NRC Publications Archive
Archives des publications du CNRC

Improved aerodynamic and road-load measurements using the coast-down method year 1: literature review and roadmapping

de Souza, Fenella; McAuliffe, Brian

For the publisher's version, please access the DOI link below./ Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/40003425
Laboratory Technical Report (National Research Council Canada. Aerospace. Aerodynamics Laboratory); no. LTR-AL-2019-0025, 2019-05

NRC Publications Archive Record / Notice des Archives des publications du CNRC :
https://nrc-publications.canada.ca/eng/view/object/?id=47b609ba-565e-44df-bdd4-c999de137bf6
https://publications-cnrc.canada.ca/fra/voir/objet/?id=47b609ba-565e-44df-bdd4-c999de137bf6

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

NRC·CNRC

AERODYNAMICS LABORATORY

Improved Aerodynamic and Road-Load Measurements Using the Coast-down Method
Year 1: Literature Review and Roadmapping

Unclassified Unlimited

LTR-AL-2019-0025

May 2019

Fenella de Souza and Brian McAuliffe

National Research Council Canada
Conseil national de recherches Canada

Canada

AERODYNAMICS LABORATORY

Improved Aerodynamic and Road-Load Measurements Using the Coast-down Method
Year 1: Literature Review and Roadmapping

Report No.: LTR-AL-2019-0025

Date: May 2019

Authors: Fenella de Souza and Brian McAuliffe

Classification:	Unclassified	**Distribution:**	Unlimited
For:	Innovation Centre ecoTECHNOLOGY for Vehicles (eTV) Transport Canada		
Project #:	A1-014712		
Submitted by:	Dr. Mike Benner, **Director of Research and Development, Aerodynamics**		
Approved by:	Dr. Ibrahim Yimer, **Director General, Aerospace Research Centre**		

Pages:	27	**Copy No:**	
Figures:	2	**Tables:**	0

Disclaimer

This report reflects the views of the authors only and does not reflect the views or policies of Transport Canada.

Neither Transport Canada, nor its employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy or completeness of any information contained in this report, or process described herein, and assumes no responsibility for anyone's use of the information. Transport Canada is not responsible for errors or omissions in this report and makes no representations as to the accuracy or completeness of the information.

Transport Canada does not endorse products or companies. Reference in this report to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or favoring by Transport Canada and shall not be used for advertising or service endorsement purposes. Trade or company names appear in this report only because they are essential to the objectives of the report.

References and hyperlinks to external web sites do not constitute endorsement by Transport Canada of the linked web sites, or the information, products or services contained therein. Transport Canada does not exercise any editorial control over the information you may find at these locations.

Executive Summary

In 2016, the transportation sector was the second largest source of greenhouse gas (GHG) emissions in Canada, accounting for 25% of total national emissions. Road transportation, which includes personal transportation (light-duty vehicles and trucks) and heavy-duty vehicles, accounted for over 70% of transport emissions in Canada. In an effort to reduce GHG emissions, manufacturers are addressing the need to make vehicles more fuel-efficient, and regulators are required to verify claims of increased fuel-efficiency and reduced emissions. Fuel-efficiency and emissions testing is generally carried out on a chassis dynamometer and requires input in the form of road load coefficients.

Coast-down testing is a convenient and effective method to obtain road load coefficients for fuel-efficiency and emissions testing. However, there is considerable variability in the results obtained from coast-down tests, indicating that there is room for improving the methodology. As such, Transport Canada, through its ecoTECHNOLOGY for Vehicles program, have commissioned a multi-phase project to investigate possible improvements in aerodynamic and road-load measurements using the coast-down method.

The main objective of this first year of the project was to lay out a detailed roadmap of the steps required to improve the reliability and accuracy of road-load measurements using coast-down testing, so as to begin developing improved measurement and analysis techniques that will be evaluated in subsequent phases of the project. The road-mapping exercise was guided by an extensive review of the literature on coast-down testing and methodologies, the summary and main findings of which are covered in this report.

It is recommended that the focus of the next year of this study be to improve coast-down data analysis methods to address the knowledge gaps identified in this study. It is suggested to revisit coast-down data previously measured by NRC as well as data obtained from other sources to develop and evaluate new analytical models, test and data analysis procedures. It is also recommended to research and investigate the effects of road surface roughness and irregularities, track geography and ambient wind variations and unsteadiness on coast-down test results. Coast-down tests that implement the improvements brought about by these recommended tasks are planned for follow-on phases of this study.

Contents

List of Figures

Nomenclature

Symbols:

A	area [m^2]
C_D	drag-force coefficient $\left(=\frac{F_D}{QA}\right)$ [ ]
F_{Aero}	aerodynamic drag force [N]
F_D	drag force [N]
F_{Grade}	grade force [N]
F_{Mech}	mechanical resistance forces [N]
F_{RR}	rolling resistance force [N]
F_{Trac}	tractive force [N]
m	vehicle mass [kg]
m_e	effective mass [kg]
Q	dynamic pressure $\left(=\frac{1}{2}\rho U^2\right)$ [Pa]
t	time [s]
V	vehicle ground speed [m/s]

Acronyms:

EC	European Commission
ECCC	Environment and Climate Change Canada

EPA	Environmental Protection Agency
eTV	ecoTECHNOLOGY for Vehicles
GEM	Greenhouse-Gas Emissions Model
GHG	Greenhouse Gas
LDV	Light-Duty Vehicle
HDV	Heavy-Duty Vehicle
IRI	International Roughness Index
NRC	National Research Council Canada
SAE	Society of Automotive Engineers
TC	Transport Canada

1. Introduction

1.1 Background

In 2016, the transportation sector was the second largest source of greenhouse gas (GHG) emissions in Canada, accounting for 25% of total national emissions. Emissions from this sector grew by 36% between 1990 and 2016. Road transportation, which includes personal transportation (light-duty vehicles and trucks) and heavy-duty vehicles, accounted for over 70% of transport emissions in Canada (Environment and Climate Change Canada, 2018). Transportation activities accounted for 28.8% of the total U.S. GHG emissions in 2017, of which over 80% was due to road transportation (United States Environmental Protection Agency, 2019).

In an effort to reduce GHG emissions, manufacturers are addressing the need to make vehicles more fuel-efficient, and regulators are required to verify claims of increased fuel-efficiency and reduced emissions. Fuel-economy and emissions testing is generally carried out on a chassis dynamometer and requires input in the form of road load coefficients. Coast-down testing is a convenient and effective method to obtain road load coefficients for fuel-economy and emissions testing. However, there is considerable variability in the results obtained from coast-down tests, indicating that there is room for improving the methodology (Wood, 2015; Passmore, 1990). As such, Transport Canada (TC), through its ecoTECHNOLOGY for Vehicles (eTV) program, have commissioned a multi-phase project to investigate improvements in aerodynamic and road-load measurements using the coast-down method.

1.2 Objectives

The main objective of this first year of the project was to lay out a detailed roadmap of the steps required to improve the reliability and accuracy of road-load measurements using the coast-down method, so as to begin developing improved measurement and analysis techniques that will be evaluated in subsequent phases of the project. The roadmapping exercise was guided by an extensive review of the literature on coast-down testing and methodologies in order to determine what is required to accomplish this objective. A summary of this literature review, including highlights of the main findings and recommendations for future work, is the topic of this report.

It is important to note that the coast-down method is not the only technique available to measure the road-load characteristics of a vehicle. The "constant-speed method" uses a different approach to quantify the road load. A description of both methods and the reason for selecting the coast-down method as the road-load measurement technique of choice is described in Chapter 2.

