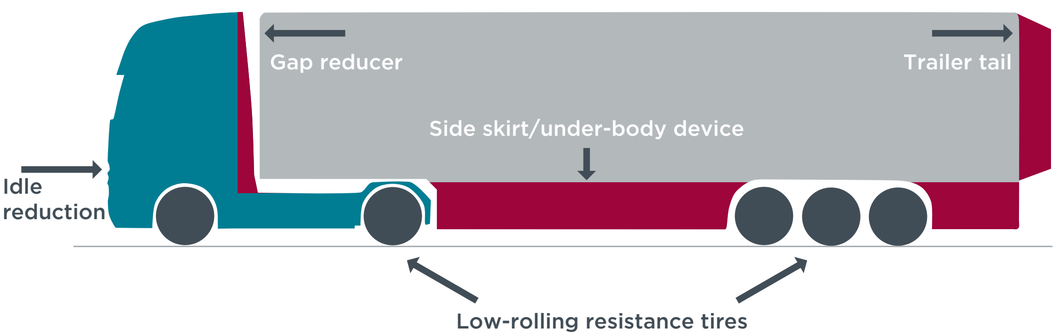

Figure 3. Available verified technology devices under SmartWay Program[2]

1.3.1 Aerodynamic testing

As a vehicle travels on the road, the surrounding air acts as a force opposing the motion of the vehicle. This aerodynamic drag force (F_{aero}) can be defined as:

$$F_{aero} = 0.5\, \rho_{air}\, C_d A\, V^2$$

where ρ_{air} is the air density; C_d is the coefficient of drag, a dimensionless number; A is the frontal area of the vehicle around which the air must flow, and V is the velocity of the vehicle relative to the air.

2 A typical Brazilian tractor-trailer configuration with a cab-over-engine, 4x2 tractor and a 3-axle trailer is shown. U.S. tractor-trailer typical configuration has a conventional (nosed) cab, 6x4 tractor and a 2-axle trailer.

Aerodynamic improvements allow the air around the vehicle to move more smoothly, reducing the Cd and increasing fuel efficiency. As the aerodynamic force is directly proportional to the square of the velocity of the vehicle, the improvements are more significant at higher speeds. Aerodynamic drag is particularly significant for long-haul tractor-trailers operating on high-speed highways.

SmartWay verifies aerodynamic devices for trailers, including gap reducers, tails, skirts, and under-trailer devices (see Figure 3). Devices are grouped into four categories based on whether they meet four levels of fuel-savings targets. These are one (1%), four (4%), five (5%), and nine (9%) percent fuel savings. A product's level of fuel savings is demonstrated using one of three primary verification test methods and one supplemental method (U.S. EPA, 2015a):

a) **Wind-tunnel testing**. This method uses a tunnel that blows wind over a stationary vehicle to evaluate air flow around an object and measure the aerodynamic efficiency of a vehicle. It typically uses a scaled model for testing rather than the actual vehicle. The method measures aerodynamic drag coefficient rather than fuel-consumption reductions. The manufacturer must first conduct baseline runs with the model without aerodynamic devices, followed by test runs with devices installed. The change in the wind-averaged[3] drag is then multiplied by factors to project the vehicle's fuel usage at different speeds. SmartWay verification is based upon the projected fuel savings from aerodynamic devices at an actual vehicle speed of 65 mph, the typical highway cruise speed in the United States (U.S. EPA, 2015b).

b) **Track testing**. This method measures actual fuel use and savings with full-scale vehicles and technologies on a test track. A modified version of the SAE J1321 (SAE, 2012) track test procedure is used to assess fuel savings of aerodynamic technologies. Fuel is measured by weighing the fuel tanks after each run (U.S. EPA 2015c). This is the only SmartWay test that directly measures fuel savings without using a factor to convert aerodynamic drag improvement to projected fuel savings. However, variations in weather and truck operating conditions can influence the test results. Thus, protocols must require controls to address sources of uncertainty to yield consistent fuel-savings measurements.

c) **Coast-down testing**. This involves accelerating a tractor-trailer to a certain high speed before disengaging the engine and drive train and letting the vehicle coast down to a lower speed. The vehicle and wind speed profiles over time are measured to calculate aerodynamic drag. Fuel usage benefits are calculated indirectly, similarly to wind-tunnel testing. Coast-down is the primary method used for American fuel-consumption regulations (U.S. EPA, 2016).

d) **Computational fluid dynamics (CFD)**. This method uses a computer simulation to model air flow around a virtual vehicle. CFD is a supplemental test method only, meaning that it must be used in combination with another method for verification purposes.

3 Wind-averaged drag area (CdA) represents an average CdA over a range of yaw angles. Yaw angle is the wind angle observed by the vehicle with respect to its direction of motion. This set of measurements taken at different angles relative to a "head on" wind, is averaged to represent typical side winds experienced on the road.

1.3.2 Tire rolling resistance

Tire rolling resistance is the force resisting the motion of the wheels on a surface. As the vehicle moves, the tire undergoes repeated cycles of deformation as it contacts the road. Some of the energy required to deform the tire is dissipated as heat when the tire recovers its shape behind the contact patch. The rolling resistance force can be defined as:

$$F_{roll} = C_{rr} mg \cos \Theta$$

Where C_{rr} is the tire rolling-resistance coefficient, m is the vehicle mass, g is the acceleration of gravity, and Θ is the road inclination. The coefficient of rolling resistance is a property of the tire and can be defined as the ratio of the resistive force to the normal force applied to the tire.

SmartWay verifies commercially available low rolling-resistance tires and retread technologies using the tire rolling-resistance testing procedures defined by SAE J1269 (SAE, 2006) or ISO 28580 (ISO, 2018). These tests measure the tire rolling-resistance coefficient using a rolling drum test bench, and tires are verified whether their C_{rr} is at or below target values prescribed for steer, drive, or trailer positions (U.S. EPA, 2018c). These targets correspond to fuel-consumption reductions of at least 3% when compared with standard baseline tires. This fuel-consumption reduction is achieved when verified low rolling-resistance tires are installed on all of the axle positions of the tractor and trailer, and all tires are properly inflated.

1.3.3 Idle reduction technology

In long-haul transportation, the energy demands of drivers during mandatory rest periods of more than eight hours must be satisfied. Traditionally, the energy required for heating or cooling the cabin and the electricity used by on-board appliances and personal electronics is supplied by idling the engine. SmartWay verifies devices that satisfy the driver’s needs without idling the main engine. These include auxiliary power units, battery-operated units, fuel-operated heaters, thermal storage units, and electrified parking spaces. The verification program evaluates the ability of such technologies to reduce idling of the main engine and increase fuel savings in long-haul trucks, such as Class 8 trucks with a sleeper cabin.

Figure 4 shows approximate ranges of fuel savings for individual technologies. The ranges highlight that technology effectiveness varies with application. For example, an aerodynamic device will perform better when the truck is driven at higher speeds (Sharpe, 2015). Technology verification serves a critical role to give fleets and other stakeholders a certain level of confidence in the real-world effectiveness of technology. A given technology can yield fuel savings as long as the average operating conditions are reasonably similar to the driving condition evaluated during the technology verification test procedure.

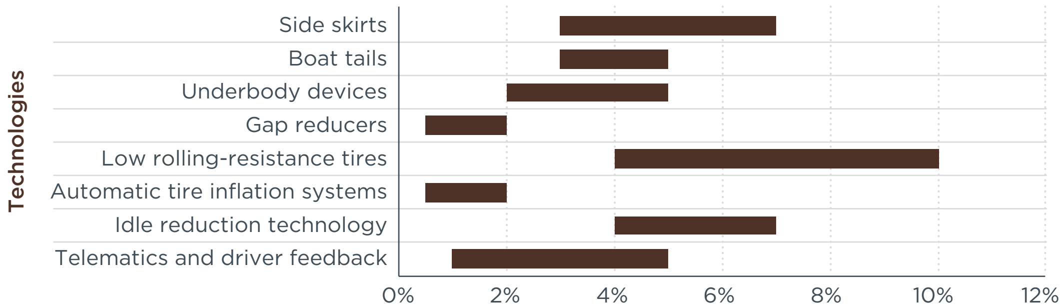

Figure 4. Approximate fuel-consumption reduction ranges for fuel-efficiency technologies for tractor-trailers in typical long-haul operations (adapted from Sharpe, 2015)

1.4 VEHICLE SIMULATION METHODS

Vehicle simulation software tools use physics-based, full-vehicle models to estimate the effects of technology adoption on efficiency and emissions. Because of its ability to incorporate complex technology interactions and analyze multiple technology permutations, vehicle simulation has become a dominant tool for designing, engineering, and regulating HDVs (Delgado & Lutsey, 2015).

