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L. RAY BUCKENDALE LECTURE

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Fuel and Freight Efficiency - Past, Present and Future Perspectives

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61ST ANNUAL L. RAY BUCKENDALE LECTURE

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This SAE technical paper presents the 61st Annual L. Ray Buckendale Lecture, which was presented during the SAE Commercial Vehicle Engineering Congress on October 5, 2016 in Rosemont, Illinois, USA.

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L. RAY BUCKENDALE LECTURE

This lecture, presented annually at the SAE Commercial Vehicle Engineering Congress, focuses on automotive ground vehicles for either on- or off-road operation in either commercial or military service. The intent is to provide procedures and data useful in formulating solutions in commercial vehicle design, manufacture, operation and maintenance.

Established in 1953, this lecture commemorates the contributions of L. Ray Buckendale, 1946 SAE President. L. Ray Buckendale, by his character and work, endeared himself to all who were associated with him. Foremost among his many interests was the desire to develop the potential abilities in young people. As he was an authority in the theory and practice of gearing, particularly as applied to automotive vehicles, it was in this field that he was best able to accomplish his purpose. To perpetuate his memory, SAE established this lecture to provide practical and useful technical information to young people involved in vehicle engineering.

The individual presenting the Buckendale Lecture will receive an honorarium and a framed certificate. All those attending the lecture receive an electronic copy of the lecture, and are invited to attend a sponsored breakfast with the lecture immediately following.



2016 LECTURER

Richard R. Mihelic

Richard R. Mihelic, as a retired Vehicle Performance & Engineering Analysis Manager, Rick's career in product development engineering and project management spans 34 years, including 20 years in commercial vehicle development for Peterbilt aerodynamic vehicles and 12 years for the DOD, NASA and DOE with Lockheed including Trident Missile program, Space Shuttle Life Sciences program, and the Superconducting Super Collider National Laboratory.

Rick has been an active participant in Truck and Engine Manufacturers (EMA) review and feedback on EPA/NHTSA Green House Gas rules regarding aerodynamics and physical testing. He was aerodynamics lead for the Peterbilt/Cummins Dept. of Energy SuperTruck program and managed support for SAE Task Forces on Type II and Type III fuel consumption test protocols and EPA's SmartWay program. The product development experiences include systems engineering, full scale drag and mpg vehicle testing, scale wind tunnel testing and computational fluid dynamics. He has published five SAE papers and is an inventor on four U.S. patents. He is President of Mihelic Vehicle Consulting. Rick is an active member of SAE and TMC regarding aerodynamics and fuel economy. He is a consultant author to NACFE on vehicle fuel economy and methodology. His volunteer SAE efforts include being co-chair, organizer and presenter for four years of COMVEC Aerodynamics tracks. Rick is a Board member of the ISEEK Corporation.

Fuel and Freight Efficiency - Past, Present and Future Perspectives

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ABSTRACT

North American on-highway tractor fuel efficiency has evolved significantly from its 1950's roots to today's Department of Energy SuperTruck prototypes and current Original Equipment Manufacturer production models. Innovating tomorrow's Environmental Protection Agency Green House Gas compliant and economically efficient designs require understanding and manipulating the complex interactions between multiple systems in the context of both how the vehicles are formally evaluated and how and where they are actually used. This SAE L. Ray Buckendale Lecture paper provides an in depth overview of fuel economy and freight efficiency evaluation methods, their contexts and limitations, especially with respect to comparisons between the different methods. The paper reviews the current state of the art in production on-highway fuel efficiency optimization while also providing insights on future demands and opportunities in vehicle system & infrastructure designs, test & analysis, instrumentation and legislation.

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INTRODUCTION

Fuel economy as a metric for performance, at face value, seems simple: miles driven divided by fuel used. Yet industry, consumers, regulators, researchers and the general public have consumed a significant amount of effort in the period from 1950 to today wrestling with the complexities inherent in assessing fuel economy. The purpose of this SAE L. Ray Buckendale paper is to provide new engineers with perspectives and insights to assist them in the steep learning curve tied to fuel economy assessment and use of results.

The paper provides historical perspective on the evolution of commercial vehicles from a collection of customer specified parts towards a future where regulations and the marketplace are requiring vehicles to be engineered and evaluated as complete systems, using tools and concepts from the Systems Engineering vocation. This is exemplified in the Department of Energy (DOE) SuperTruck programs and the level of efforts needed to meet current and future Environmental Protection Agency (EPA) and National Highway Transportation Safety Administration (NHTSA) commercial vehicle standards.

The paper highlights the large volume of available public information resources related to fuel economy assessment, systems engineering, and the commercial vehicle world. The report identifies that fuel economy is extremely context sensitive. Details in assessment methods and differences between methods are critical to making constructive use of test results. The report highlights the challenges faced by regulators in aggregating 50-state comprehensive regulations related to fuel economy, where individual vehicle operating profiles vary considerably.

The paper provides details demonstrating that different assessment methods include elements that are measured, assumed, estimated, rationalized, and on occasion, purposely ignored. The paper suggests that two methods that both produce fuel economy values are likely providing different results because they are not measuring the same factors using identical inputs.

The goal of the paper is "not to bury fuel economy assessment, but to praise it," in all deference to Shakespeare [1]. Significant progress in understanding and quantifying fuel economy has occurred through industry, government, market, public and research forces. This maturation of knowledge is inherent in the scientific process. It has been helped on its path by economic competitive forces and the importance of fuel price as a factor in business success. Environmental regulations have pushed progress in fuel economy both because improving fuel economy can directly reduce emissions, and indirectly because some emission reduction technologies effectively degrade fuel economy which manufacturers must then find ways to offset through developments in other parts of the systems. Public perception of stagnation in fuel economy improvement of commercial vehicles has fueled debate and investment in research.

There are thousands of pages of methods, regulations, evaluations, editorials, testimony, and research on commercial vehicle fuel economy. This body of knowledge can be both intimidating and confusing. This paper attempts to outline some of the major causes of confusion and to provide starting points for the new engineer's investigations.

The history of fuel economy assessment has been one of adding complexity as factors previously thought irrelevant have proven to be significant and worthy of inclusion. New engineers and experienced ones alike have contributed to identifying opportunities for continuous improvement in the area of fuel economy assessment and use. They build off the years of progress and development to avoid creating redundancies and challenge.

The future will include hybrid, zero emission along with growth in semi-autonomous and autonomous vehicles in parallel with today's and yesterday's vehicles. It is not atypical for commercial tractors and trailers to last 10 to 25 years through multiple owners and uses, and the penetration rate of new technologies in the vehicle population can take decades. This paper discusses key future trends that will impact measurement, interpretation and use of fuel economy data.

This paper focuses primarily on the North American commercial vehicle fuel economy perspective, but references to international activities are included as many countries are focused on similar interrelated goals of improving fuel economy, reducing greenhouse gas emissions, and improving freight hauling profitability.

The structure of this paper is as follows:

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SAE L. RAY BUCKENDALE LECTURE BACKGROUND

David Merrion's 1994 40th L. Ray Buckendale Lecture abstract in SAE 940130, succinctly describes the annual series as "The L. Ray Buckendale Lectures, inaugurated in 1954, commemorate the contributions of the 1946 SAE President as developer of the latent abilities of young engineers and as an authority in the theory and practice of gearing, particularly as applied to automotive vehicles. ... The Lectures are directed toward filling the needs of young engineers and students for up-to-date practical knowledge" [2].

L. Ray Buckendale was the 1946 SAE President, who "by his character and work, endeared himself to all who were associated with him. Foremost among his many interests was the desire to develop the potential abilities in young people. To this end, the lecture is directed primarily to the needs of young engineers and students with emphasis on practical aspects of the topic" [3].

One of Buckendale's earliest contributions to SAE is paper 260042, dating from 1926 on the Automotive Worm Gear and covering information beginning in 1912 at the very start of automotive engineering [4]. Buckendale's emphasis on developing potential abilities goes hand in hand with the need for young engineers to show initiative to identify, research and build on relevant prior work by a

multitude of capable predecessors. There have been 60 Buckendale Lectures preceding this paper. These are listed in [Appendix B](#) as a collection so that this document can be referenced in future papers.