A summary of the relevant literature on coast-down testing and methodologies is provided in Chapter 3. The literature review identified significant knowledge gaps that need to be filled in order to improve the accuracy of aerodynamic and road load measurements using the coast-down method. These knowledge gaps are summarized in Chapter 4. The findings of the literature review were used to lay out a detailed roadmap of steps to be taken to address the identified knowledge gaps. This roadmap will guide the subsequent phases of this project and is detailed in Section 4.2 of Chapter 4. Chapter 5 summarizes the main findings of this first year of the project.

2. Coast-down method versus constant-speed method

A primary purpose of the coast-down method is to evaluate the road-load characteristics of a vehicle, whereby the road load represents the external loads acting on the vehicle that resist its forward motion. However, the coast-down method is not the only technique available to measure the road-load characteristics of a vehicle. The "constant-speed method" uses a different approach to quantify the road load. To permit a comparison of the two methods and to explain why the coast-down method is the focus of this document, the road-load acting on a vehicle must be considered. Figure 2.1 shows a simplified free-body diagram of a vehicle in motion, with the corresponding forces that are important to consider for the coast-down and the constant-speed methods. Forces that can affect forward motion of the vehicle are:

- Tractive Force (F_{Trac}) - force delivered by the driven wheels to maintain speed;
- Aerodynamic Drag (F_{Aero}) - resistive force as the vehicle moves through the air;
- Rolling Resistance (F_{RR}) - resistive force due to deformation of the tire material at the interface with the ground;
- Grade Force (F_{Grade}) - component of the vehicle weight in the direction of motion due to the grade/inclination of the road surface from horizontal; and
- Mechanical Resistances (F_{Mech}) - resistance to motion due to friction within mechanical components such as bearings, differentials, and the transmission.

The aerodynamic drag, rolling resistance and grade force contribute to the road load (F_{RL}) and represent the combination of external forces acting on the vehicle while in motion. The mechanical resistances behave as resistive forces, but are considered part of the internal vehicle system, not the external factors that act on the vehicle, and therefore are not considered part of the road load.

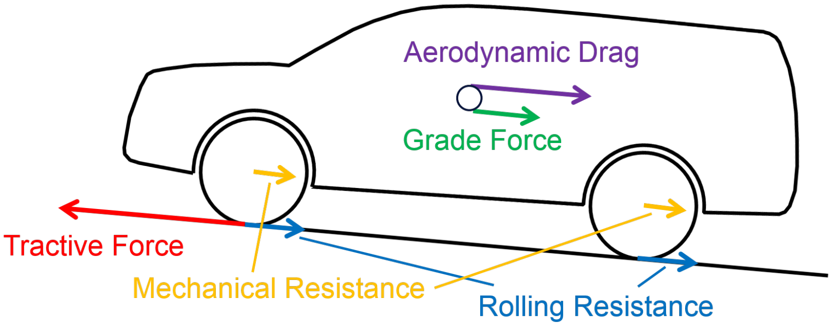

Figure 2.1: Free-body diagram of a vehicle in a coast-down.

Applying Newton's 2^{nd} law of motion in the direction of motion of the vehicle, the resulting equation is

$$m_e \frac{dV}{dt} = F_{Trac} - F_{Aero} - F_{RR} - F_{Grade} - F_{Mech} \tag{2.1}$$

for which m_e is the effective mass that includes the rotational inertia of the wheels and rotating drivetrain components.The term on the left-hand side of Equation 2.3 represents the inertial force component associated with the vehicle acceleration. The principle differences between the coast-down and constant-speed methods are the assumptions made based on the type of motion that the vehicle experiences.

Coast-down method: For a vehicle in an un-powered coast, there is no tractive force. In this scenario, the vehicle acceleration/deceleration is influenced by the external (road load) and internal (mechanical) resistances to forward motion. The equation of motion then becomes:

$$m_e \frac{dV}{dt} = -F_{Aero} - F_{RR} - F_{Grade} - F_{Mech} \tag{2.2}$$

With the coast-down method, road-load components and mechanical resistances are modelled or measured to permit quantification of unknown parameters. For example, measurements of the vehicle deceleration rate and road grade leave a combined force representing the aerodynamic, rolling-resistance, and mechanical-resistance forces. With appropriate modelling of the manner in which these individual forces behave with speed, each can be inferred from the measurements. The content of this document summarizes various ways to infer these individual force components and techniques to quantify their respective performance parameters, such as the aerodynamic-drag coefficient or the rolling-resistance coefficient. To improve the quality and accuracy of the results, many coasts are performed and the road load curves measured from each coast are analysed either on a per-coast basis and then averaged, or in an aggregate form.

Constant-speed method: For a vehicle traveling at constant speed, there is no acceleration. In this scenario, the vehicle resistive forces are balanced by the tractive force exerted by the wheels at the ground. The equation of motion then becomes:

$$0 = F_{Trac} - F_{Aero} - F_{RR} - F_{Grade} \tag{2.3}$$

Here, the acceleration term is assumed zero. Also, the mechanical-resistance force is no longer applicable because its power losses occur upstream of the wheel-ground interface at which the tractive force is applied. In a similar manner to the coast-down method, the road-load components are modelled or measured individually to permit quantification of the unknown parameters. To quantify the road-load variation with speed, permitting application of these models, constant-speed tests are performed at numerous speeds such that the combination of numerous test runs will provide a road-load characteristic from which the aerodynamic drag and rolling resistance components can be inferred.

Recent comparisons of the coast-down and constant-speed methods have been initiated primarily with respect to heavy-duty-vehicle test procedures enacted in the context of greenhouse-gas (GHG) emissions regulations. In 2016, the U.S. Environmental Protection Agency (EPA) published the second phase of its greenhouse-gas (GHG) regulations for heavy-duty vehicles

(HDVs) (U.S. Environmental Protection Agency and U.S. Department of Transportation, 2016) to begin for model years 2021 and beyond. In Canada, Environment and Climate Change Canada (ECCC) recently published its corresponding greenhouse-gas regulations (Environment & Climate Change Canada, 2017). The European Commission (EC) is also in the process of developing GHG regulations (Luz *et al.*, n.d.). These regulations require vehicle manufacturers to demonstrate efficiency and emissions levels of the vehicles they sell for use in the various jurisdictions. The Greenhouse-gas Emissions Model (GEM), the simulation tool used by the EPA and ECCC for calculating these emissions levels, requires an aerodynamic input represented by the vehicle drag area (C_DA) (U.S. Environmental Protection Agency and U.S. Department of Transportation, 2011). The reference method to determine the drag-area, defined by the EPA and ECCC, is the coast-down measurement technique. In contrast, the constant-speed method has been adopted as the principle test method by the EC for its GHG reporting program (Fontaras *et al.*, 2014). During the development of the EPA Phase 2 procedures, the constant-speed method was evaluated as a possible reference method, based on a request from some vehicle manufacturers, because of its greater potential to characterize the variability of drag area to yaw angle. After an evaluation of the two methods (Gururaja, 2016*a*; Gururaja, 2016*b*), the coast-down method was retained by the EPA as the reference method, but a constant-speed procedure has been defined for use as an alternate method, along with wind-tunnel and computational methods, to use for yaw characterization of the drag area. There is yet no known standard or formal best-practices for the use of the constant-speed method. Work undertaken by NRC and TC in 2015/16 to support the EPA and ECCC regulatory-development processes showed that aerodynamic-drag measurements using the coast-down and the constant-speed methods for the same vehicle compared well (McAuliffe and Chuang, 2016*a*).