These tools rely on vehicle component testing as input data. Key components include characteristics of the engine, transmission, rear axle, vehicle aerodynamics, tires, and accessories. Table 1 summarizes typical inputs required for the definition of a vehicle model. Depending on the required level of detail, generic representative values for a given truck category or model-specific component data might be used. Besides vehicle data, duty cycle inputs are also required, including vehicle route information such as speeds and road inclination and truck payload.

Table 1. Main model inputs

Component	Input Required
Engine	Fuel consumption map, full-load torque curve, motoring friction curve
Transmission	Transmission type, gear ratios, efficiency or torque-loss map
Axle	Axle ratio, efficiency or torque-loss map
Aerodynamic drag	Air drag area (CdA)
Tires	Tire rolling resistance coefficient (C_{rr}) for each axle (steer, drive, trailer), tire dimensions
Accessories	Power demand of cooling fan, steering system, electric system, pneumatic system, air conditioning system and power take-off
Vehicle	Curb vehicle weight, gross vehicle weight rating, axle configuration
Duty cycle	Speed, road grade, payload

For a given duty cycle, the simulation tools use the component data inputs to feed mathematical models that simulate the longitudinal dynamics of the vehicle and the energy flows between the different components. The output depends on the tool used and generally includes second-by-second and cumulative vehicle energy use at different locations in the powertrain, fuel consumption, and other performance metrics. Figure 5 illustrates the typical layout of a simulation tool inputs and outputs in a simplified flowchart.

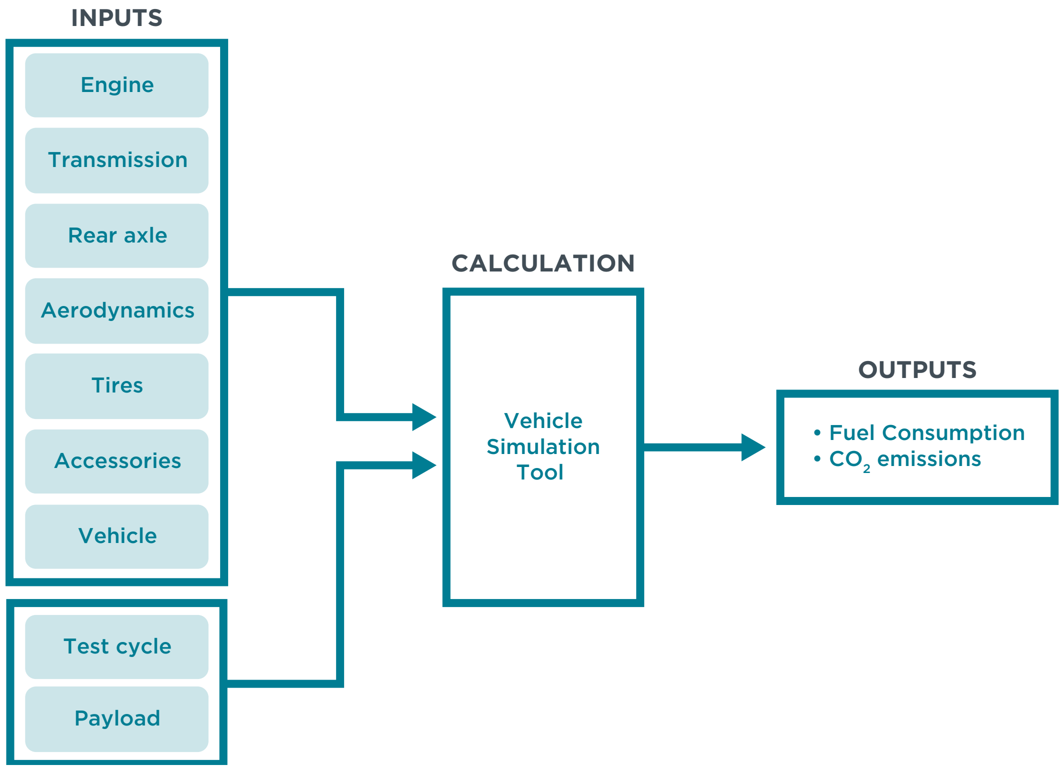

Figure 5. Vehicle simulation flowchart

2. METHODOLOGY

This study assesses the feasibility of adapting existing vehicle simulation tools as a streamlined approach to technology verification and speedier technology adoption under nascent green freight programs. This simplified tool, the Technology Verification Tool (TVT), can be used by various stakeholders to estimate the potential fuel savings of technology improvements on their fleets without extensive real-world testing.

VECTO and GEM, used within fuel-consumption and CO_2 certification methodologies for HDV regulations in the EU and the U.S., were deemed suitable candidates for adaptation purposes as they are both open source and publicly available. GEM and VECTO are physics-based models that simulate the longitudinal dynamics of HDVs.

This study creates vehicle models with both tools and simplifies the user inputs to create TVTs to estimate fuel-consumption benefits from verified aerodynamic devices and low rolling-resistance tires. A recent ICCT study (Rodriguez, 2018) provides further details of how GEM and VECTO function and finds that, under the same input parameters, the outputs of VECTO and GEM are essentially the same.

2.1 TOOL MODIFICATION

This study focuses on a generic tractor-trailer typically used in Latin America to leverage the recent momentum of green freight programs in Mexico, Argentina, and Chile. With this tool, fuel savings from selected technologies can be estimated for other tractor-trailers that may not exactly match the reference vehicle configuration, but the use of relative fuel-consumption reductions is expected to produce acceptable accuracy. Figure 6 illustrates screenshots of the user versions of the two tools that were adapted to develop the technology verification tools.

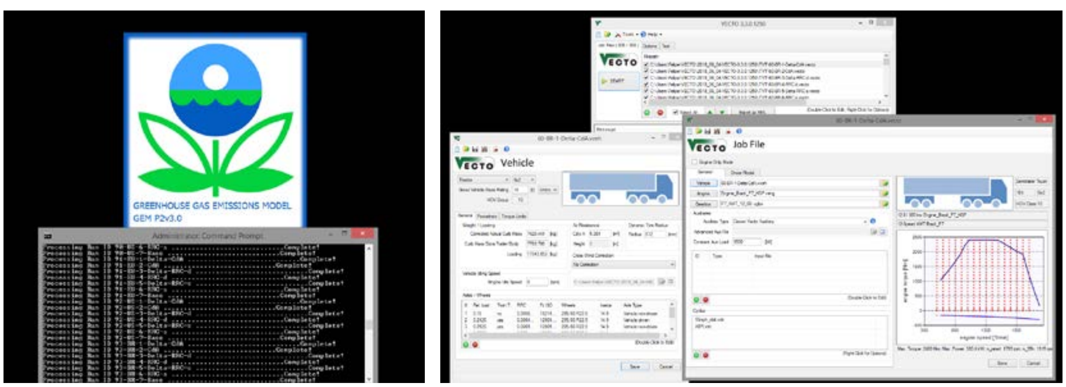

Figure 6. Screenshots of publicly available versions of GEM (left) and VECTO (right)

Vehicle models were created in the simulation environment of GEM and VECTO based on a typical Brazilian tractor-trailer model that was analyzed in a previous ICCT assessment (Delgado, Miller, Sharpe, & Muncrief, 2016). The vehicle specifications are summarized in Table 2. The input data were gathered from best-available information from previous ICCT projects. The fuel map was provided by a recognized engineering service provider, AVL List GmbH. VECTO's engineering mode provides a user-friendly interface to modify duty cycles, payloads, and vehicle details. The publicly available version of GEM, on the other hand, does not allow for some modifications, which can be made only by accessing the source code, suggesting additional efforts that are needed in the adaptation as a TVT. Pre-defined, non-editable parameters in GEM include, among others, duty cycles and payloads, electric and mechanical accessory power consumption of the tractor, trailer rolling resistance, and weight distribution over the axles. This analysis adapted the original Brazilian tractor-trailer model to match GEM's pre-defined, non-editable parameters.