Victor Raviolo in his 1968 Buckendale Lecture titled Planning a Product stated "...the shape of the future can be deduced only from careful study of the past. Several universal requirements emerge as the principal controls on the work of the designer. First among these are the current and anticipated needs of the customer" [5]. Many of the past Buckendale series lectures remain relevant for years after they are published, including being cited by new papers from a variety of organizations and countries. One example cited in this document is Rick Drollinger's 1987 Buckendale SAE Paper 870001 titled "Heavy Truck Aerodynamics" [6]. A quick search with a web search engine shows this paper has been cited by at least 22 other authors, with at least 12 citations since 2010. The actual number of recent citations is greater.

A typical university text book used in past introductory courses on engineering titled Engineering, an Introduction to a Creative Professions, states "Primarily, science builds its store of knowledge on facts which, once determined, are available from then on for further discovery." The book states "Basically, the role of the engineer has not changed in centuries. (The) job is to take knowledge and make practical use of it. (To) convert scientific theory into useful application" [7]. In David Billington's 2006 book Power, Speed and Form, Engineers and the Making of the 20th Century, the authors state "Modern Engineering is more coherent and more appealing when introduced as a historical sequence of ideas and events" [8]. He goes on to state "Modern Engineering would not be possible without the contribution of larger groups of people, and interactions with society and culture have shaped it in crucial ways" [8].

Today's new engineers have ready access to an immense amount of past engineering information through current web based databases, search engines and repositories such as SAE's extensive databases, training and conferences. These storehouses of information when taken piecemeal as might be done in quick research, can lack context and connection. This paper will introduce engineers to a number of sources on heavy truck fuel economy measurement, interpretation and use with the goal of giving new engineers insights and historical context for researching and innovating future fuel economy systems and processes, in the professional spirit of L. Ray Buckendale.

SYSTEMS VS. COLLECTION OF ASSEMBLED COMPONENTS

The quick pace of modern engineering and demands for efficient use of business resources can create a form of engineering tunnel vision, isolating components and subsystems from their interconnected systems. A simple example of this can be demonstrated by the nomenclature used to describe common vehicle systems. Common vernacular would label the systems in [Figure 1](#) as ships and airplanes, although they are separated by decades of innovation and capability. Yet industry and government consistently differentiate the taxonomic labels in [Figure 2](#), raising the two distinctly different vehicle genres to their own family levels such as "traditional" or

"classic" versus "aerodynamic" [9][10][11][12][13]. The history on this differentiation includes marketing, customer, political and performance factors that have changed with time, yet fundamentally both are trucks, or more specifically tractors. They are both subject to the same physics defined by equations of motion, both transit the same infrastructure, both perform the same task of moving freight, are both controlled by one driver and both are subject to a majority of the same laws and regulations.



Figure 1. System nomenclature - "ships" and "airplanes" [14].



Figure 2. System nomenclature - "Traditional" and "Aerodynamic" [14].

One origin of this artificial system label differentiation in North America originates from how tractors have been marketed, specified and purchased from the 1950's. Original Equipment Manufacturers (OEMs), the tractor makers, make vehicles to customer orders in a process abbreviated as "spec'ing." While the OEMs largely are legally responsible as the end item assemblers for the vehicles, the component level spec'ing was often the result of customer's demanding use of specific components and subsystems, such as engines, brakes, axles, tires, transmissions, wheels, mirrors, alternators, steering, etc. In essence, customers, with influence of vehicle dealers and component suppliers, requested a combination of individual components and subsystems, and the OEMs did their best to accommodate the requests while concurrently attempting to meet all regulations and performance objectives. Where there were conflicts, the OEM exercised final authority as the legally liable manufacturer, but where the customer was adamant about specific combinations of parts, the OEM would engineer and validate that new permutation in the interest of maintaining good customer relations. Customers and dealers drew expertise in spec'ing from their own prior experience in both formal and also somewhat trial and error field testing of vehicles, from competitor experience, from media reporting, from component and subsystem manufacturer representatives, and the consultation with the OEMs.

Figure 3 illustrates a representative on-highway vehicle specification order sheet dating from 1960. The three images are reproduced in Appendix B for greater clarity. These sheets show that tractor spec'ing required selecting approximately 135 vehicle components or subsystems. This buyer may have had prior vehicles built similar to this specification that were performing well in the field, so the selection process might be reduced to discussing what changes in products may have evolved into existence since that last order. A less secure customer with no prior experience might demand a pilot vehicle build for evaluation before committing to larger sales volumes. In both cases, the customer tended to drive the system definition.

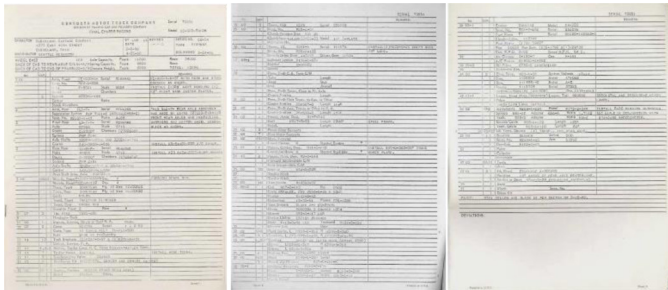


Figure 3. 1960 on-highway tractor specification order sheet [15]*.

From a systems engineering perspective, these customer spec'd vehicles could be viewed as more a collection of parts, rather than engineered systems. OEMs did develop whole vehicle models with preferred component specifications, but the customer/dealer spec'ing process emulated the old marketing sage advice "the customer is always right."

This level of customer control of specifications exists in aircraft, ship and train vehicle sales, so it is not unique to the trucking industry. The process for the truck industry has, however, had some unintended consequences with respect to evaluating performance by differentiating the physics relevant to the two types of vehicles in Figure 2. This will be discussed in detail in the Fuel Economy Historical Perspective section, but first this paper will provide background on Systems and Systems Engineering which are critical concepts to establishing and validating fuel economy requirements.

Systems Engineering Basics

How one defines a system inherently constrains the potential opportunity for improvement. A 2012 graphic in Figure 4 presented by Mihelic at the Automotive World Commercial Vehicle Megatrends Conference and again at the 2015 SAE Commercial Vehicle Congress (COMVEC) highlights this point with respect to tractor/trailer innovation [16]. If the project constrains itself to being a bumper, engine, fender, trailer skirt, or other component level improvement, the envelope for improvement is constrained to the maximum attainable by that one part. Expanding the envelope to include multiple components working in concert expands the opportunity to some composite potential.

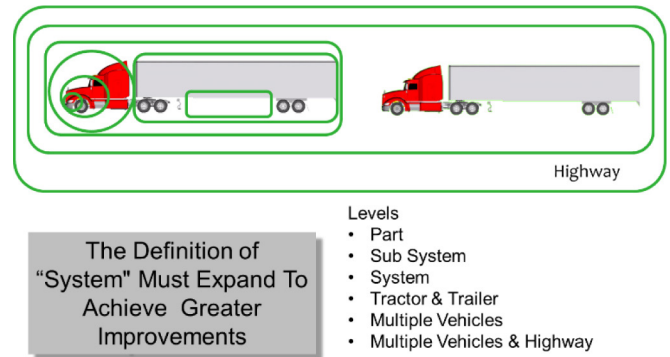


Figure 4. System nomenclature - where to define the system boundary [16].

As the example shows, the system can be defined as a bumper (part), a front end (sub system), a complete tractor (system), a tractor-trailer combination, multiple vehicles, and multiple vehicles in a highway infrastructure. Where improving a bumper's weight and aerodynamics might net a 1% improvement in fuel economy, improvement of an entire tractor trailer might net 50% or greater fuel economy improvement as demonstrated in 2014 by the Cummins/Peterbilt and in 2015 by Daimler on the Department of Energy SuperTruck Program prototypes against baseline Model Year 2009 units over representative drive cycles [17]. Further gains could be achieved by platooning two or more of these prototype tractor-trailers on a dedicated truck highway lane [18].