The principle differences between the two testing methods is the primary measurement that is required. The coast-down method requires the vehicle deceleration or speed to be quantified accurately over the duration of a coast, for which GPS measurement systems are most-commonly used, and for which sufficient accuracy is attained with track-test-specific systems that are commercially available. The constant-speed method requires accurate quantification of the tractive force at the wheel/ground interface, which is most commonly done using wheel-torque transducers. Such transducers are commercially-available but are costly (much more so than track-test-specific GPS measurement systems). Furthermore, a wheel-torque transducer is required for each driven wheel on a vehicle, meaning four-wheel-drive passenger or commercial vehicles require a greater number of instruments at a higher cost. A less-costly option for constant-speed measurements is to measure the torque at the primary driveshaft such that only a single measurement is required. This, however, requires a separate set of measurements to quantify the mechanical friction between the driveshaft and the wheel/ground interface. An additional drawback to the constant-speed method is that, under variable road-load conditions due to road-surface roughness/bumpiness or wind gusts, the assumption of zero acceleration at all times is not necessarily valid. For heavier vehicles, such as large commercial trucks, the high weight of the vehicles combined with small accelerations can contribute to an inertial-force component (left-hand side of Equation 2.3) that may be of sufficient magnitude to require its inclusion. This then requires an additional GPS measurement system to quantify the inertial force term in the analysis.

In general, coast-down has been the preferred, and most-often used, option for road-load characterization due to its simpler and less costly instrumentation requirements. As such, more effort has been exerted to improve the coast-down method, and it is likely to retain its status as a principle technique for road-load quantification of ground vehicles.

3. Literature Review

3.1 SAE standards for coast-down testing

The original SAE (Society of Automotive Engineers) standard for road load measurement and dynamometer simulation using coast-down techniques is SAE J1263 (2010). This standard is supplemented by SAE J2263 (2008), which incorporates changes such as the inclusion of real-time onboard anemometry to measure and compensate for wind conditions directly in front of the vehicle. This makes it possible to test in higher wind conditions than those prescribed by SAE J1263 (2010), which relies on average wind conditions measured at distances of up to several kilometres from the test vehicle. Another major change is that SAE J2263 (2008) uses a three-term equation to model road load force over an extended speed range (115 km/h to 15 km/h) whereas with SAE J1263 (2010) the road load force is modeled by a two-term equation and was typically simulated on a hydrokinetic dynamometer capable of being adjusted to reproduce this force at only one speed. SAE J2263 (2008) also authorizes "split" coastdown runs if the test track is not long enough to allow a complete coast-down run over the full speed range. SAE J2263 (2008) is currently under revision in order to align it with SAE J2264 (Chassis Dynamometer Simulation of Road Load Using Coastdown Techniques) and the US Environmental Protection Agency (EPA) guidance letter CD-15-04 (U.S. Environmental Protection Agency, 2015).

The SAE is currently developing a recommended practice for coast-down testing heavy-duty vehicles (SAE J2978, 2017), for which one of the authors of this report is a member of its development task force. SAE J2978 will be based in part on J1263 and J2263, with additional considerations specific to testing of heavy-duty vehicles.

3.2 Classification of coast-down studies

An extensive review of the relevant literature on coast-down testing and methodologies revealed that most studies can be classified into four main categories according to the main purpose of the study. It was found that the main reasons for conducting coast-down tests and studies were generally one of the following:

1. to characterize the aerodynamic and other vehicle road load components;
2. to determine road load coefficients for fuel economy and emissions testing;
3. to assess and validate wind tunnel results; or
4. to improve the coast-down method, including analytical modelling of road load components and experimental techniques.

The significant literature related to each of these categories is described in the next sections of this chapter.

3.3 Characterization of aerodynamic and other road-load components

A number of studies were performed for the purpose of analyzing systematic aerodynamic modifications of light-duty vehicles (LDV) and/or heavy-duty vehicles (HDV) in real-world road conditions. In order to do this, vehicles were tested in their baseline configuration as well as with aerodynamic modifications or add-on parts. The main objective of these studies was to characterize changes in the vehicle drag coefficient, C_D, which is a function of the relative wind angle. Often, the results are compared with wind tunnel test or numerical data, which can serve to validate these methods.

In order to isolate the aerodynamic drag (F_{Aero} in equation 2.2), it is necessary to determine the contributions of the rolling (F_{RR}) and mechanical resistances (F_{Mech}) to the total road load acting on the vehicle, assuming that the grade force is known. Thus these resistances must be either measured directly or modeled analytically in a way that reflects their typical behaviour but leaves a reasonable number of unknown quantities to be solved, typically through an iterative regression analysis.

3.3.1 Early studies

White and Korst (1972) proposed a coast-down analysis method based on a simplified dynamic model that used a closed mathematical form of the solution and allowed the separation of the aerodynamic and rolling resistance forces. They obtained results from coast-down tests with a variety of passenger cars. However, their method assumed that the rolling resistance is independent of speed and that the mechanical resistance is negligible. The method also neglected the effects of ambient wind, so that no wind angle dependence of the drag coefficient could be assessed.

Walston *et al.* (1976) recognized the shortcomings and limitations of neglecting the wind and proposed a coast-down test procedure specifically designed to determine the aerodynamic drag on a vehicle operating in a windy environment. Tests were conducted on a tractor-trailer truck at baseline conditions and equipped with four different drag-reduction devices. The analysis of the data obtained from these tests was presented by Buckley *et al.* (1976) in a separate publication. Full-scale drag coefficients were evaluated over a yaw angle range of -10° to 10°, and the results were compared with wind-tunnel measurements. In order to reduce the number of unknown quantities in the analysis, the moment of inertia of the wheel and tire assembly as well as the driveline drag (which is a mechanical resistance) were determined experimentally prior to the coast-down tests. The inertia of the wheel and tire assembly was measured as described by Anderson *et al.* (1964). The driveline drag was estimated by jacking up the wheels, spinning them up to road speed using the engine and then allowing them to coast down. The driveline drag was found to be a linear function of vehicle speed. The rolling resistance was modeled as a linear function of vehicle speed based on the model of Smith (1965) and on more recent measurements from the literature.

In the study of Walston *et al.* (1976) and Buckley *et al.* (1976), ambient winds were accounted for using a boom-mounted propeller anemometer aligned with the relative airstream by a vane. The anemometer was located 3 m in front of the tractor and 2 m above the ground at approximately the mid-height of the vehicle. The anemometer was calibrated for vehicle interference in a wind tunnel and by considering data from pairs of successive coast-downs in opposite directions with nearly steady breezes at near zero yaw angles.

In comparing their wind tunnel and coast-down results, Buckley *et al.* (1976) identified a number of issues and limitations of their methodology, some of which remain knowledge gaps to this day. These include:

- In windy conditions, due to ground effects, a vehicle on the road can be subjected to wind shear and skewness, as the relative wind speed and angle varies over the height of the vehicle. This was not reproduced in the wind tunnel nor taken into account by the coast-down analysis method, since the ambient wind was only measured at the mid-height of the vehicle. Accounting for the effect of wind shear and skewness in the analysis of coast-down data remains a significant knowledge gap.

- The unsteadiness or turbulence of the wind was not reproduced in the wind tunnel and its effect on a vehicle in coast-down can cause the drag coefficient to vary with time. This was resolved by solving the equation of motion and evaluating the drag coefficient over overlapping time bands of the coast-down that were sufficiently broad to be several times the period of the turbulence but sufficiently small such that the drag coefficient remained reasonably constant. While the computed data were somewhat scattered, they obtained C_D versus yaw curves that were quite similar to those found in wind tunnel studies. However, in order to better account for wind turbulence, the true relative wind speed, and not the wind speed that is perturbed by the proximity of the vehicle, should be measured in real time. As of now, only Tanguay (2018) has successfully measured the true, undisturbed wind vector relative to a coasting vehicle in real time. However, since this wind speed was measured at only one height, the effects of wind shear or skewness still remain to be characterized.