Table 2. Vehicle specifications - Brazilian truck

Vehicle specification	Assigned default value
Gross vehicle weight (t)	36
Vehicle curb weight (t)	14.7
Payload (t)	17.2
Maximum payload (t)	21.3
Axle configuration	6x2
Engine displacement (L)	13.0
Engine power (kW)	380
Engine emissions standard	Proconve P7 (Euro V)
Transmission type	AMT
Transmission gear number	12
Transmission gear ratios	11.32-1.0
Transmission efficiency	96% indirect, 98% direct drive
Rear axle ratio	3.6
Rear axle efficiency	96%
Tire type	Radial
Tire size	295/80R22.5
Aerodynamic drag area CdA (m^2)	6
Steer Tires Crr (N/kN)	6
Drive tires Crr (N/kN)	6.3
Trailer tires Crr (N/kN)	6
Accessories power consumption (kW)	3.5

The developed TVTs simplify the required user-specified inputs, as they are limited to:

1. The duty cycle for which fuel-consumption reductions are to be estimated.
2. The choice of technology that are verified within the specific green freight program.

The use of a default reference vehicle is necessary as most end users will not have access to engine, transmission, and other detailed vehicle inputs that require costly and time-consuming component testing. Table 3 shows the default and user-defined parameters in this study. Vehicle default parameters can be updated regularly based on information gathered by green freight programs.

Table 3. User-defined and default model inputs

Component	User-defined?
Engine	✗ Representative engine is selected and used.
Transmission	✗ Representative transmission is selected and used.
Axle	✗ Representative rear axle is selected and used.
Aerodynamic drag	✓ User inputs a "delta CdA."
Tires	✓ User inputs an absolute value of C_{rr}.
Accessories	✗ Representative power demand is used.
Vehicle	✗ Only the tractor-trailer category is assessed.
Duty cycle	Optional. Users could specify their own or select for a set of predetermined cycles.

Note: ✓: user-defined input, ✗: default value is used as input

User input is simplified by calculating fuel-consumption reductions based on a predefined generic vehicle configuration, the reference vehicle, which is deemed sufficiently representative of the truck category and operational vocation to be analyzed. Rather than estimating absolute fuel consumption values, the model reports relative fuel-consumption reduction as a percentage based on the reference vehicle. This is expected to accurately represent the fuel-consumption reduction for the actual vehicle.

Within the scope of a TVT in a green freight program, the tool should be calibrated so that the absolute fuel consumption and CO_2 emissions of the reference vehicle match those observed in a real-world application as closely as possible. As the technology and efficiency levels of the fleet evolve, the reference-vehicle model would ideally be calibrated against real-world testing data on a regular basis so that the fuel savings are appropriately estimated in the simulation.

This study focuses on two of the technologies that are currently verified in the SmartWay program: aerodynamic devices and low rolling-resistance tires. Carriers that are interested in adopting these technologies can input their own duty cycles and payloads and select potential combinations from a list of pre-specified technologies. This list can be based on actual verification testing conducted by technology suppliers, or from already-verified technologies in a different verification program.

The technology inputs are transferred to the simulation model as physical parameters such as coefficient of aerodynamic drag, or CdA, and coefficient of rolling resistance, or C_{rr}. The tool then simulates the reference vehicle with and without the list of technologies selected by the user. Simulated fuel consumption and CO_2 emissions are then used to determine the relative benefits of the technologies. Since the actual carrier's vehicle is not being simulated, the tool output is in terms of relative fuel-consumption reduction rather than in absolute fuel-consumption units.

Table 4 shows the simulation parameters that need to be defined by the user within a fully operational TVT. At the time of publication, the duty cycles and payloads are hard-coded and thus cannot be edited in the publicly available executable version of GEM, which limits its versatility. VECTO's engineering mode offers full flexibility to change the required input data without access to the source code. This does not mean, however, that GEM cannot be adapted for other purposes such as technology verification or HDV efficiency standards in other markets. It just implies that access to the source code[4] is necessary for such adaptation.

Table 4. TVT user-defined inputs

User-defined input	Editable in GEM	Editable in VECTO
Aerodynamic technology (CdA)	✓	✓
Low-rolling resistance tire (Crr)	✓	✓
Duty cycle (speed, grade)	×	✓
Vehicle payload	×	✓

2.2. CASE STUDIES

Three case studies were developed to assess the effects of aerodynamic drag-reduction devices, low rolling-resistance tires, and duty cycles. The first two cases were conducted in VECTO and GEM, and the third was conducted only in VECTO because duty cycles cannot be changed in GEM.

The first two case studies assessed the feasibility of estimating the effects of a given technology by simulating its effects on a reference vehicle that is similar to but not exactly the same as the actual tool user's vehicle. With that in mind, this analysis simulates the effects of the technology in randomly designed variants of the reference vehicle and compares the observed fuel-consumption reductions to those observed for the reference vehicle. To emulate different potential tool users, 100 vehicle variants were randomly generated by modifying reference-vehicle parameters within the ranges listed in Table 5.

Table 5. Range of parameters used to define randomly generated vehicle variants

Vehicle specification	Range for random variant
Curb weight (t)	11.7 to 14.7
Payload* (t)	17.2 to 18.2
Engines**	Proconve P7, 380 kW, 13 L Euro VI, 350 kW, 13 L EPA 2010, 339 kW, 15 L
Rear axle ratio	3.42 to 3.78
Aerodynamic drag area CdA (m^2)	5.7 to 6.3
Steer Tires Crr (N/kN)	5.7 to 6.3
Drive tires Crr (N/kN)	6.0 to 6.6

*In GEM the payload used in simulation is linked to the weight reduction. Therefore, curb weight is the independent variable.
** Three engines were used to assess the effect of the engine fuel-consumption map. In generation of the random variants, each map has an equal probability of being chosen.

4 ICCT has access to GEM's power-user version, which contains the MATLAB-based source files as well as the Simulink model instead of the executable file which is publicly available on the EPA website. However, the power-user version is still limited in its ability to be modified, as the drive cycles are hard-coded in internal executable files. Access to the source code that creates such executable files is necessary to have full flexibility to adapt the GEM tool. At the moment, the ICCT does not have such access.

Each vehicle variant was simulated twice, with and without the technology being analyzed, using both GEM and VECTO. The simulations were performed over a transient cycle without grade, representative of urban operations, and over a constant speed cycle with grade at 88 km/h (55 mph), representative of highway operations (see Figure 7).

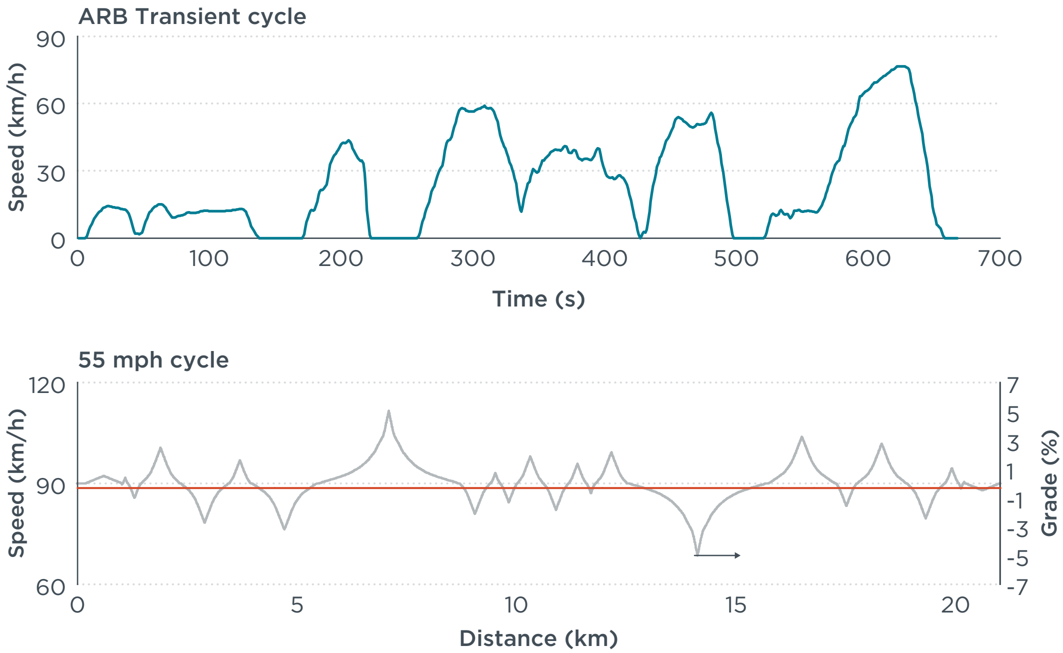

Figure 7. Transient and constant speed duty cycles used for case studies 1 and 2.