Complexity and cost can increase with this expansion in system definition, but recognizing that fuel economy is a tractor-trailer level measurement illustrates that fuel economy performance is the result of the interaction of multiple subsystems and components, the driver, the load, the road, speed limits, grades, the environmental conditions and surrounding traffic.

Marks' Handbook for Mechanical Engineers discusses that the "power requirements for a given vehicle must be known before an engine and driveline can be selected. Power required is the sum of air, rolling, and grade resistances. Assuming the road surface remains constant, the grade resistance may be considered as increased rolling resistance. The total resistance and the power required can be determined when the following factors are known: Gross Vehicle Weight, Maximum Frontal Cross Sectional Area, Drag Coefficient, Vehicle Speed, Road Surface and Grade" [19].

The Marks' Handbook, in Figure 5, reproduces a 1994 SAE Motor Truck Engineering Handbook Power Required versus Vehicle Speed graph to emphasize that the gross required engine horsepower is a combination of somewhat linear rolling resistance factors and somewhat quadratic aerodynamic resistance, as if these are distinctly separable [19][20].

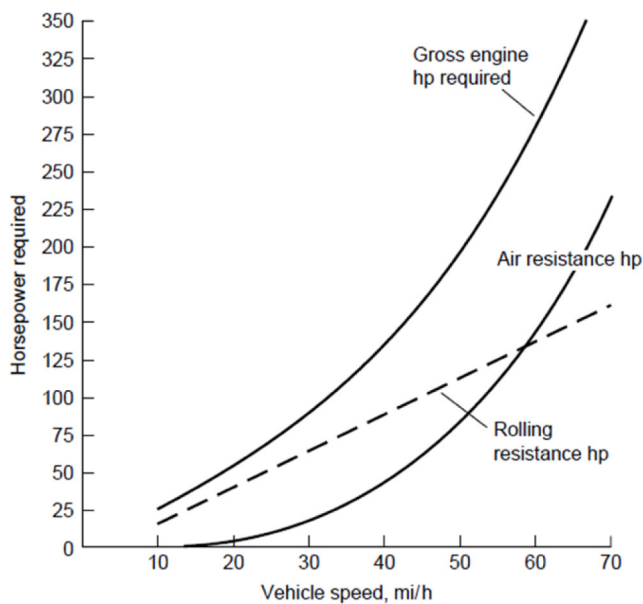


Figure 5. Aerodynamic drag effect on truck power requirement to overcome air resistance [19][20].

This type of representation of the real world contains many simplifications, qualifiers and assumptions which in the past could be marginalized by industry as insignificant as discussed in the North American Council for Freight Efficiency (NACFE) 2016 paper Determining Efficiency [21]. These factors have now become critical topics as industry is increasingly concerned with attaining even fractions of percent improvement [21]. The understanding of the tractor/trailer as a system has evolved along with improvements in quantifying the qualifiers. Much more demanding regulatory and competitive requirements have been implemented to improve vehicle fuel economy as discussed in the U.S. Environmental Protection Agency (EPA) 2011 Final Rulemaking to Establish Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles Regulatory Impact Analysis (RIA) for the Phase 1 greenhouse gas (GHG) rules, and their 2015 Draft RIA for the proposed Phase 2 GHG Rules [22][23].

What is a system? John Leonard defined the term system in his 1999 Systems Engineering Fundamentals report: “Simply stated, a system is an integrated composite of people, products and processes that provide a capability to satisfy a stated need or objective.” [24].

A history of Systems Engineering is succinctly documented by Guey-Shin Chang, Horng-Linn Perng and Jer-Nan Juang in their Journal of Biomechanics Engineering paper, A Review of Systems Engineering Standards and Processes [25].

Leonard provides a definition of Systems Engineering from 1994 EIA Standard IS-632, Systems Engineering: “An interdisciplinary approach that encompasses the entire technical effort, and evolves into and verifies an integrated and life cycle balanced set of system people, products, and process solutions that satisfy customer needs” [24] [26].

Lee Armstrong in his 1996 Systems Engineering as a Structured Process SAE Paper 962178 states “Systems Engineering...is not just another engineering discipline, but also a structured process for solving any complex problem. The discipline skills required include an understanding of this process and how to modify it to meet the demands of each project” [27].

Armstrong represents Systems Engineering as a series of tradeoffs as illustrated in Figure 6. This perspective highlights that net vehicle performance is the product of consideration of all the factors relevant to the system. This system view of the tractor/trailer is critical to current and future vehicle fuel economy assessment and innovation.

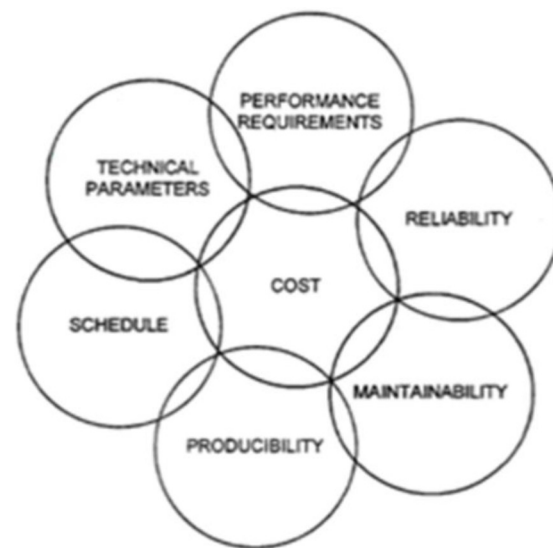


Figure 6. Systems Engineering is a series of tradeoff analyses [27]

Systems Engineering processes are detailed in the NASA Systems Engineering Handbooks, including one using an example premise that “NASA decides that there is a need for a transportation system that will act like a ‘truck’ to carry large pieces of equipment into ... orbit” [28]. A more recent NASA handbook, Marshall Space Flight Center’s 2012 MFSC-HDBK-3173, Project Management and Systems Engineering, provides additional references, background and tools for Systems Engineering [29]. The new engineer should take in these examples that similar and relevant insights may exist in alternative industries.

The International Council on Systems Engineering (INCOSE) publishes the Systems Engineering Handbook to describe key process activities performed by systems engineers and other engineering professionals throughout the life cycle of a system [30]. This organization also has a certification program for Systems Engineers.

Many of these more recent guides on Systems Engineering trace their origins to the 1969 U.S. Department of Defense MIL-STD-499 and its subsequent revisions. While the government decided in the 1990’s to move away from MIL-STD’s and cancelled this document, it evolved through industry and professional organizations into several new ones [25].

Many Systems Engineering resources are available to the new engineer through the web, including free on-line courses and class materials through open courseware such as the Massachusetts Institute of Technology (MIT) OpenCourseWare (OCS) program [31].

A key point made in Armstrong's paper is that Systems Engineering is tailored to the project, team, requirements, and other factors [27]. While strict implementation of a complete Systems Engineering process can require significant effort and discipline, elements of it can be adapted individually or in subsets to greatly facilitate and improve any product development project.

System Requirements Definition

The starting point of any product development effort is to define the goals and objectives. These are generally termed as requirements, which can be segregated into levels. Top level requirements apply to an entire system. Fuel economy for a tractor/trailer is a top level requirement as it is the result of all the subsystems, environment, operations, etc.

Requirements should be quantifiable and verifiable. For example, stating that a tractor/trailer should have improved fuel economy is an incomplete and inadequate requirement for engineering the system. The engineer needs to consider context, basis and metrics in the requirements statement. A better requirement would be that the proposed new tractor/trailer combination shall demonstrate a minimum of 5.0% improvement versus a specific prior model year tractor and the same baseline 53' dry van trailer when both are evaluated concurrently using SAE-xxxxxxx with the vehicles operating at a gross vehicle weight rating (GVWR) of 65,000 GVWR on Test Track xxxxxx.

This added specificity highlights that interpretation of improvement can be confusing without sufficient detail to provide the engineer with a path to meeting the requirement and satisfying the customer or management's system level objective.

Functional Decomposition

Top level requirements must be allocated to constituent subsystems and components to allow the developers of those systems to have meaningful individual targets to contribute to the entire system meeting the top level objectives.