- Since the inferred aerodynamic drag depends on knowledge of the rolling resistance, it is important that more information be obtained on rolling resistance, including an evaluation on how it is affected by the side loads due to high cross-winds, since most laboratory tests to measure rolling resistance do not account for this.

White and Korst (1972), Walston *et al.* (1976) and Buckley *et al.* (1976) performed influential studies that guided the elaboration of the SAE J2263 standard. Walston *et al.* (1976) and Buckley *et al.* (1976) appear to have been the first to address the unknown effects of wind shear, skewness, turbulence and high cross-winds. Many studies have been done since then but these issues have not yet been completely resolved. Some of these studies are described in the next section.

3.3.2 Subsequent studies

Passmore (1990) undertook a comprehensive study of the methods of acquiring and analysing road load data at a test track. He developed a mathematical model for a vehicle travelling in a straight line in the presence of ambient wind that could be applied to both coast-down and constant-speed test data, but showed that the coast-down method is preferable to the constant-speed method for measuring vehicle road load and separating it into its components. His model included tire (rolling resistance) losses as a function of load, speed and ambient temperature, transmission and un-driven wheel (mechanical) losses and aerodynamic forces. Passmore's rolling resistance model consisted of a constant plus a linear function of speed, which was deemed to be appropriate up to 113 km/h. At higher speeds, a large increase in rolling resistance may necessitate a higher order model. Transmission losses were measured directly during coast-down tests using wheel torque meters and were included in the analysis in the form of a look-up table. This method was assumed to avoid the introduction of errors that can occur if an empirical model for mechanical losses is used, but the wheel torque meters had a significant effect on the aerodynamic drag. Passmore recommended that in order to avoid this change in aerodynamic drag, an empirical model of the transmission losses as a function of speed and transmission oil temperature should be developed, with the loss coefficients determined in separate tests. This knowledge gap remains a challenge at the present time.

The model of Passmore (1990) accounted for the effects of aerodynamic drag as a two-coefficient function of relative airspeed and yaw angle, which allowed for realistic ambient wind, and for the effect of lift on the rolling resistance. It did not account for changes of vehicle attitude due to lift nor the effect of aerodynamic side force on the rolling resistance. The latter effect could become significant in high cross-wind conditions, which can occur at certain test tracks, and should be investigated.

Passmore and Jenkins (1990), Passmore and Good (1994) and Buckley (1995) also carried out studies to determine the overall road load of a vehicle and separate it into its various components using the coast-down method. All of these studies used on-board anemometers to continuously measure and account for the ambient wind, but relied on accurate correction of the anemometer measurements for the effects of its proximity to the vheicle. It was found that the accuracy of the results depended on the number of coast-down tests performed. These studies did not account for the effects of aerodynamic side forces on the rolling resistance. They also neglected the effects of turbulence and the variation of the aerodynamic drag coefficient with speed (also known as the Reynolds-number influence).

More recently, McAuliffe and Chuang (2016*b*), Gururaja (2016*a*), Zolet *et al.* (2015), Surcel and Shetty (2015) and Altinisik (2017) have described studies to determine the aerodynamic drag and other road load components from coast-down testing of both light- and heavy-duty vehicles. Baldissera (2016) appears to be the first to propose a coast-down modelling method for which the aerodynamic drag is described by speed-dependent coefficients. The model was developed for human-powered vehicles, which operate in a lower Reynolds number range where speed dependence is more of an issue. However, as passenger vehicles become more aerodynamic, and therefore more susceptible to Reynolds number effects, it may be advisable to account for the speed-dependence of the aerodynamic drag coefficient in coast-down analysis of these vehicles as well.

3.3.3 Studies to characterize rolling and mechanical resistances

For a number of studies (Dayman, 1976; Smith *et al.*, 1978; Ivens and Lawser, 1984; Roche and Mammetti, 2015; Skrúcaný *et al.*, 2018; Pałasz *et al.*, 2019*b*), the main objective of performing coast-down tests was to characterize or capture changes in the tire rolling resistance and/or mechanical resistances.

Dayman (1976) suggested the tire rolling resistance, and in particular its variation with vehicle speed, should be characterized from laboratory rotating drum tests carried out by the manufacturers, while the zero-velocity intercept of the rolling resistance should be left as an unknown to solve in the coast-down data analysis. Dayman mentioned that a good understanding of all the road load components is needed in order to separate the rolling resistance from the aerodynamic and mechanical resistances. He suggested that the best way to handle the mechanical resistances was to minimize them whenever possible, or measure and characterize them in separate tests. He found that the rolling and mechanical resistances could be approximately modeled as linear functions of vehicle speed. By comparison, Smith *et al.* (1978) modelled the tire rolling resistance as a sum of a constant term and a second-order term in velocity, both of which were functions of tire characteristics. Their model was fairly representative of laboratory-measured rolling resistance data up to about 80 km/h, above which it underpredicted rolling resistance.

Ivens and Lawser (1984) measured driveline losses with a wheel torque transducer while freewheeling and by comparing coast-down and constant speed results. This greatly improved the accuracy of the inferred rolling resistance and drag coefficient estimates. Pałasz *et al.* (2019*b*) performed very-low-speed coast-down tests to infer the rolling resitance.

In general, these studies conclude that there are too many unknowns to determine aerodynamic drag and rolling resistance from coast-down tests only. It is therefore necessary to measure and characterize rolling and mechanical resistances in the laboratory, including their variation with speed, in order to reduce the number of unknown quantities. Questions raised in a number of these studies were how the tire rolling resistance varies with temperature, how to correct for temperature variations and what temperature to use for this correction (i.e., ambient, road or tire surface or internal tire temperature). Roche and Mammetti (2015) and Ejsmont *et al.* (2017) discuss these issues in detail, and Mammetti *et al.* (2013) discusses temperature correction specifically for HDV tire rolling resistance. Further study and research on the variation of rolling and mechanical resistances with speed and temperature is required.

3.3.4 Recurring themes in the literature

A number of common observations have been made in the above studies that suggest where improvements to the coast-down measurement and analysis methods are required. Many have observed that the drag coefficient inferred from coast-down testing does not always match that measured in a wind tunnel. Apart from the fact that it is generally not possible to measure the wheel aerodynamic torque drag in the wind tunnel (see Vdovin *et al.* (2014) for a discussion on wheel aerodynamic torque drag, sometimes referred to as "ventilation drag" or "ventilation torque"), these differences can arise from the inadequate simulation of the real-world wind conditions in a wind tunnel, and/or the inability to properly measure and account for variations in ambient wind on the test track. Often, a large number of coast-down tests are required to obtain sufficient accuracy and precision in the results, which could be a result of variations in ambient conditions, particularly the wind. How best to account and correct for variations in ambient conditions such as wind and temperature, including how to properly calibrate the on-board anemometer to accurately measure the wind in real-time, remains a challenge. The establishment of appropriate wind limits are related to this challenge, as the cross-winds must be low enough to ensure good repeatability but high enough to capture the yaw-dependence of the aerodynamic drag. Analytical models and/or laboratory measurements to characterize the aerodynamic drag and mechanical and rolling resistances vary throughout the literature but are crucial for correct separation of the total road load into its individual components. These models and measurement procedures should be assessed and optimized. The effects of vehicle attitude, ride height changes and deformation due to aerodynamic forces and road roughness were identified as possible significant factors by Tripp *et al.* (2018) but have not been addressed adequately in the literature to date. In fact, very little has been written about how best to account for track surface roughness and irregularities in analyzing coast-down data; Andersen and Larsen (2015) provide some insight but further study is required. Finally, the above studies describe a variety of ways to solve the equation of motion: through full or segmented regression analysis of each coast-down or even a simplified analytical solution. Segmented analysis might better account for changing ambient conditions and any speed-dependence of coefficients. Further investigation is required to determine how best to analyze the data.