2.2.1 Case study #1 - Aerodynamic devices

A full-fledged technology verification process collects aerodynamic test data for a technology, which is tested on several tractor-trailer configurations and, depending on the specific test, is reported in terms of relative fuel-consumption reduction or absolute aerodynamic drag area (CdA in m^2). The relevant input parameter for simulation purposes is CdA.

Typical freight operations involve the use of different tractors for a given trailer. Some variation in aerodynamic performance of trailer aerodynamic devices is expected, as tractor aerodynamics can influence those of the trailer. In the Phase 2 regulations, the EPA decided to use a "delta CdA" approach, in which the effect of adding the device is measured relative to the baseline aerodynamic performance in units of aerodynamic drag area. A delta CdA approach is used in lieu of requiring an absolute CdA test. An absolute CdA test would require a specific standard tractor for testing to ensure an equitable comparison of the aerodynamic test results. A delta CdA approach allows variations in the tractor used by device manufacturers to perform tests on their devices and have them pre-approved for any original equipment manufacturer to apply on its products.

This study assessed the feasibility of estimating the effects of an aerodynamic device by simulating its effects on a generic vehicle. With that in mind, this analysis simulates the effects of a trailer aerodynamic device that reduces the air drag area by 0.5 m^2 over 100 randomly designed variants of the reference vehicle. This analysis then compares the observed fuel-consumption reductions, in percentage units, to those observed for the reference vehicle, as defined in Table 2.

2.2.2 Case study #2 - Low rolling-resistance tires

The technology verification process for low rolling-resistance tires directly reports the relevant metric to be used in simulation, the rolling-resistance coefficient. A green freight program may decide to use actual model-specific rolling-resistance values or use established thresholds or bins corresponding to verified low rolling-resistance ranges. This case study assesses the feasibility of estimating the effects of low rolling-resistance tires by simulating their effects on a generic vehicle. We simulate the effects of a given set of low rolling-resistance drive tires on both the reference vehicle and a set of 100 randomly generated variants of the reference vehicle, representing vehicles from different tool users. Note that the actual rolling resistance that affects fuel consumption is not the measured coefficient of rolling resistance for individual tires, but rather a weighted average of the rolling-resistance force multiplied by the load placed on each axle.[5] In this case, the analysis applies low rolling-resistance tires only on the drive and tandem axles. For the study, the coefficient of the low rolling-resistance tires was set to 5.4 N/kN, below the threshold for SmartWay verification, which is 5.6 N/kN under the ISO 28580 test.

2.2.3 Case study # 3 - Duty cycle effects

This study also evaluated the effect of duty cycles on fuel-consumption reduction of the technologies analyzed in the first two case studies. Only VECTO was used as GEM duty cycles are hard-coded in the source code. The technologies were evaluated over five duty cycles: The GEM ARB transient and 55 mph constant speed cycles (see Figure 7), and three VECTO cycles: Urban Delivery, Regional Delivery and Long Haul (see Figure 8).

5 $Crr_{tractor\text{-}trailer} = Crr_{steer}W_{steer} + Crr_{drive}W_{drive} + Crr_{trailer}W_{trailer}$ where W_i is the relative load put on axle i.

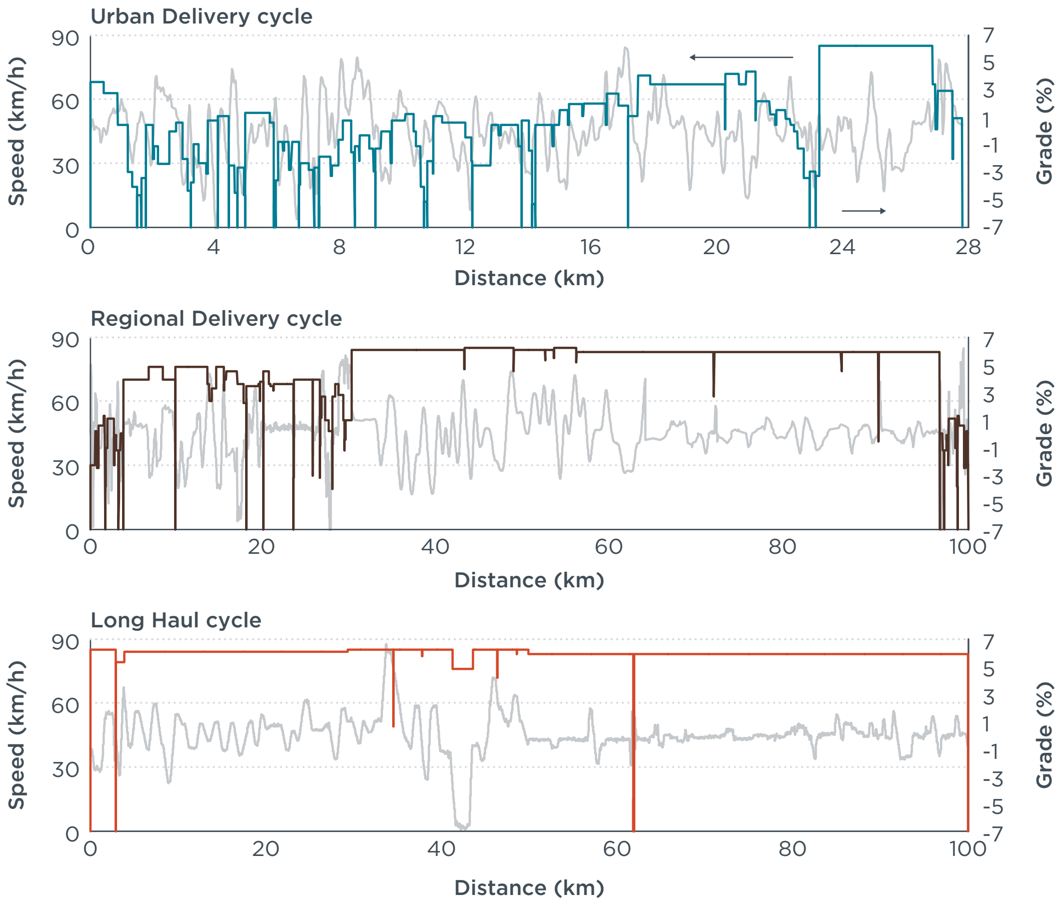

Figure 8. VECTO cycles used for analyzing the effect of duty cycle on fuel-consumption reduction effectiveness

3. RESULTS AND ANALYSIS

3.1 CASE STUDY #1 RESULTS – AERODYNAMIC DEVICES

Figure 9 shows results of projected fuel-consumption impacts of improving the aerodynamic drag (CdA) of the Brazilian standard tractor-trailer by 0.5 m^2 over the 100 randomized vehicle configurations for the constant speed cycle. The results are presented as empirical cumulative probability distribution curves in blue, with a normal distribution fitting in red. The mean and standard deviation of the normal distribution fits are shown in the individual diagrams. The fuel-consumption reduction observed for the reference vehicle (Table 2) after applying the delta CdA reduction is represented by the vertical dashed line.