A structure for this requires decomposing the system into useful constituent subsystems and components. The approach to this depends on the scope of the project and size and organization of the project team. Many new projects, such as those related to tractors, can build off pre-existing product and organization structures as a new tractor is generally some combination of existing carry-over parts and newly designed ones, as illustrated in Figure 7. Mihelic and Ray provide this insight to a tractor functional breakdown and system for allocating requirements to subsystems in their 2003 SAE paper, A

Systems Approach for the Evolving Nature of Part Costs [32]. While the title of the paper focuses on Part Cost, the process can be applied to a range of attributes such as weight, energy consumption, warranty, installation labor, design life, safety margins, mean time to failure, reliability, etc.

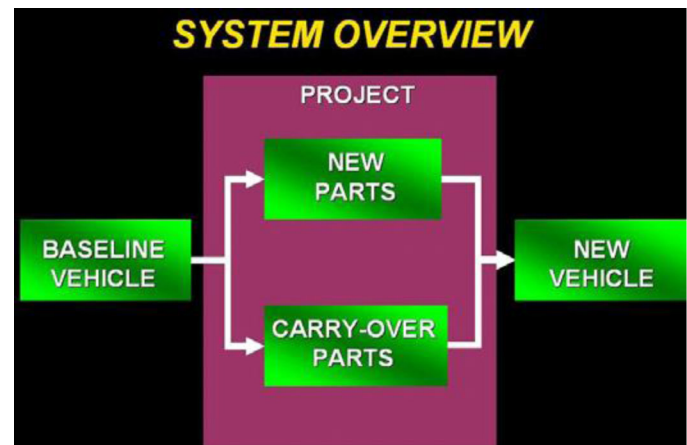


Figure 7. New vehicle systems are a combination of new and carry-over parts [32]

The top level in their example is a truck. The truck is then decomposed into major subsystems, which can be further decomposed to constituent sub-systems, then components and if necessary, individual parts, as shown in Figure 8. In many systems engineering guides, this is called a Work Breakdown Structure (WBS) [24][28][29][30].

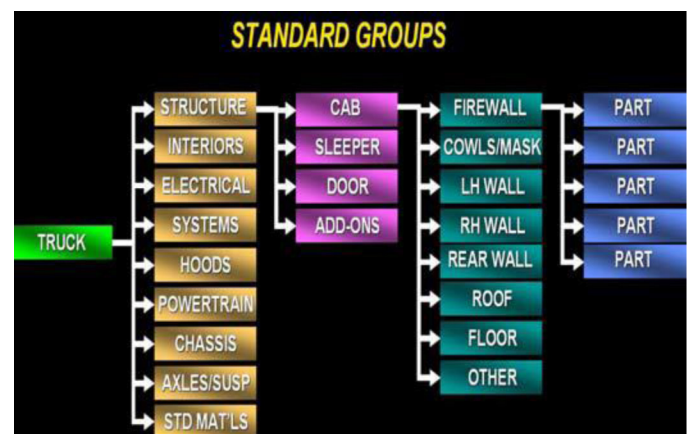


Figure 8. Example functional system breakdown [32]

The objective of this system decomposition is to tailor and allocate the project goals to the appropriate organizational or team level to permit that level to successfully accomplish its task and contribute to the overall project success. These divisions come with the necessity of defining interfaces between the elements and allocating or apportioning the top level requirements to those elements. A mechanism for doing this is a Boundary Diagram, as shown in the Figure 9 example.

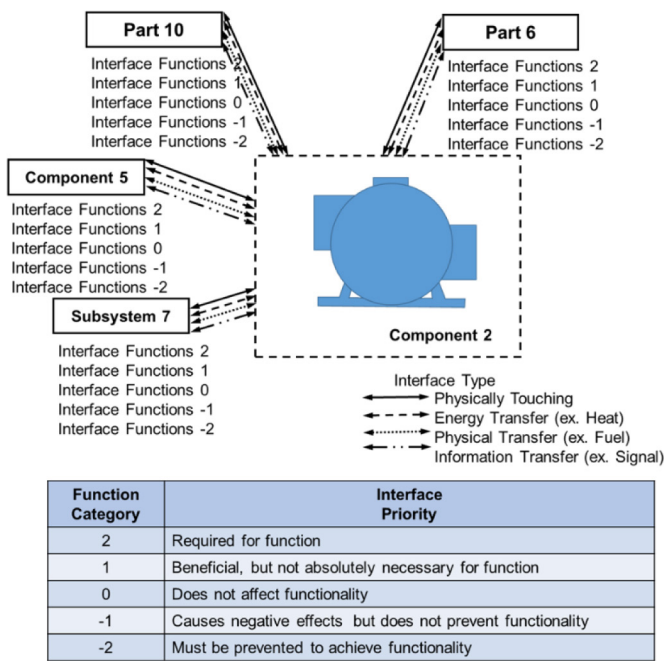


Figure 9. Example boundary diagram

The primary purpose of this graphical tool is to facilitate identifying all the interfaces of a system element, classifying the type of interface and its relevance or priority.

In the case of an established product platform such as a tractor, a company may have done this level of definition previously as the boundary diagrams fundamentally change very little in evolutionary product development. Revolutionary products likely require developing an entirely new diagram, but once created, they become useful for later projects.

A simple tool for use at the beginning of a project to facilitate early product decomposition is the use of yellow sticky tabs in a team meeting focused on this objective, a simple example of which is shown in Figure 10. Participants representing the various product areas pencil in individual elements on tabs, one element to a tab and paste them on a marker board wall. As the team works through the process, they can begin to organize by using markers to highlight interfaces between elements, highlighting which ones are intended to be carry-over versus new developments.

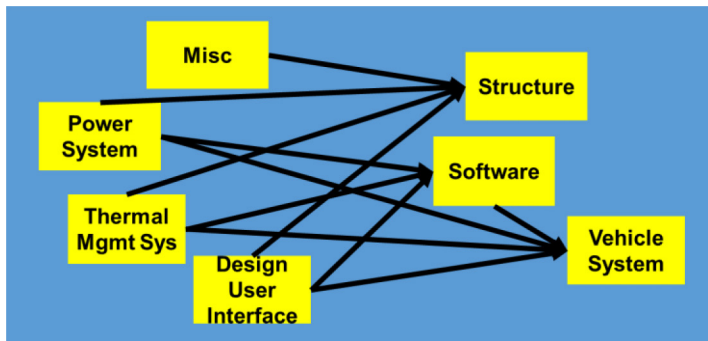


Figure 10. Simple example using yellow sticky tabs to describe and organize a system, its elements and possible interfaces [33]

Each arrow implies a connection; a probable interface needing definition and agreement, and can also lead to discussions of sequences, priorities, confidence level, carry-over vs. new, etc. that can help with many aspects of the more formal Boundary Diagram and other project needs.

The boundary diagram process identifies known interfaces, but of equal importance, it can identify ones previously not considered. This concept will be revisited in the section on Fuel Economy Perspective as it is fundamental to understanding the contexts, limitations and application of fuel economy test information for heavy trucks.

A fundamental objective of systems engineering is to take complex systems and requirements and break them down to constituent parts and information that can be used to develop the individual elements of the system with assurance that the end product will meet the system top level needs. The process is not a static or serial one, as the level of knowledge and experience about a developing system improves with effort and time, and the top level requirements are also subject to change due to the evolving nature of customer demands and regulatory requirements. The process requires revisiting requirements and assumptions to agree they are still relevant and appropriate. A project management tool for this has many names, including Stage Gate, PACE, Waterfall, Tollgate, Phase Review, Phase Gate, etc., but they all share the common theme that as projects progress from idea to end product, the project benefits from interim reviews of both the engineering readiness, and review of the objectives and requirements for currency and appropriateness [33] [34][35][36][37][38].

Engineering projects start from a need and evolve into a production product. Figure 11 provides an overview of trends in a development project and highlights one possible series of program toll gates. At the start of a program, a good deal is typically not known with certainty, so risk is high of achieving success. Few hard decisions have been made and little investment has been expended at that point so design flexibility is greatest at the project start. Additionally, project oversight tends to be less at the start of projects before major investment is in need of management approval and designs or testing have not yet begun.