3.4 Determination of road-load coefficients for fuel economy and emissions testing

3.4.1 Studies to determine road-load coefficients for dynamometer testing

Another principal use of coast-down testing is to provide coefficients to simulate vehicle road load on a chassis dynamometer for fuel economy or emissions testing. Sometimes it is for third-party verification of manufacturer-supplied road load coefficients or fuel economy and emissions data. Performing coast-down tests specifically for this purpose is described in the studies by Yasin (1978), Passmore and Jenkins (1990), Passmore (1990) and Roche and Mammetti (2015).

A common observation in these studies is that obtaining adequate test repeatability requires accurate correction of observed road loads to standard conditions (i.e., with no wind and at standard temperature and pressure), which is still a challenge. For example, it is not always clear whether the ambient, tire or track surface temperature should be used to correct the rolling resistance coefficient. Also, it was often observed that good repeatability occurs only when testing is performed in steady, low winds with small wind angles relative to the vehicle. This implies that accounting for the effects of high winds and wind angles is still challenging. One reason for this is that most studies neglect changes to the rolling resistance resulting from side forces on the tires induced by aerodynamic side loads in cross-wind conditions. In general, most studies agree that wind is still a major source of variance in coast-down data, and that efforts to improve its measurement and to establish acceptable limits for coast-down tests are still required. The geography of the test track plays a significant role in the exposure of a coasting vehicle to wind and should be considered in the analysis.

Another source of variance between real-world fuel-economy and predictions based on road-load coefficients determined by coast-down testing is that coast-down test tracks do not necessarily represent real-world road and driving conditions. It was suggested that the effects of factors such as road gradient and roughness, driving style, traffic and using different parts of the track for runs in opposite directions need further investigation.

3.4.2 Assessing correlation of road-load coefficient and fuel economy results

Somewhat related to the above studies, Lopes and Carbonara (2017) discusses an alternative approach for evaluating fuel economy by estimating road load energy loss during a standard test driving profile that would be employed on a chassis dynamometer. They derive equations describing this energy loss as a function of the road-load coefficients. This results in a simpler, more robust evaluation for test-to-test and vehicle-to-vehicle road-load comparison with direct physical meaning and a stronger correlation with fuel economy than simply comparing road-load equations or curves. However, Lopes and Carbonara (2017) use a simplified road-load equation without a linear term in vehicle speed and do not take into account varying ambient conditions such as wind and temperature. Kim, Lee, Park, Myung and Park (2016) and Kim, Lee, Myung and Park (2016) also describe methods to correlate (and validate) different road-load results of the same vehicle, but use more sophisticated analytical modeling. The techniques described in these studies would be useful for third-party verification of road-load coefficients or fuel economy and emissions data.

3.4.3 Direct measurement of road-load coefficients in a wind tunnel

Although not strictly a coast-down study, it is worth mentioning that Stellato and Betti (2018) presented a study on direct measurement of road-load coefficients in a specially-equipped wind tunnel. It would be instructive to compare results obtained in this wind tunnel with coast-down measurements obtained on a test track.

3.5 Studies to assess and validate wind tunnel results

Similar to the purposes of the studies discussed in Section 3.3, a number of coast-down studies were carried out to characterize aerodynamic drag of vehicles in real-world conditions, but specifically to assess, validate or improve wind tunnel simulation (Walston *et al.*, 1976; Buckley *et al.*, 1976; Dayman, 1978; Buckley, 1995; Good *et al.*, 1998; Walter *et al.*, 2001; Howell *et al.*, 2002; Zolet *et al.*, 2015; Surcel and Shetty, 2015; Altinisik, 2017). Some of these studies were motivated by the fact that real-world fuel consumption doesn't always match predictions based on wind tunnel drag measurements. Some studies were performed to evaluate specific wind tunnel techniques such as ground simulation and blockage correction. A common theme was the difficulty in accounting for the effects of ambient winds. It was suggested to conduct more coast-down tests in the presence and absence of winds to assess the effect of wind variation and turbulence on aerodynamic drag. It was also acknowledged that wind shear and skewness occurs on the road but is generally not reproduced in a wind tunnel. Further research would be required to characterize the effects of non-uniform winds on a vehicle. This could also be evaluated using computational fluid dynamics or specialized wind tunnels.

3.6 Studies to improve the coast-down method

A large number of studies address improvements to various aspects of coast-down testing and analysis methodologies. This includes improving the analytical modelling of the road-load components in the equation of motion to be solved as well as improving experimental techniques.

3.6.1 Improving data analysis techniques

Studies to improve data analysis techniques such as modelling of road-load components in the equation of motion and correction for variation in ambient conditions were carried out by Passmore (1990), Buckley (1995), Andrews and Pruess (1997), Good *et al.* (1998), Walter *et al.* (2001), Roche and Mammetti (2015), Gururaja (2016*a*), Wiegand (2016), Greiner *et al.* (2017), Ejsmont *et al.* (2017), Thiriet *et al.* (2017), Tripp *et al.* (2018), Mashadi *et al.* (2018) and Sina *et al.* (2018). Wiegand (2016), Greiner *et al.* (2017), Thiriet *et al.* (2017), Mashadi *et al.* (2018) and Sina *et al.* (2018) propose various models for rolling resistance based on relevant factors such as speed, inflation pressure and tire temperature. The model of Sina *et al.* (2018) is novel in that it accounts for tire longitudinal slip. Ejsmont *et al.* (2017) discusses the temperature correction of the rolling resistance. Tripp *et al.* (2018) proposes to improve the analysis method by accounting for vehicle attitude changes during coast-down testing.

3.6.2 Improving experimental methods

Ivens and Lawser (1984), Pałasz *et al.* (2019*a*) and Pałasz *et al.* (2019*b*) suggest experimental methods to improve the estimation of rolling and mechanical resistances. Ivens and Lawser (1984) use a wheel torque transducer to measure mechanical resistances, although these affect the aerodynamic drag. Pałasz *et al.* (2019*a*) present a method for measuring rolling resistance characteristics in the laboratory, while Pałasz *et al.* (2019*b*) describe a method to characterize the rolling resistance through low-speed coast-down tests on a track.

Tanguay (2016) describes a novel technique to optimize the prediction of free-stream velocity from ground-based anemometric measurements. Tanguay (2018) has also developed a novel free-stream anemometry system that measures the true ambient wind speed and angle experienced by a vehicle in real-time.