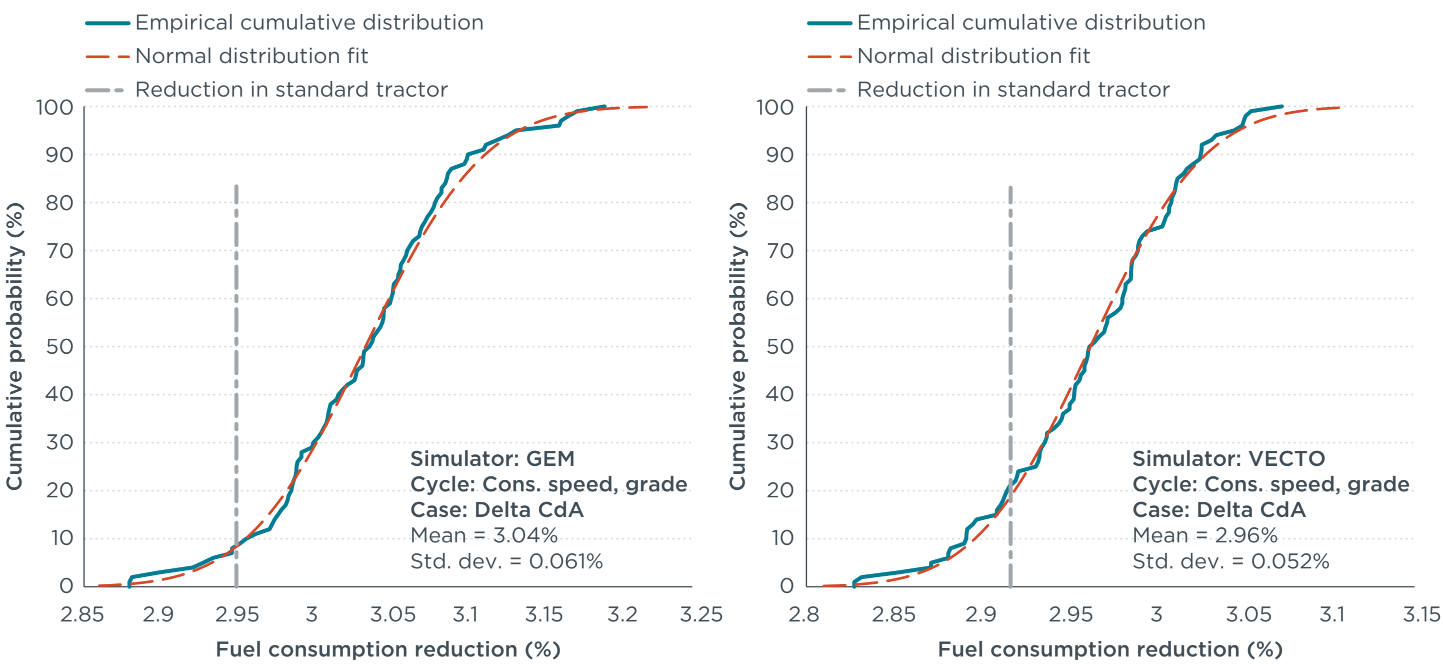

Figure 9. Cumulative probability curves for aerodynamic device fuel-consumption reduction for 100 vehicle variants over the highway cycle. GEM results (left), VECTO results (right).

The aerodynamic device reduces fuel consumption of the reference vehicle by 2.95% when simulated in GEM and 2.92% with VECTO, showing consistency across both tools. The simulation of the same aerodynamic device over the 100 vehicle variants results in fuel-consumption reduction estimates that are normally distributed with a mean value of 3.04% when simulated in GEM and 2.96% in VECTO. In both simulation tools, the reference vehicle exhibits a fuel-consumption reduction that is below the 20^{th} percentile. However, the standard deviation of the results is very low, at around 0.06% for GEM and 0.05% for VECTO. The confidence intervals that can be extracted from the data distributions from GEM and VECTO simulations (see Figure 9) imply that approximately 90% of the users applying this aerodynamic device will experience a fuel-consumption reduction in a narrow range between 2.85% and 3.15%.

Figure 10 shows results of the fuel-consumption reduction of the hypothetical aerodynamic device over the 100 randomized vehicle variants for the transient cycle. Due to the lower speed of the cycle, the fuel-consumption reduction is significantly lower when compared with the highway cycle. Still, the results are also normally distributed, with mean reduction values of 0.44% for the GEM simulations and 0.45% for the VECTO simulations, and standard deviations of 0.01% for GEM and 0.03% for VECTO. The confidence intervals that can be extracted from the data distributions from GEM and VECTO simulations (see Figure 10) imply that 90% of the users of this particular technology can expect a reduction between 0.4% and 0.5% over ARB's transient cycle.

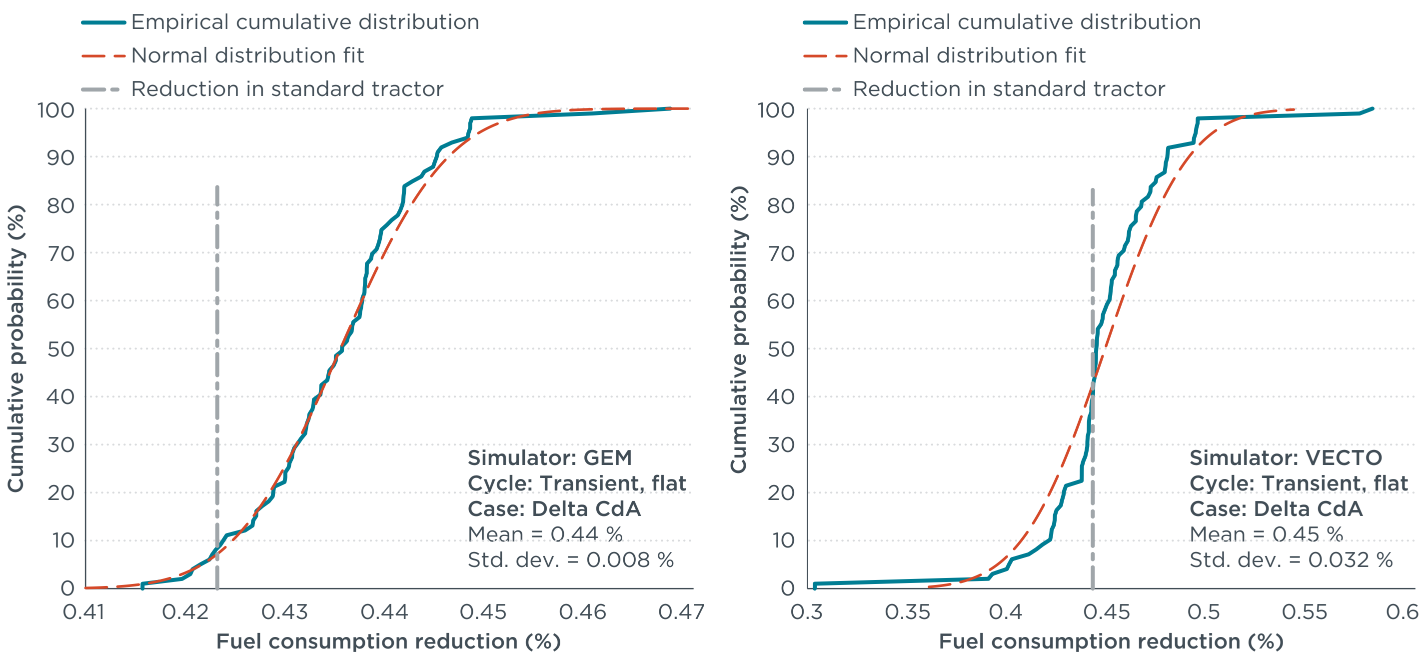

Figure 10. Cumulative probability curve for aerodynamic device fuel-consumption reduction for 100 vehicle variants over the urban transient cycle. GEM results (left), VECTO results (right).

Depending on the test methodology followed, a supplier of aerodynamic technologies would report either delta CdA values from wind tunnel or coast-down testing or fuel consumption reduction values from track testing. In the latter case, the user would need to use the simulation tool to reverse-engineer the delta CdA values based on provided fuel-consumption reduction values. This would also require reporting of duty-cycle data.

3.2 CASE STUDY #2 RESULTS – LOW ROLLING-RESISTANCE TIRES

Figure 11 shows empirical cumulative distribution curves of the fuel-consumption reduction results of applying low rolling-resistance tires only to the drive axle of the 100 randomized vehicle variants. The runs were conducted over the constant-speed highway cycle using both GEM and VECTO. As in the examination of the aerodynamic device, the results are well fitted by normal distributions. The fuel-consumption reductions observed by the reference vehicle, shown as a dark dashed vertical line, in GEM and VECTO are very close to the respective means of the randomized simulation runs, at 1.96% for GEM and 1.91% for VECTO. The confidence intervals that can be extracted from the data distributions from GEM and VECTO simulations (see Figure 11) imply that

90% of the users equipping these particular low rolling-resistance tires would observe a fuel-consumption reduction of between 1.5% and 2.5%.