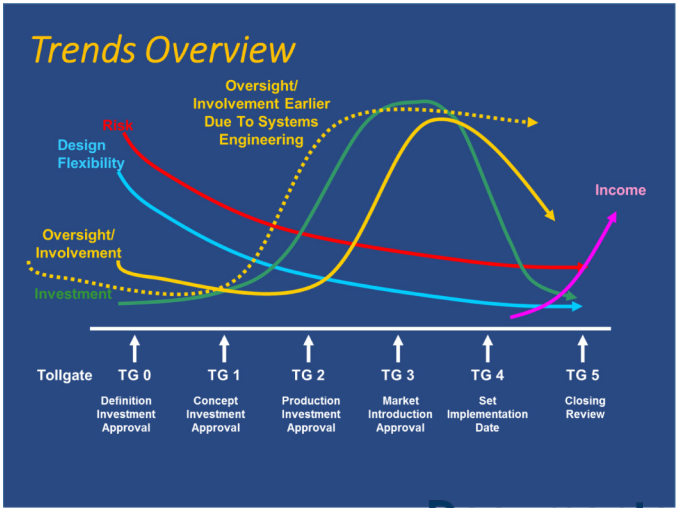


Figure 11. Engineering project trends and example tollgates [33]*

The Systems Engineering process helps move that oversight more towards the program start, shown by the dashed yellow line, helping to reduce waste and rework by clarifying and agreeing early on the goals and constraints. As projects progress, decisions are made, investments ramp up, and design flexibility decreases. The project eventually gets implemented and initial production begins, where for commercial products, income starts to be realized. Work remains as the product enters the field and must be supported, problems corrected, designs refined based on field history and evolving customer demands. A key point in the Systems Engineering guides is that engineering needs to focus on the entire life cycle of a product when developing systems [24][28][29][30]. The new engineer may be exposed to industry computer database systems labelled as Product Lifecycle Maintenance (PLM) that can encompass aspects of Systems Engineering such as requirements allocation and work breakdown structures [39].

The relevance of this total life cycle perspective is again critical to fuel economy as many factors controlling fuel economy performance change with time, age, context and mileage, as will be discussed in the Fuel Economy Assessment Perspective.

Systems Perspective - Convergence of Programs

Two commercial vehicle programs that highlight the potential of viewing vehicle development from a system perspective versus a collection of independent component technologies are the U.S. EPA/NHTSA Green House Gas Phase 1 rules and the Department of Energy SuperTruck programs, somewhat concurrently evolving in the 2007-2011 period as the result of many parallel efforts. These two have origins in the on-going DOE 21st Century Truck Partnership (21st CTP) which originated in the 1998-2000 [40][41][42][43].

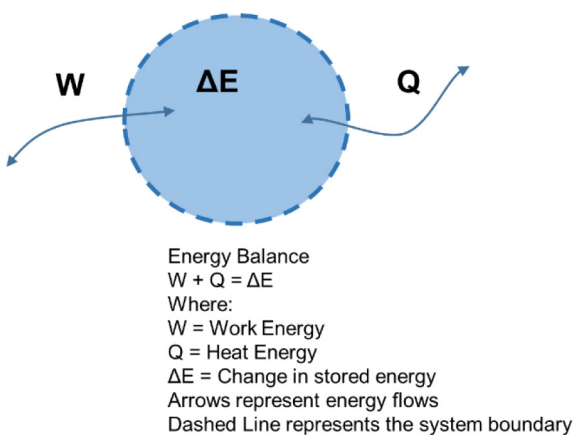


Figure 12. Energy balance diagram and equation

The EPA/NHTSA Phase 1 draft Regulatory Impact Analysis (RIA) issued in 2010 describes the 21st CTP as contributing to the reduction of greenhouse gas emissions through “Integrated vehicle systems research and development to validate and deploy advanced technologies.” [40]. The RIA outlines a system perspective, stating “In discussing the potential for CO₂ emission and fuel consumption reductions, it can be helpful to think of the work flow through the system. The initial work input is fuel. Each gallon of fuel has the potential to produce some amount of work and will produce a set

amount of CO₂ (about 22 pounds of CO₂ per gallon of diesel fuel). The engine converts the chemical energy in the fuel to useable work to move the truck” [40]. Simplistically, this is illustrated in Figure 12 as new engineers should recognize as the fundamental conservation of energy flow diagram.

The 2000 DOE 21st CTP Technology Roadmap defined this energy balance for a M916A2 heavy tractor as shown in Figure 13.

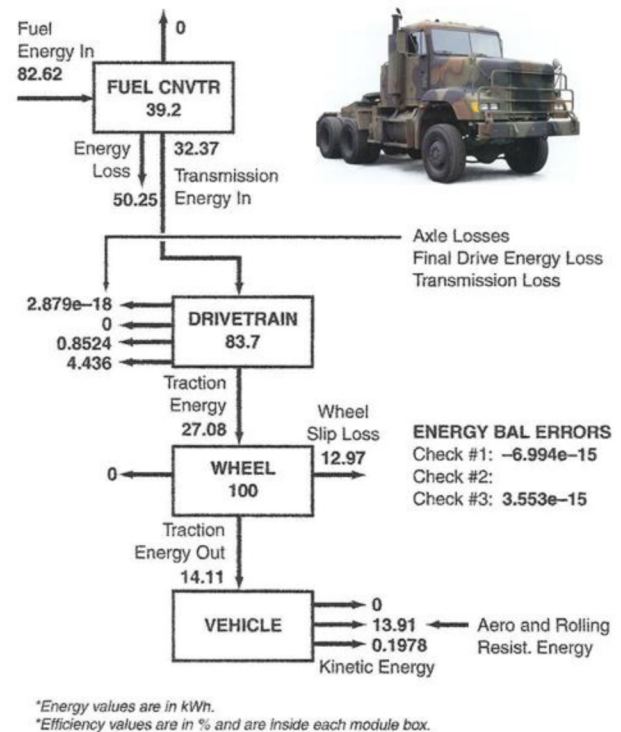


Figure 13. Energy balance for heavy truck from 21st CTP Technology Roadmap [42]*

The 21st CTP displayed a commercial truck energy audit in their 2006 Roadmap and Technical White Papers, shown in Figure 14 [43].

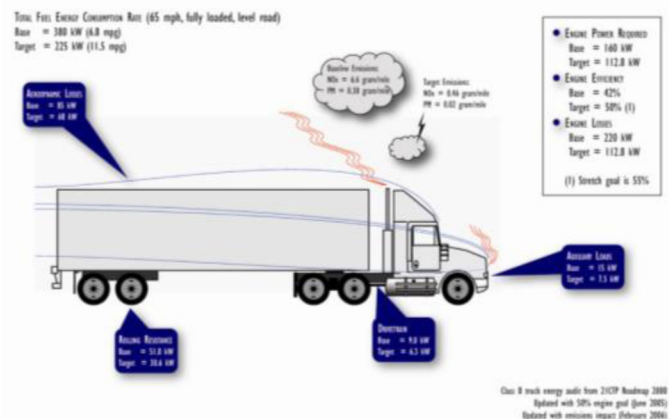


Figure 14. Energy balance for heavy truck from 21st CTP Technology Roadmap [43]*

The 21st Century Truck audit divides the energy balance into supposedly discrete contributors Aerodynamic Losses, Rolling Resistance, Drivetrain and Auxiliary Loads, while maintaining a 65mph velocity with fully loaded vehicle on a level road [43].

The DOE SuperTruck's full title is "Recovery Act - Systems Level Technology Development, Integration, and Demonstration for Efficient Class 8 Trucks (SuperTruck) and Advanced Technology Powertrains for Light-Duty Vehicles (ATP-LD)" [41]. The emphasis on "System Level" demonstration is clearly stated in the Objective, "The goal of Area of Interest 1 is to develop and demonstrate a 50% improvement in overall freight efficiency on a heavy-duty Class 8 tractor-trailer measured in ton-miles per gallon." The objective measurement being on the entire tractor/trailer combination.