3.6.3 Limitations to current coast-down methods

A number of limitations have been identified through the review of the literature listed in this section. These are summarized below:

- A common theme in many studies attempting to improve coast-down methodologies is the need to improve the vehicle freestream wind-measurement technique. This includes improving the method to calibrate the vehicle-mounted anemometer as well as to account for the drag of the anemometer itself.
- Another limitation of current methods is that most ignore tire slip angles due to aerodynamic side forces (as a result of vehicle cross-winds) and their effect on rolling resistance. Rolling resistance in cross-winds has been found to increase with the square of the product of the yaw angle and the square of the relative airspeed, so ignoring these effects is only appropriate in low cross-wind conditions. In general, better analytical models for the rolling resistance are required. It has been suggested that the models may need to be tire-specific, requiring laboratory rolling resistance data for the particular tire.
- Almost all studies ignore the variation of aerodynamic drag coefficient with speed. The validity of the assumption that the drag coefficient is constant over range of coast-down speeds needs to be verified. One solution could be to use a segmented analysis method to determine the drag coefficient as a function of the Reynolds number.
- Most studies ignore the effect of wind turbulence and unsteadiness on the aerodynamic drag coefficient. This issue requires further study, including detailed frequency analysis of the ambient wind and the vehicle response.
- The variation of mechanical resistance with speed can be quite irregular depending on the test vehicle. As a result, the mechanical resistance is not always appropriately modelled as a linear or quadratic function in vehicle speed, as it has been suggested in the literature and in SAE J2263 (2008). The temperature sensitivity of the mechanical resistance also needs to be characterized and accounted for in the model. Since mechanical resistance can account for roughly 15% of the total drag, its estimation can be a source of considerable error.
- The effect of road surface characteristics on the estimate of rolling resistance and other road-load components require further research. Track surface roughness increases the inferred vehicle rolling resistance. Larger undulations, as characterized by the International Roughness Index (IRI), can change the vehicle ride-height and attitude, which can influence the aerodynamic drag force as well as the rolling and mechanical resistances (due to changing vertical load). In addition to these effects of surface roughness and

irregularities, it is not obvious how the road surface temperature might affect the estimation of rolling resistance due to road surface properties.

- Selection of the appropriate temperature (i.e., road, air or tire temperature) to correct the rolling resistance to standard conditions needs further study. It is also possible that the coefficient of temperature sensitivity of the rolling resistance changes from tire to tire and with temperature, for example at very low or very high ambient temperature.
- The contribution of the rotational inertia of the wheels and rotating drivetrain components to the resistance of the vehicle to forward motion, also referred to as the equivalent mass of rotating components, must be added to the vehicle mass in order to obtain the effective mass of the test vehicle (which appears on the left-hand side of equation 2.2). Despite the fact that this quantity can be estimated experimentally (Walston *et al.*, 1976) or analytically, the equivalent mass of rotating components is often assumed to be 3% of the vehicle test mass for passenger cars, as recommended by SAE J2263 (2008), or a nominal mass per wheel for HDVs (McAuliffe and Chuang, 2016*b*). Better estimation of this quantity would increase the accuracy of road-load components inferred from coast-down testing.

4. Knowledge gaps and roadmapping

4.1 Summary of knowledge gaps

The literature review identified many knowledge gaps that need to be filled in order to improve the accuracy of aerodynamic and road-load measurements using the coast-down method. These knowledge gaps are classified and summarized below.

Characteristics of road-load components

- Mechanical Resistance
  - Need to develop a more realistic analytical model including speed and temperature dependence.
  - What temperature and temperature correction coefficient should be used to correct to standard ambient conditions?
  - How/where to obtain mechanical resistance data to feed into the analytical model in the equation of motion: track or laboratory tests?
- Rolling Resistance
  - Need to develop a more realistic analytical model based on relevant factors such as speed, temperature, inflation pressure, tire material, etc.
  - What temperature and temperature correction coefficient should be used to correct to standard ambient conditions and does the correction coefficient change with temperature or tire material?
  - How to estimate and correct for effects of road surface roughness on rolling resistance?
  - Need to investigate and model the effect of cross-winds on rolling resistance.
  - How/where to obtain tire rolling resistance data to feed into the analytical model in the equation of motion: laboratory or low-speed track tests? A flat surface with side forces present may be more realistic than typical rotating drum laboratory tests.
- Aerodynamic Drag
  - Need to establish an appropriate and robust model for the aerodynamic drag term that reflects its dependence on wind angle and, if significant, on speed (Reynolds number) for the particular test vehicle.
  - Wind-tunnel measured drag coefficients don't always match those inferred from coast-down testing. What are the reasons?
  - Real-world fuel consumption doesn't always match predictions inferred from

coast-down testing or wind tunnel drag measurements. How to make coast-down test predictions more realistic?

  - The effect of wind shear, skewness and turbulence on vehicle drag needs further study.

- The estimation of the equivalent mass of rotating components (due to rotational inertia) needs improvement in order to better estimate all road load components.

Test procedures

- Establishing the number of coast-down runs required for sufficient accuracy and precision in test standards, when improved modeling provides better accuracy for each run.
- Should ambient conditions such as temperature and wind speeds be further limited? In setting wind limits, how can good repeatability be reconciled with the need to capture the yaw dependence of the drag coefficient?
- The calibration of the on-board anemometer and accurate measurement of the real-time relative wind speed and angle need improvement.
- Further study is needed to better account for variations in wind, including unsteadiness and turbulence, throughout the coast-down test.
- How to measure and account for the effect of vehicle attitude and ride height changes and vehicle deformation during a coast due to aerodynamic forces and road surface roughness?

Data analysis

- Further study is required to account for track surface roughness and irregularities and the effect of track surface temperature in the data analysis.
- Should data be analyzed over the full coast or in a segmented manner? Is a simpler analytical solution possible?

4.2 Roadmap for future work

The findings of the literature review were used to develop a roadmap to guide the subsequent phases of this project. The tasks listed below are recommended in order to address the knowledge gaps identified in the literature review. These have been laid out schematically in the roadmap shown in Figure 4.1.

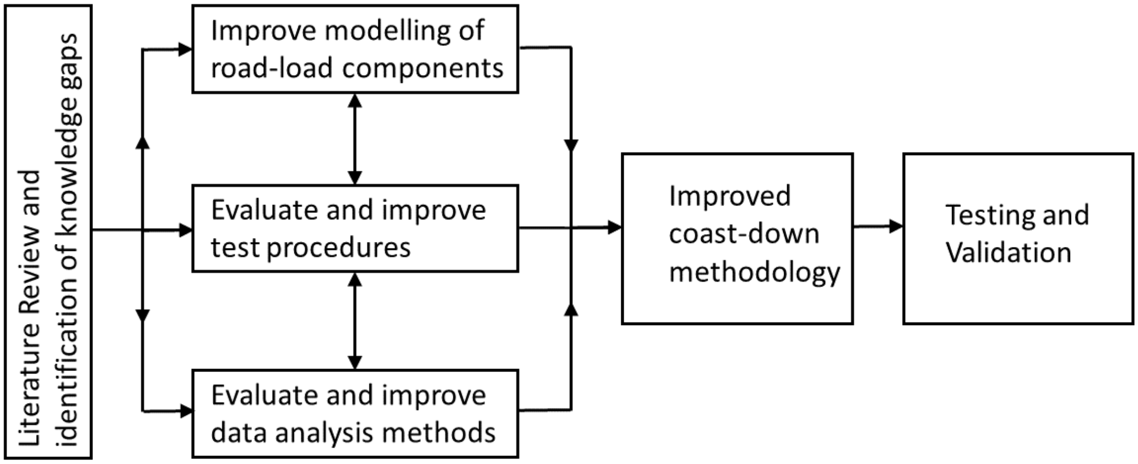

Figure 4.1: Schematic of roadmap for future work.

Improve modelling of road-load components

1. Targeted research to address specific knowledge gaps identified in this study:
   - Effects of temperature, materials and road surface roughness and irregularities on rolling and mechanical resistances;
   - Influence of wind shear, skewness, unsteadiness and turbulence scale on vehicle aerodynamics;
   - Investigate influence of changes in vehicle attitude, ride height and deformation during a coast due to aerodynamic forces and road surface irregularities.
2. Get data from other sources or plan experiments to investigate the best way to measure and/or model all terms in the equation of motion:
   - Obtain rolling and mechanical resistance data as well as relevant information on tires and wheels from other sources (including tire and vehicle manufacturers, TC, ECCC and the U.S. EPA) and/or devise experimental procedures to improve the estimation of the rolling and mechanical resistances and of the inertia of rotating components in the equation of motion.
   - Determine if wind tunnel data, if available for the specific test vehicle, can be used to help estimate the effects of aerodynamic side and lift forces on rolling and mechanical resistances.
   - Get data and/or plan experiments to determine the influence of (and sensitivity to) wind shear, skewness, unsteadiness and turbulence scale. A detailed frequency analysis of the wind and vehicle and on-board anemometer response could be useful to determine the effects of wind turbulence scale on vehicle aerodynamics.