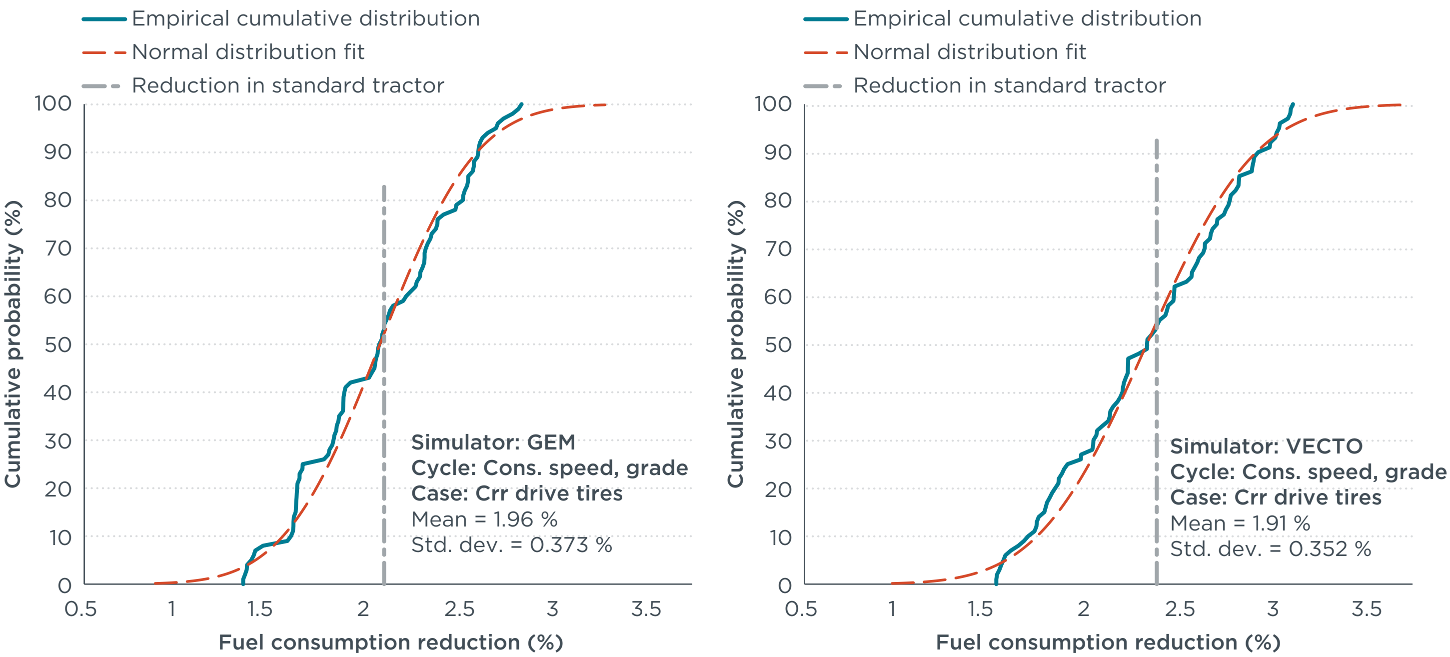

Figure 11. Cumulative probability curve for low rolling-resistance tires fuel-consumption reduction for 100 vehicle variants. GEM results (left), VECTO results (right) over the highway cycle.

Similarly, Figure 12 shows the fuel-consumption reduction results from low rolling-resistance drive tires over the urban transient cycle and the corresponding normal distribution fittings. The empirical cumulative distribution curve of the simulations using GEM exhibits a step-wise behavior that can be attributed to the internal rounding done by the simulation tool to the rolling resistance that was randomly assigned to the vehicle variants. Nevertheless, the mean of the results and the fuel-consumption reduction observed by the reference vehicle, shown as the dark dashed vertical line, are very close to each other around 1%, with a standard deviation of 0.19%.

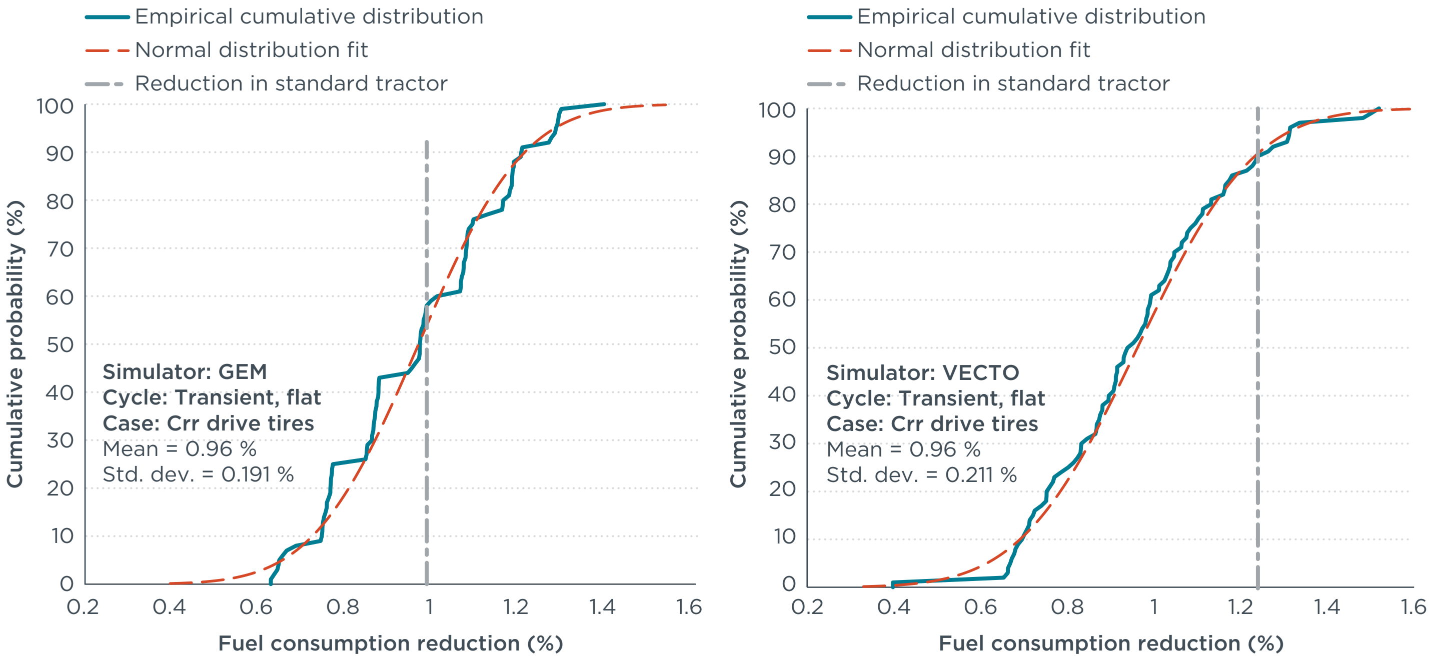

Figure 12. Cumulative probability curve for low rolling-resistance tires fuel-consumption reduction for 100 vehicle variants. GEM results (left), VECTO results (right) over the urban transient cycle.

The mean of the reductions simulated by VECTO over the 100 random variants has the same numerical value as the GEM results. However, the VECTO simulation of the reduction observed by the reference vehicle is discernibly higher at 1.24%, bordering the 90th percentile of the empirical results. This observation cannot be fully explained. The confidence intervals that can be extracted from the data distributions from GEM and VECTO simulations (see Figure 12) imply it can be stated that approximately 80% of the TVT users would experience a fuel-consumption reduction of between 0.7% and 1.2% from low rolling-resistance drive tires over the ARB transient cycle.

3.3 CASE #3 RESULTS – DUTY CYCLE EFFECTS

Figure 13 shows fuel-consumption reduction as a function of aerodynamic drag and drive tire rolling-resistance change for the five duty cycles listed above. A linear regression is performed to each set of results to evaluate the sensitivity to duty cycles.

Similarly to the previous two cases, a random process was used to generate the vehicles to be simulated. In this case, the air drag and drive tire rolling resistance for the reference vehicle (Table 2) were randomly modified in a bounded range. The resulting vehicles were simulated in VECTO and their fuel consumption compared with that of the reference vehicle. These simulations were carried out only in VECTO because it was impossible to input user-defined duty cycles in GEM. In the figures below, the origin of the plots represents the reference vehicle. The right and left quadrants represent vehicle variants with worse and better air drag and rolling-resistance coefficients.