Further SuperTruck system level requirements are stated "The vehicle freight efficiency improvement must be achieved while meeting prevailing emission standards and Class 8 tractor-trailers vehicle safety and regulatory requirements. The systems developed shall be validated as cost effective via a business case analysis and will be reviewed for commercialization potential in later project phases as part of the phase gate review process" [41]. They stated the comparison point being a "Best-in-Class" 2009 commercially available Class 8 Vehicle maintaining comparable performance" and provided operational requirements of 65,000 lb vehicle weight, evaluated over a test cycle proposed by the industry team" [41].

These three examples illustrate that these government efforts have an understanding of the energy balance for heavy trucks that conservation of energy applies to the entire system. For example, as stated in the SuperTruck Funding Opportunity, "Achieving significant increases in vehicle efficiency for Class 8 trucks will require an integrated systems approach to ensure that the various components of the vehicle work synergistically to provide maximum benefit" [41]. The challenge is the need to decompose the top level complete vehicle objectives to more manageable lower subsystems and allocate the performance requirements as if the lower systems operate independently. This is where context, complexity, assumption, simplification and compromise begin to assert themselves and introduce errors or misunderstandings. These factors can cumulatively create significant deviation between reality and expectation, as will be discussed in more detail in later sections of this paper.

Systems Engineering Summary

Defining the boundaries of a system also can limit the potential attainable improvement and can inhibit creativity. The phrase "out-of-the-box" accurately describes that significant innovation may require expanding the solution space by including a larger system perspective. Systems Engineering includes tools and methodology to help early clarification of system level objectives, and ways to allocate those to subsystems and components to facilitate individual progress that can successfully combine to meet group goals. The

Systems Engineering process can help define and manage interfaces between subsystems in ways that permit each to develop in some isolation with security of successfully combining in the end product. The processes also enforce review and adjustment of original goals based on evolving conditions through a tollgate review process.

This paper will show that commercial vehicle perspectives have evolved to include the tractor and trailer as a complete system, and recent work is now focusing on multiple vehicles and the infrastructure in which they operate. Future opportunities for innovation in freight efficiency improvement lie in moving beyond the paradigm of the ubiquitous single 53' dry van, two axle trailer as the primary definition of on-highway freight hauling system in the U.S.

FUEL ECONOMY ASSESSMENT PERSPECTIVES

Freight hauling is the business of providing a service to a customer to move product from one location to another for a fee. There are multiple freight transportation modes in North America, but the greatest share of freight is consistently transported by tractor/trailers [44]. A 2014 Federal Highway Administration and Bureau of Transportation Statistics report shows total tonnage by truck significantly exceeded that by all other modes combined representing 67% in 2007 and 2012, and projected to be 66% in 2040 as shown in Figure 15.

Weight of Shipments by Transportation Mode

	(Millions of tons)		
	2007	2012	2040
Total	18,879	19,662	28,520
Truck	12,778	13,182	18,786
Rail	1,900	2,018	2,770
Water	950	975	1,070
Air, air & truck	13	15	53
Multiple modes & mail	1,429	1,588	3,575
Pipeline	1,493	1,546	1,740
Other & unknown	316	338	526

Figure 15. Weight of shipments by transportation mode: 2007, 2012, and 2040 (millions of tons) [44]*

These significant North American freight volume multipliers make fuel economy of trucks critical to a broad spectrum of organizations and to the public. Fuel economy is one of several cost factors managed by freight haulers [45][46][47]. These relative magnitudes vary slightly by year, depending on many factors such as inflation, fuel pricing, market freight rates, etc., but the top three tend to be Fuel, Driver Wages and Vehicle Capital Investments (the truck and trailers) as shown in Figure 16 [47] and Figure 17 [47]. These significant factors are similar in precedence for European freight haulers as reported by Rentema at the 2012 Platform for Aerodynamic Road Transport (PART) symposium as shown in Figure 18 [48].

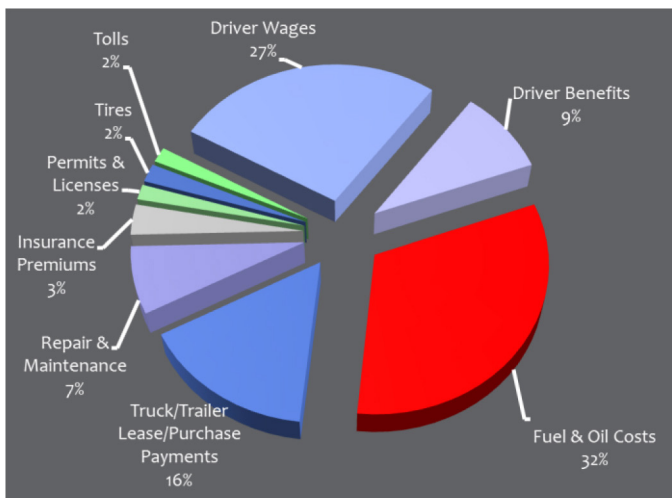


Figure 16. 2011 truck freight hauling costs adapted from ATRI tabulated data [45][46]

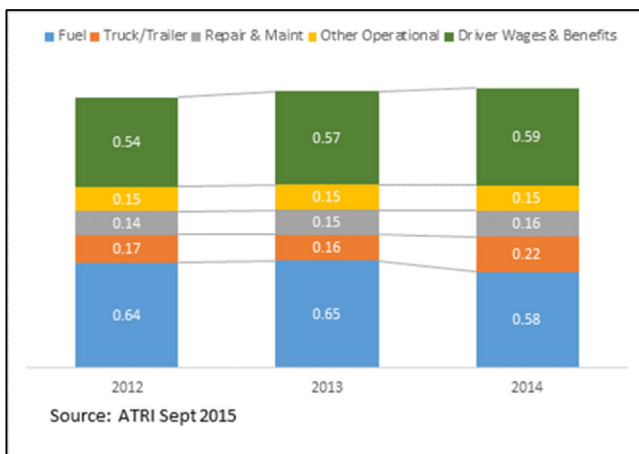


Figure 17. 2014 truck freight hauling costs adapted from ATRI tabulated data [47]

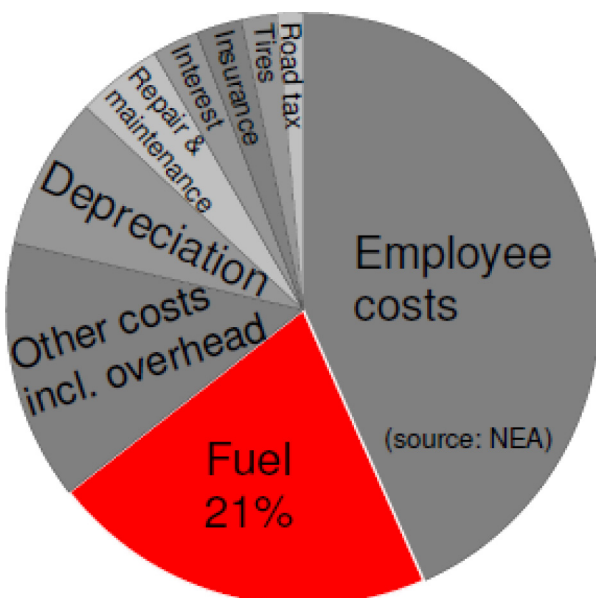


Figure 18. 2012 European truck freight hauling costs [48]

Prior to addition of electronic control modules (ECM's) to manage engine functions via software systems in the 1990's, vehicle fuel economy measurement at the operator level was primarily limited to manually recording volume of fuel pumped and miles driven per trip, then analyzed over specified periods of time, miles or routes.

Company annual performance consolidated this data for entire fleets over a year, coming up with fleet average fuel economy numbers based on net miles driven divided by net fuel pumped. This macro level assessment meant that many variable factors such as freight density, weather, seasons, traffic, driver habits, etc. were amalgamated, making individual technology contributions to fuel economy difficult to separate. Fundamental annual trends could be reasonably assessed to see if progress was being made overall, but accurately assigning cause to the progress would be questionable.