3. Develop and evaluate improved analytical models for all terms in the equation of motion.
    - Revisit existing NRC coast-down data and request permission to use additional data from other sources (including TC, ECCC and the U.S. EPA) to test the new models and methods and compare the results.
    - Investigate the effects of test site, including track surface roughness and irregularities and track geography (as it affects typical wind characteristics) by comparing coast-down test results obtained on different test tracks, if available.

Evaluate and improve test procedures

1. With improved modelling and by revisiting existing data, determine number of coast-down runs required for sufficient accuracy and precision;
2. Similarly, determine if ambient conditions (wind, temperature) need to be further limited;
3. With better characterization of wind effects, improve measurement of instantaneous relative wind speed and angle, including calibration of the on-board anemometer;
4. If found to be significant, develop procedures to account for changes in vehicle attitude, ride height and deformation during a coast.

Evaluate and improve data analysis methods

1. Determine how to account for track surface roughness and irregularities in the data analysis;
2. Compare full and segmented coast-down analysis to determine which is preferable, and investigate if simpler analytical solutions to the equation of motion can be useful.

Based on the knowledge gained from the above activities, coast-down tests will be planned for the final year of this study in order to test and validate the improved coast-down test methodologies.

5. Summary

In an effort to reduce GHG emissions, manufacturers are addressing the need to make vehicles more fuel-efficient, and regulators are required to verify claims of increased fuel-efficiency and reduced emissions. Fuel-efficiency and emissions testing are generally carried out on a chassis dynamometer and require input in the form of road load coefficients.

Coast-down testing is a convenient and effective method to obtain road load coefficients for fuel-efficiency and emissions testing. However, there is considerable variability in the results obtained from coast-down tests, indicating that there is room for improving the methodology. As such, Transport Canada (TC), through its ecoTECHNOLOGY for Vehicles program, commissioned a multi-phase project to investigate improvements in aerodynamic and road-load measurements using the coast-down method.

The main objective of this first year of the project was to lay out a detailed road-mapping of the steps required to improve the reliability and accuracy of coast-down testing, so as to begin developing improved measurement and analysis techniques that will be evaluated in subsequent phases of the project. The road-mapping exercise was guided by an extensive review of the literature on coast-down testing and methodologies.

It is recommended that the focus of the next year of this study be to improve coast-down data analysis methods to address the knowledge gaps identified in this study. It is suggested to revisit coast-down data previously measured by NRC as well as data obtained from other sources to develop and evaluate new analytical models, test and data analysis procedures. It is also recommended to research and investigate the effects of road surface roughness and irregularities, track geography and ambient wind variations and unsteadiness on coast-down test results. Coast-down tests that implement the improvements brought about by these recommended tasks are planned for follow-on phases of this study.

Bibliography

Altinisik, A. (2017), "Aerodynamic coastdown analysis of a passenger car for various configurations," International Journal of Automotive Technology, **18**, pp. 245–254.

Andersen, L. G. and Larsen, J. K. (2015), "Introducing Functional Data Analysis to Coast Down Modeling for Rolling Resistance Estimation," SAE International Journal of Passenger Cars - Mechanical Systems, **8**.

Anderson, J. W., Firey, J. C., Ford, P. W. and Kieling, W. C. (1964), "Truck Drag Components by Road Test Measurement," *SAE Technical Paper Series*, SAE International.

Andrews, R. W. and Pruess, D. J. (1997), "Determination of Coastdown Mechanical Loss Ambient Correction Factors for use with J2263 Road Tests," *SAE Technical Paper Series*, SAE International.

Baldissera, P. (2016), "Proposal of a coast-down model including speed-dependent coefficients for the retarding forces," Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, **231**, pp. 154–163.

Buckley, F. T. (1995), "ABCD - An Improved Coast Down Test and Analysis Method," *SAE Technical Paper Series*, SAE International.

Buckley, F. T., Marks, C. H. and Walston, W. H. (1976), "Analysis of Coast-Down Data to Assess Aerodynamic Drag Reduction on Full-Scale Tractor-Trailer Trucks in Windy Environments," *SAE Technical Paper Series*, SAE International.

Dayman, B. (1976), "Tire Rolling Resistance Measurements From Coast-Down Tests," *SAE Technical Paper Series*, SAE International.

Dayman, B. (1978), "Realistic Effects of Winds on the Aerodynamic Resistance of Automobiles," *SAE Technical Paper Series*, SAE International.

Ejsmont, J., Taryma, S., Ronowski, G. and Swieczko-Zurek, B. (2017), "Influence of temperature on the tyre rolling resistance," International Journal of Automotive Technology, **19**, pp. 45–54.

Environment & Climate Change Canada (2017), "Regulations Amending the Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations and Other Regulations Made Under the Canadian Environmental Protection Act, 1999," Canada Gazette Part I, **151(9)**.

Environment and Climate Change Canada (2018), "National Inverntory Report 1990-2016: Greenhous Gas Sources and Sinks in Canada," , *Environment and Climate Change Canada*.

Fontaras, G., Dilara, P., Berner, M., Volkers, T., Kies, A., Rexeis, M. and Hausberger, S. (2014), "An Experimental Methodology for Measuring of Aerodynamic Resistances of Heavy Duty Vehicles in the Framework of European CO_2 Emissions Monitoring Scheme," SAE Int. J. Commer. Veh., **7(1),** doi:10.4271/2014-01-0595.

Good, G. M. L., Howell, J. P., Passmore, M. A. and Cogotti, A. (1998), "A Comparison of On-Road Aerodynamic Drag Measurements with Wind Tunnel Data from Pininfarina and MIRA," *SAE Technical Paper Series*, SAE International.

Greiner, M., Unrau, H.-J. and Gauterin, F. (2017), "A model for prediction of the transient rolling resistance of tyres based on inner-liner temperatures," Vehicle System Dynamics, **56**, pp. 78–94.

Gururaja, P. (2016*a*), "Evaluation of Coastdown Analysis Techniques to Determine Aerodynamic Drag of Heavy-Duty Vehicles," *SAE Technical Paper Series*, SAE International.

Gururaja, P. (2016*b*), "Wind-Averaged Drag Determination of Heavy-Duty Vehicles from On-Road Constant-Speed Torque Tests," SAE Paper No. 2016-01-8153.

Howell, J., Sherwin, C., Passmore, M. and Good, G. L. (2002), "Aerodynamic Drag of a Compact SUV as Measured On-Road and in the Wind Tunnel," *SAE Technical Paper Series*, SAE International.

Ivens, J. and Lawser, J. J. (1984), "Experimental Test Track Methods Of Estimating Vehicle Tractive Resistance," *SAE Technical Paper Series*, SAE International.

Kim, C., Lee, H., Myung, C.-L. and Park, S. (2016), "A Study on Validation Procedure for Vehicle Road Load with Energy Balance Method," *FISITA 2016 World Automotive Congress, Busan, Korea*.

Kim, C., Lee, H., Park, Y., Myung, C.-L. and Park, S. (2016), "Study on the Criteria for the Determination of the Road Load Correlation for Automobiles and an Analysis of Key Factors," Energies, **9**, pp. 575.