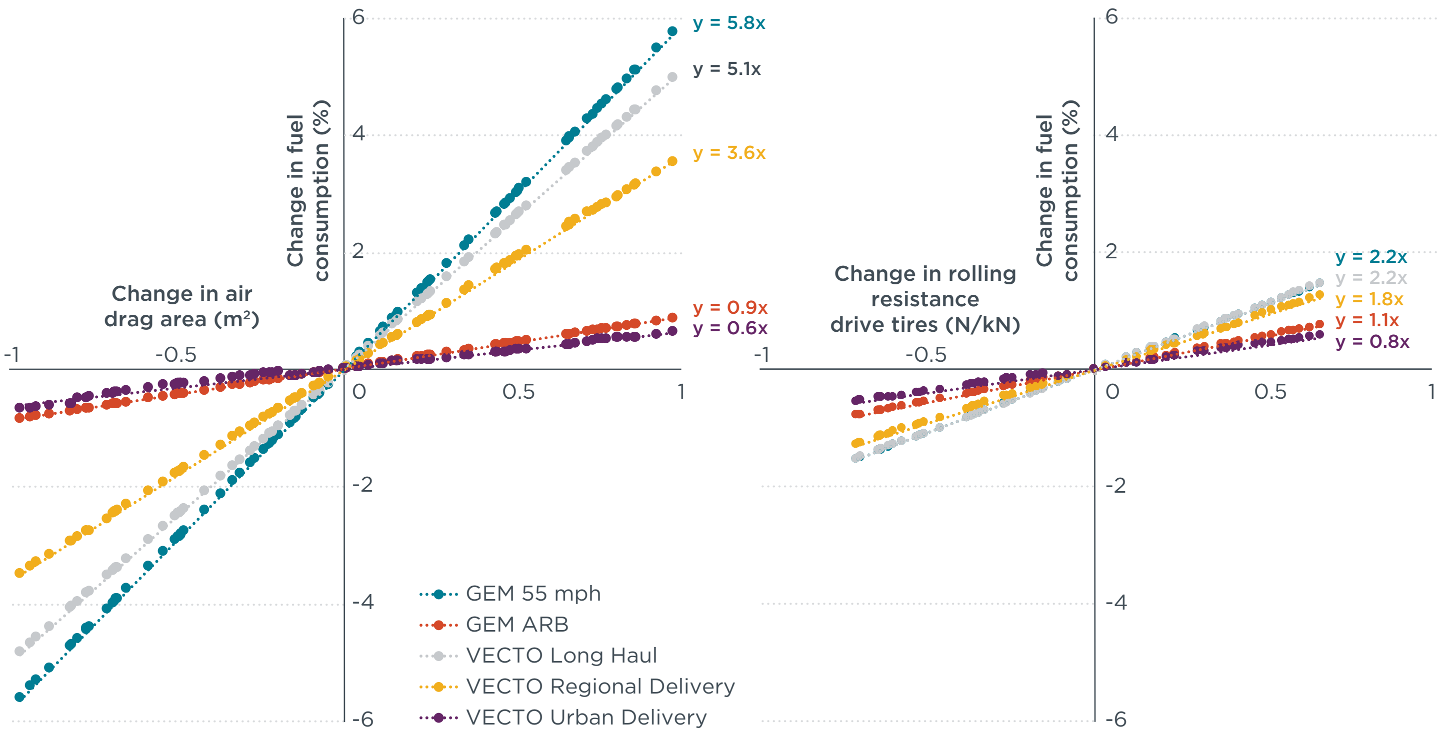

Figure 13. Cycle-dependent fuel-consumption reduction from a) low rolling-resistance drive tires and b) an aerodynamic device

Figure 13 illustrates that the fuel-consumption reduction is heavily dependent on the duty cycle. The sensitivity of fuel consumption relative to the duty cycle is more pronounced for air drag changes than for rolling-resistance changes. For the urban cycles of GEM ARB and VECTO Urban Delivery, the change in fuel-consumption reduction for a unit change[6] in air drag area is very similar to the fuel-consumption reduction observed for a unit change in drive tire rolling-resistance coefficient. This can be deduced from the similar slopes of the GEM ARB and VECTO Urban Delivery cycles, which represent lower-speed urban driving. However, as duty cycle speeds increase under the GEM 55 mph, VECTO Long Haul, and VECTO Regional Delivery schemes, and given that the aerodynamic drag scales with the square of vehicle speed, the benefits of reducing the air drag area by 1 m^2 are at least twice the reduction from a change of 1 N/kN in drive tire rolling resistance.

3.4 SUMMARY

Figure 14 shows two sets of boxplots with the distribution of fuel-consumption reductions simulated by VECTO when using a) an aerodynamic device and b) low rolling-resistance tires. Each set shows the results over three cycles: 1) a transient cycle, the GEM ARB Transient; 2) a highway cycle, the GEM 55 mph cycle; and 3) a mixed cycle consisting of 100 random combinations of the first two cycles. This was defined based on a randomly generated variable representing the time fraction driven over the 55 mph cycle, with the remaining time fraction driven over the ARB cycle. This means that if the random variable is 1, the cycle is exactly the 55 mph cycle, and if the random variable is

6 Despite having different units, the numerical value of air drag area and tire rolling resistance is very similar in the reference vehicle. Therefore, this study analyzed absolute changes in these two parameters.

0, the cycle is the ARB cycle. The traveled distance of the mixed cycles is also random as a result of how it is defined. Note that the results for the two first cycles have already been shown in empirical distribution curves in Figures 9-12.

The key message of Figure 14 is that the effect of duty cycles is larger than the effect of vehicle technology parameters, in particular for the aerodynamic drag case. For the transient and constant speed cycles, the observed distributions are narrower for aerodynamic drag reduction devices than for low rolling-resistance tires. This is explained in part by the fact that the assumed reduction in aerodynamic drag represents an absolute change of such parameter, so that delta CdA = 0.5 m^2, while the assumed reduction in rolling resistance represents an absolute value, or Crr= 5.4N/kN. This means that the use of delta CdA reduces the variability of the results as all the vehicle variants receive the same magnitude of reduction in CdA, regardless of initial value of CdA, while the magnitude of reduction of Crr varies depending on the value of Crr of the vehicle variants.

The effectiveness of verified technologies to reduce fuel consumption depends on how the vehicle is operated. This case study highlights the importance of inputting a user-specified duty cycle in the TVT, or to offer a sufficiently diverse set of predefined duty cycles that can closely resemble a user's particular operation. Having said so, it is desirable for a technology verification program to specify a single, representative duty cycle for designation of fuel benefits, so that each technology is consistently compared.