At the other end from composite corporate fuel economy analysis methods, individual vehicle testing standards permitted assessment of specific vehicle fuel economy under specific contexts. The nature of fuel economy performance testing is a tradeoff between precision (also termed repeatability) and accuracy (nearness to a reference value). These two terms are not interchangeable. A general conclusion is that the greater the repeatability, the less the accuracy, because to attain the precision, the variables must be controlled and reduced. Daimler's Jason Krajewski summarized these tradeoffs with respect to truck evaluation at the Diesel Emissions Conference & DEF Forum USA 2012 as shown in Figure 19 [49].

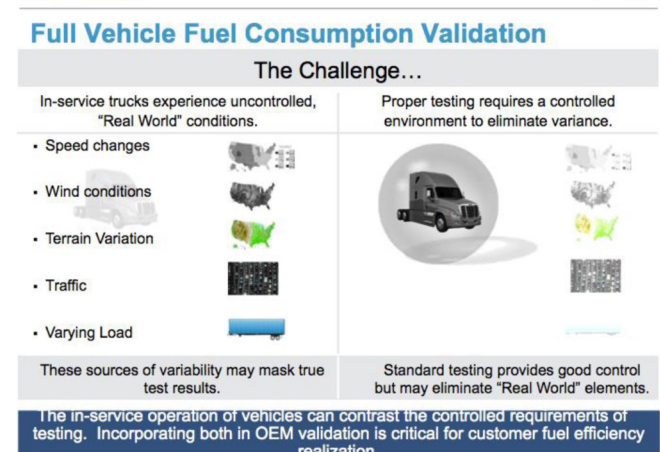


Figure 19. Tradeoff between real world variability and controlled test conditions [49]*

The relation between precision and accuracy is shown in Figure 20. More detailed explanations can be found through the U.S. National Institute of Standards and Technology, NIST, or various universities such as Purdue [50][51]. ISO 5725 adds the term "trueness" to convey the closeness of agreement between the arithmetic mean of a large number of test results and the true or accepted reference value, and "precision" as the closeness of agreement between test results. Complicating the use of terms, the ISO standard bundles both precision and trueness into the single general term "accuracy" [52]. For the purposes of this paper, the convention shown in Figure 20 will be used.

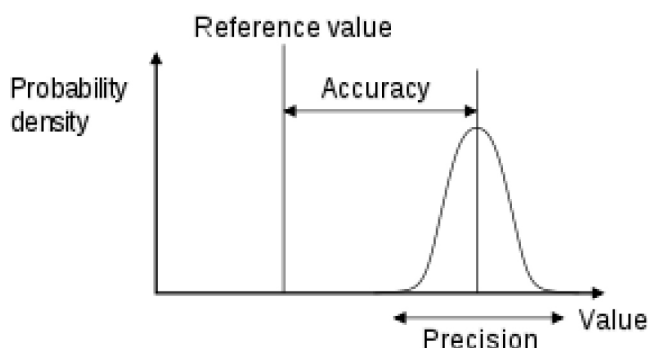


Figure 20. Relation between accuracy and precision [49]

A particular fuel economy assessment method may have very good repeatability, meaning the same test produces nearly similar results for repeated tests of the same vehicle, i.e. the statistical distribution is narrowly grouped around a mean measurement. This says nothing about how accurate the value is with respect to a true reference vehicle, such as a real truck, operating in a real environment, with real driver, loads, weather conditions, etc. In the context of the specific assessment method and the particular vehicle being assessed, a precise result potentially can be used to perform a qualitative evaluation of the same vehicle after it has been modified. This type of evaluation may be described as an A-to-B comparison and typically expresses that vehicle variation B differs in fuel economy performance in the context of the test procedure by some percent difference. The expectation is that in the real world, some probability exists that the B variation would similarly differ from the A vehicle by a similar percentage as found in the controlled test. Quantifying this probability is challenging since the real world conditions are complex and extremely varied.

A simple example of this variability is provided in the draft EPA Phase 2 RIA when describing various common drive cycles used to estimate environments for the entire population of U.S. high roof tractors pulling van trailers [23]. A duty cycle is the operational profile of a vehicle over the course of a period, such as a single work shift or 24-hour period, or week, etc. EPA provides an overview of the complications in aggregating a multitude of duty cycle variables into a single national set in section 3.4 of the proposed Phase 2 RIA starting by describing “For HD Phase 2, the agencies carefully considered which duty cycles are appropriate for the different regulatory subcategories. We considered several duty cycles in the development of the rulemaking including EPA’s Motor Vehicle Emissions Simulator (MOVES) model; the Light-Duty Federal Test Procedure 75 (FTP75) and Highway Fuel Economy Dynamometer procedure (HFET); Heavy-Duty Urban Dynamometer Driving Schedule (UDDS); World Wide Transient Vehicle Cycle (WTV); Highway Line Haul; Hybrid Truck User Forum (HTUF) cycles; and California Air Resources Board (CARB)’s Heavy-Heavy-Duty Truck 5 Mode Cycle” [23]. The proposed weighting factors for duty cycles in the draft Phase 2 GHG rules are described in § 1037.510 as shown in Figure 21 [53].

	Distance-weighted			Time-weighted		Average Speed While Moving, (mph)
	Transient	55 mph Cruise	65 mph Cruise	Idle	Non-idle	
Day Cabs	19%	17%	64%	—	—	—
Sleeper Cabs	5%	9%	86%	—	—	—
Heavy-haul tractors	19%	17%	64%	—	—	—
Vocational—Multi-Purpose	82%	15%	3%	15%	85%	20.9
Vocational—Regional	50%	28%	22%	10%	90%	28.1
Vocational—Urban	94%	6%	0%	20%	80%	19.2
Vocational with conventional powertrain (Phase 1 only)	42%	21%	37%	—	—	—
Vocational Hybrid Vehicles (Phase 1 only)	75%	9%	16%	—	—	—

Figure 21. Weighting factors for duty cycles from EPA Phase 2 §1037.510 [53]*

One example of the difference between real world and a particular assessment protocol is highlighted by this national regulation in that the sleeper cab duty cycle is apportioned as 86% at 65mph cruise speeds, which may be statistically accurate for the aggregate of 50 states, but is incorrect for California where truck speeds are limited to 55 mph [53]. Context of the assessment methodology is critical to making use of the results with respect to specific real world operations. This example is not isolated, many exist, including regional weather differences, differences in freight densities by product type and fleet, routing, traffic densities, dead-heading percentages, driver experience level, vehicle specifications, road surface types, grades, altitudes, vehicle vintages, maintenance levels, etc.

This complexity of balancing test precision (repeatability) against the extensive real world variability has resulted in creation of a number of fuel economy test methodologies by a variety of agencies.

What Is So Complicated About Fuel Economy Measurement

Fuel economy as a term has a significant potential for having multiple interpretations. As a comparison metric, it is somewhat inadequate when applied to commercial freight hauling.

Case in point is discussed by Mihelic, Roeth and Schaller in the 2016 North American Council for Freight Efficiency (NACFE) white paper titled Confidence Report: Tractor Aerodynamics [54]. Typical fleet hauling requires operating at some point moving empty trailers between locations. This is termed “dead heading”. The amount of dead-heading can be between 11% and 13% for some large fleets based on analysis of U.S. Securities and Exchange Commission (SEC) EDGAR system financial reporting for publicly traded fleets [54][55][56]. Since travelling with empty trailers does not generally produce freight income, this particular ratio is a competitive differentiator.

Consider fuel economy with respect to two equivalent fleets operating the same equipment, same routes, same miles, equally skilled drivers, etc. (all other factors being equivalent) where one fleet operates with a 8% dead heading ratio and the other with a 13% ratio. The annual consolidated fuel economy for each will differ due to the fuel efficiency differences from the weight variance. The fleet with the lower 8% ratio will haul more freight requiring greater fuel consumption, and thus have worse aggregate fuel economy, yet from a competitive perspective, it is hauling more freight.