Lopes, R. and Carbonara, A. (2017), "A Brief Discussion on Vehicle Coast-Down Comparative Analysis," *SAE Technical Paper Series*, SAE International.

Luz, R., Rexeis, M., Hausberger, S., Jajcevic, D., Lang, W., Schulte, L., Hammer, J., Lessmann, L., van Pim, M., Verbeek, R. and Steven, H. (n.d.), "Development and validation of a methodology for monitoring and certification of greenhouse gas emissions from heavy duty vehicles through vehicle simulation - Draft Final Report," European Commission Report No. I 07/14/Rex EM-I 2012/08 699, *European Commission*.

Mammetti, M., Gallegos, D., Freixas, A. and Muñoz, J. (2013), "The Influence of Rolling Resistance on Fuel Consumption in Heavy-Duty Vehicles," *SAE Technical Paper Series*, SAE International.

Mashadi, B., Ebrahimi-Nejad, S. and Abbaspour, M. (2018), "A rolling resistance estimate using nonlinear finite element numerical analysis of a full three-dimensional tyre model," Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, **233**, pp. 147–160.

McAuliffe, B. R. and Chuang, D. (2016*a*), "Coast-down and Constant-speed Testing of a Tractor-trailer Combination in Support of Regulatory Developments for Greenhouse Gas Emissions," NRC Report No. LTR-AL-2016-0019-R, *National Research Council Canada*.

McAuliffe, B. R. and Chuang, D. (2016*b*), "Track-Based Aerodynamic Testing of a Heavy-Duty Vehicle: Coast-Down Measurements," SAE International Journal of Commercial Vehicles, **9**, pp. 381–396.

Pałasz, B., Waluś, K. J. and Warguła, Ł. (2019*a*), "The determination of the rolling resistance coefficient of a passenger vehicle with the use of roller test bench method," MATEC Web of Conferences, **254**, pp. 04007.

Pałasz, B., Waluś, K. J. and Warguła, Ł. (2019*b*), "The determination of the rolling resistance coefficient of a passenger vehicle with the use of selected road tests methods," MATEC Web of Conferences, **254**, pp. 04006.

Passmore, M. A. (1990), "The measurement and analyais of road vehicle drag forces," Ph.D. thesis, Loughborough University.

Passmore, M. A. and Good, G. M. L. (1994), "A Detailed Drag Study Using the Coastdown Method," *SAE Technical Paper Series*, SAE International.

Passmore, M. A. and Jenkins, E. G. (1990), "Measuring Vehicle Drag Forces Using an On-Board Microcomputer," Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, **204**, pp. 77–82.

Roche, M. and Mammetti, M. (2015), "Accurate Measurements in Proving Ground for Fuel Consumption Reduction Study in Heavy-Duty Vehicles," .

SAE J1263 (2010), "Road Load Measurements and Dynamometer Simulation Using Coast-down Techniques," Surface Vehicle Recommended Practice No. J1263.

SAE J2263 (2008), "Road Load Measurements Using Onboard Anemometery and Coastdown Techniques," Surface Vehicle Recommended Practice No. J2263.

SAE J2978 (2017), "Road Load Measurement Using Coastdown Techniques," Surface Vehicle Recommended Practice - Work in Progress URL:http://standards.sae.org/wip/j2978/ .

Sina, N., Esfahanian, V., Yazdi, M. R. H. and Azadi, S. (2018), "Introducing the Modified Tire Power Loss and Resistant Force Regarding Longitudinal Slip," SAE International Journal of Passenger Cars - Mechanical Systems, **11**.

Skrúcaný, T., Semanová, Š., Kendra, M., Figlus, T. and Vrábel, J. (2018), "MEASURING OF MECHANICAL RESISTANCES OF A HEAVY GOOD VEHICLE BY COASTDOWN TEST," Advances in Science and Technology Research Journal, **12**, pp. 214–221.

Smith, G. (1965), "Discussion of Truck Drag Components by Road Test Measurement," SAE Transactions, **73**, pp. 157.

Smith, J. R., Tracy, J. C. and Potter, D. S. (1978), "Tire Rolling Resistance - A Speed Dependent Contribution," *SAE Technical Paper Series*, SAE International.

Stellato, M. and Betti, L. (2018), "FCA Full Scale Wind Tunnel: WLTP and Coast Down Test Performed With Wind Tunnel Method," *SAE Technical Paper Series*, SAE International.

Surcel, M.-D. and Shetty, M. (2015), "The Impact of Design, Position and Combination of Aerodynamic Devices on Drag and Fuel Consumption," SAE International Journal of Commercial Vehicles, **8**, pp. 722–731.

Tanguay, B. (2016), "A novel technique to optimize the prediction of free-stream velocity from ground-based anemometric measurements," SAE Int. J. Commer. Veh., **9(2),** doi: 10.4271/2016-01-8023.

Tanguay, B. (2018), "On-track validation of the NRC Free-Stream Anemometer," NRC Report No. LTR-AL-2018-0003, *National Research Council Canada*.

Thiriet, A. B., Pujatti, F. J. P. and Araújo, P. C. S. (2017), "Influence of Inflation Pressure of a Tire on Rolling Resistance and Fuel Consumption," *SAE Technical Paper Series*, SAE International.

Tripp, J., Lounsberry, T., Guzman, A. and Fadler, G. (2018), "Vehicle Attitude Changes from Aerodynamic Forces," *SAE Technical Paper Series*, SAE International.

United States Environmental Protection Agency (2019), "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2017," No. EPA 430-P-19-001, *US EPA*.

U.S. Environmental Protection Agency (2015), "Determination and Use Of Vehicle Road-Load Force and Dynamometer Settings," Guidance Letter No. CD-15-04 (LDV/LDT/ICI/LIMO).

U.S. Environmental Protection Agency and U.S. Department of Transportation (2011), "Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles," US Federal Register, **76(179)**, pp. 57106–57513.

U.S. Environmental Protection Agency and U.S. Department of Transportation (2016), "Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2," US Federal Register, **81(206)**, pp. 73478–74274.

Vdovin, A., Lofdahl, L. and Sebben, S. (2014), "Investigation of Wheel Aerodynamic Resistance of Passenger Cars," SAE International Journal of Passenger Cars - Mechanical Systems, **7**, pp. 639–645.

Walston, W. H., Buckley, F. T. and Marks, C. H. (1976), "Test Procedures for the Evaluation of Aerodynamic Drag on Full-Scale Vehicles in Windy Environments," *SAE Technical Paper Series*, SAE International.

Walter, J. A., Pruess, D. J. and Romberg, G. F. (2001), "Coastdown/Wind Tunnel Drag Correlation and Uncertainty Analysis," *SAE Technical Paper Series*, SAE International.

White, R. A. and Korst, H. H. (1972), "The Determination of Vehicle Drag Contributions from Coast-Down Tests," *SAE Technical Paper Series*, SAE International.

Wiegand, B. P. (2016), "Estimation of the Rolling Resistance of Tires," *SAE Technical Paper Series*, SAE International.

Wood, R. (2015), "Reynolds Number Impact on Commercial Vehicle Aerodynamics and Performance," SAE International Journal of Commercial Vehicles, **8**, pp. 590–667.

Yasin, T. P. (1978), "The Analytical Basis of Automobile Coastdown Testing," *SAE Technical Paper Series*, SAE International.

Zolet, T. L., Rosa, S. C. and Bicalho, S. (2015), "Correlation between Aerodynamic Drag Found on CFD Simulations, Wind Tunel Testing and CoastDown Testing," *SAE Technical Paper Series*, SAE International.