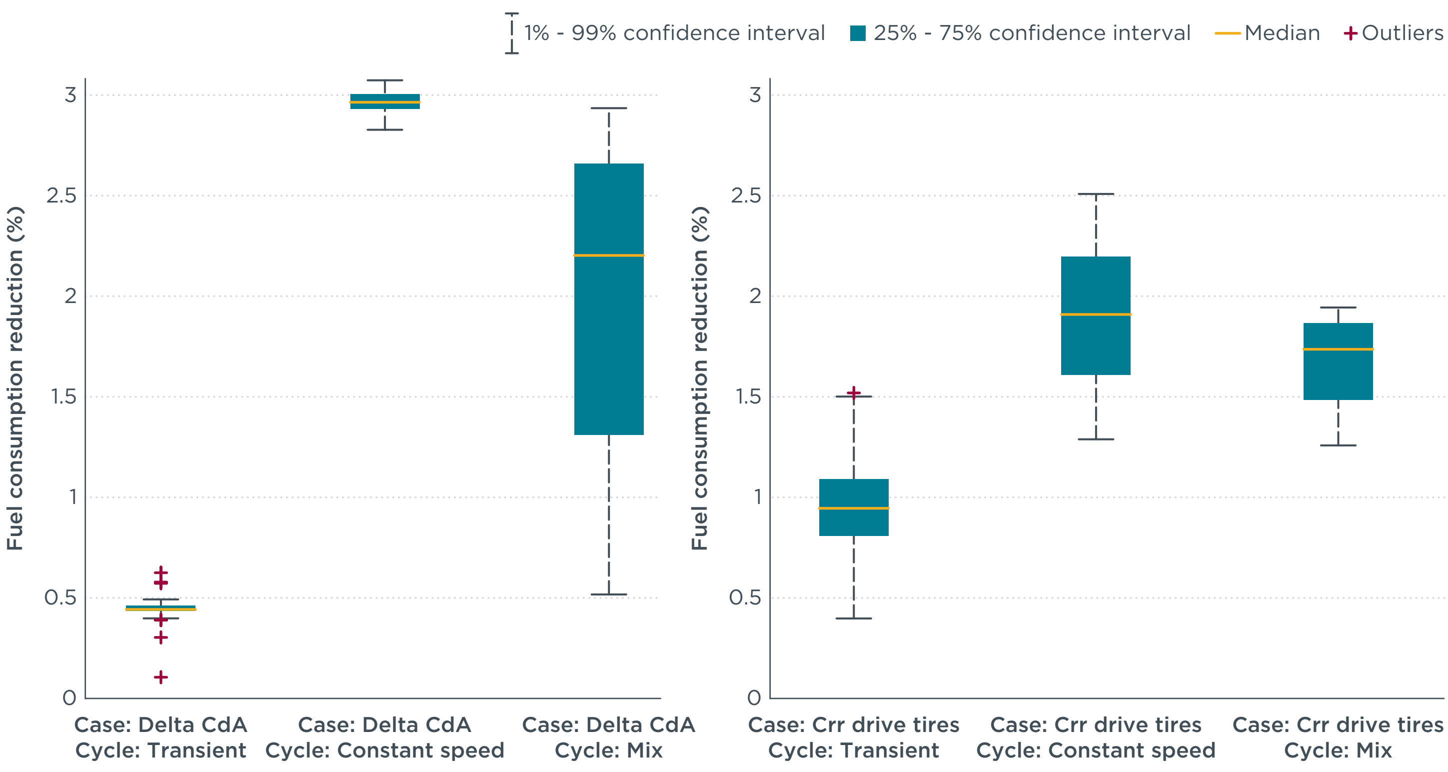

Figure 14. Boxplots of cycle-dependent fuel-consumption reduction distributions

4. CONCLUSIONS

Results indicate that both GEM and VECTO-based tools show consistent results in terms of mean and range of efficiency improvements. More importantly, the simulations indicate a relatively narrow range in efficiency improvements with a variation in truck parameters. In other words, different trucks within the same truck category should experience similar efficiency improvements when using the same technology. On the other hand, the variation in efficiency improvements is generally wider when changing driving cycles, in particular for aerodynamic devices whose effectiveness varies widely with vehicle speed. This supports the advantages of using a TVT to amplify the range of driving conditions and obtain a more representative range of efficiency improvements for a given carrier's operations.

The key conclusion of this study is that it is feasible to use an existing, publicly available vehicle simulation tool to develop the TVT and simulate fuel-consumption reduction with reasonable accuracy. Both GEM and VECTO show consistent results when applied under a similar set of input parameters, but VECTO for now offers higher flexibility for adaptation into the TVT. Ideally, an open version of GEM would be developed.

There are multiple benefits from using a TVT under a green freight program:

1. Carriers can justify technology investments without extensive real-world testing.
2. Technology suppliers can test products once and use simulation to estimate the technology benefits over a wider range of truck profiles and driving cycles.
3. The tool could benefit green freight programs by building credibility for technologies and awareness with carriers.
4. Adoption of similar tools worldwide could make technology verification synergetic across regions, reducing costs.

5. OUTLOOK FOR FUTURE RESEARCH

As illustrated in Figure 15, comprehensive green freight programs, primarily the North American SmartWay program, rely on extensive real-world testing for technology verification. The TVT can streamline technology verification for green freight programs and initiatives that do not have resources for extensive real-world testing, referred to as streamlined green freight programs. In addition, the TVT can also be used as a fleet tool to project fuel-saving benefits more tailored to specific fleet configuration and operations. This study developed an adapted version of the existing vehicle simulation models GEM and VECTO to prove the technical viability of a TVT for use by green freight programs. Next steps for future research include the analytical work to develop representative duty cycles and reference vehicles for a specific region, which requires a freight assessment, supporting literature review, and the collection of telematics data. The TVT will also need to rely on some real-world testing to calibrate the tool and better approximate modeled to real-world results. Such validation should ideally performed before initial use of the tool under a green freight program.

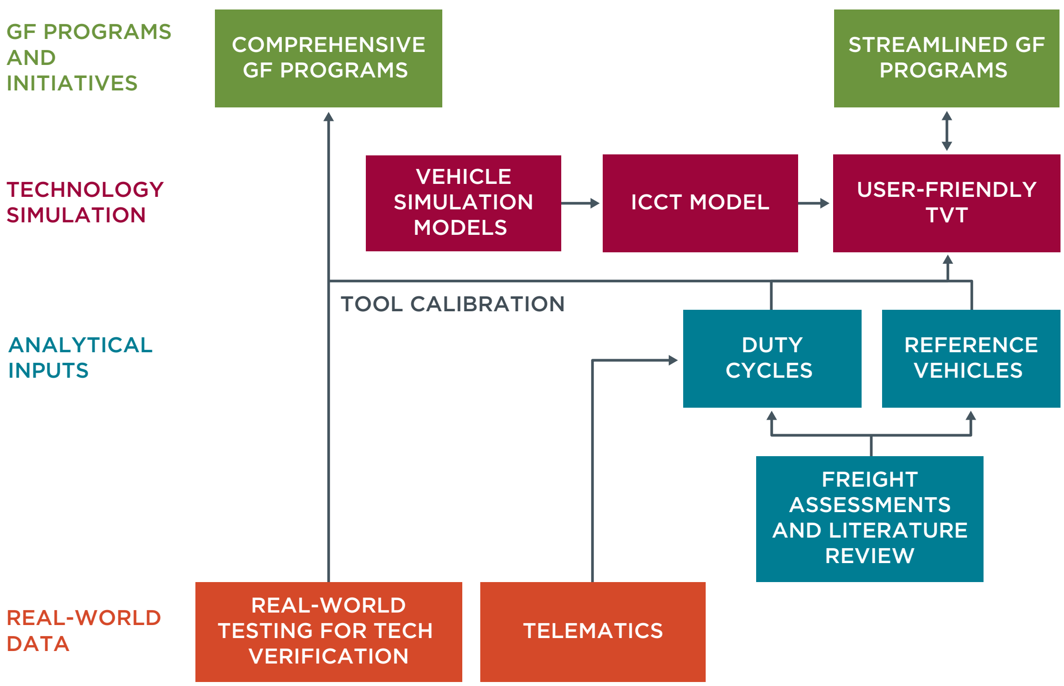

Figure 15. Outlook for future technology verification research

5.1 TECHNOLOGY SIMULATION

Further research would involve developing a user-friendly TVT and testing it in a green freight pilot project. The ICCT customized VECTO and GEM to advance the development of the TVT, showing consistent results across both tools, and proving that they can be used to streamline technology verification processes under the framework of a green freight program. The analysis also showed that VECTO is a better option for adaptation purposes because users can more easily input customized duty cycles. Ideally, an open version of GEM would be developed. After this initial adaptation, the next step would involve creating a user-friendly tool interface for testing under a pilot project, most likely in Latin America because of progress in national green freight programs in Argentina, Brazil, and Chile. After an initial trial, a web-based tool can be developed by the program and accessed independently by users, without requiring effort from program managers and allowing for more effective use of resources.

5.2 ANALYTICAL INPUTS

The TVT will need two key inputs: representative duty cycles and reference vehicles. Future research needs to develop these inputs, ideally under a pilot project to ensure a direct link between research and application. The goal is to populate the TVT with predefined duty cycles and default reference vehicles that users can select if they don't have sufficient data to develop their own. A national freight assessment would be a good first step to gather relevant information for the development of duty cycles and reference vehicles, so a natural next step would be to complete such assessments for key regions. There is already comprehensive guidance on how to conduct such an assessment, which typically includes a characterization of the freight market, vehicle technical parameters, and operational profiles, among other things (Sharpe, 2017). Another way to develop representative duty cycles would be to use telematics data from pilot partners.

5.3 REAL-WORLD DATA

A robust technology verification program will always need some real-world testing, even if limited. The proposed framework includes some real-world testing to calibrate the tool and better approximate modeled to real-world results. A feedback mechanism might be introduced in which partner carriers that adopt fuel-saving technologies report their observed benefits with respect to the tool's estimates. The addition of the impacts of operational strategies such as eco-driving training might enhance the scope of the TVT. Finally, the use of telematics data will provide insights in the development of representative duty cycles, as well as fuel-saving impacts of technologies if sufficient data are available.

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