A mechanism was introduced by researchers, regulators and industry to better tailor a fuel use metric by including carried freight weight [9][22][23][40][41][47][53]. One selected term, freight efficiency, is the freight weight carried times the fuel economy and can be expressed as freight-ton-miles-per gallon. While this better clarifies the use of fuel energy to move freight, it again is subject to interpretation based on the context and constraints of specific evaluation methods. For example, the freight efficiency for a fleet hauling on routes in the relatively flat Great Plains, will be higher than fleets hauling through the Rocky Mountains, all other factors being equal, due to grade, altitude and temperature variables. Ones hauling in the north mid-western states will be worse than those hauling in the south eastern ones, all other factors being equal, due to differences in prevailing regional ambient wind conditions as illustrated in Figure 22 [21][57].

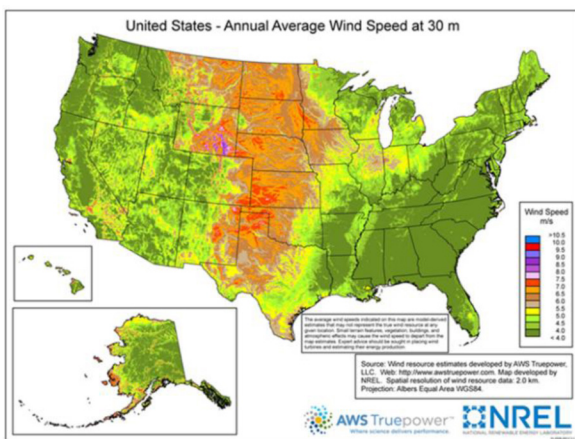


Figure 22. Average wind speeds by region [21][57]*

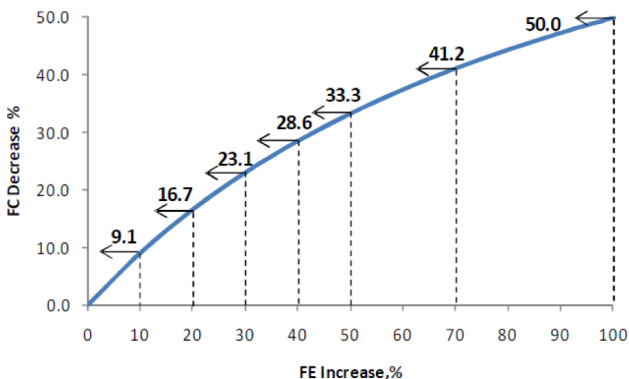


Figure 23. Fuel Consumption % Decrease versus Fuel Economy % Increase. [9]

Another aspect of fuel efficiency is that some methods report and measure fuel consumption, i.e. gallons per mile, rather than fuel economy, miles per gallon. This inverse relationship, graphed in Figure 23, illustrates the importance of specificity when discussing fuel use percentage gains [9]. The 2010 National Academy of Sciences

graph and analysis concluded “The relationship between the percent improvement in fuel economy (FE) and the percent reduction in fuel consumption (FC) is nonlinear; e.g., a 10 percent increase in FE (miles per gallon) corresponds to a 9.1 percent decrease in FC, whereas a 100 percent increase in FE corresponds to a 50 percent decrease in FC. This nonlinearity leads to widespread consumer confusion as to the fuel-savings potential of the various technologies, especially at low absolute values of FE” [9]. This emphasizes for the new engineer that understanding and agreeing on the measurement system terminology is critical to any consistent interpretation of results.

The starting point for understanding fuel economy evaluation is the physics described by the equation of motion, including all factors in the equation. The equation starts from Newton’s $F = ma$, force equals mass times acceleration, relationship. One method in literature from the SAE J2263 Road Load Measurement Using Onboard Anemometry and Coastdown Techniques expands the Force term to three constituent parts [59]:

$$-(M_e)(dV/dt) = D_{\text{mech}} + D_{\text{aero}} + D_{\text{grav}}$$

Where:

M_e = vehicle mass

dV/dt = acceleration

D_{mech} = the mechanical forces

D_{aero} = Aerodynamic forces

D_{grav} = Gravity Forces such as introduced by road grade

This standard, and its similar SAE J1263 Road Load Measurement and Dynamometer Simulation Using Coastdown Techniques, were developed for automotive use. In the absence of commercial heavy vehicle standards, expediency can result in use or adaptation of automotive standards for trucks, buses and tractor/trailers [40][53][60]. These adaptations struggle with the significant fundamental differences in configuration between a relatively small and light two axle car and, for example, a very heavy and large five axle tractor-trailer combination. Factors insignificant to automobiles take on new magnitudes when applied to trucks [21]. The new engineer should be cautious in adapting test protocols where the test subjects or environments vary significantly, taking care to validate and quantify errors involved in any assumptions.

An example focused on determining the aerodynamic portion for a coastdown test evaluation in absence of winds is described by Korst, White and Metz in SAE Paper 2007-01-4297 as outlined in Figure 24 [21][61].

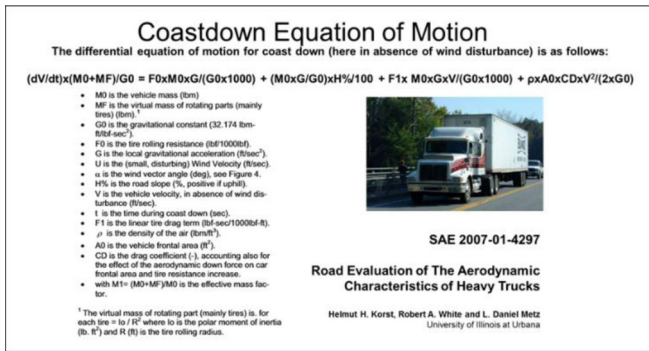


Figure 24. Equation of motion for coastdown evaluation [21][61]*

Where the real world is complicated, investigators attempt to simplify and quantify constituent factors including rationalizing that by controlling some conditions their impacts are marginalized as being insignificant. Each of these compromises adds some level of risk that the tested value does not represent the desired real world value. Mihelic presented additional detail on coastdown methodology in the equation of motion for a version in his 2013 SAE COMVEC Aerodynamics Track Plenary session, shown in Figure 25 [62].

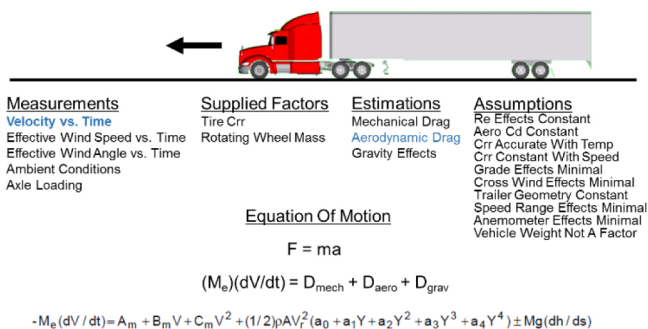


Figure 25. Coastdown test factors [21][62]*

Figure 25 describes that what is actually being measured may be different than the result being reported. The test measures velocity vs. time during coastdown, but the test output estimates aerodynamic drag coefficient. The test methodology can make use of supplied factors from component tests that may or may not represent the actual condition of the complete vehicle system when tested. An example of this is tire rolling resistance as measured with a small sampling of new tires on a standard steel rolling drum versus the actual flat concrete of the specific test facility with tires that may have more mileage. There are many simplifying assumptions often included to permit resolution of a test outcome. The correctness or adequacy of these assumptions may be open to question such as whether even low ambient wind speeds can be considered inconsequential, versus the desired difficult-to-attain zero ambient wind speeds. Evaluations by PACCAR's Peter Kilcline for this same plenary presentation showed that a 4 mph constant crosswind permissible in some test protocols, could create a difference of 4.5% in drag [62]. Even small errors when combined with many other small errors, can produce significant differences between test and the actual desired performance metric.

New engineers should rightly question assumptions and compromises used in evaluations, not blindly accept the status quo. Their fresh perspectives may highlight new opportunities for refinement in

methods, needed improvement in data quality and improved quantification of error bounds. The process of continuous improvement inherently assumes there are always new opportunities.

Real world factors to consider in evaluating or applying controlled fuel economy test results are described by Mihelic in NACFE's 2016 Confidence Report: Determining Efficiency, summarized here [21]:

- Ambient Temperature vs. test temperature.
- Ambient, Instantaneous Winds vs. test winds
- Rain, snow, ice, etc. precipitation vs. dry test conditions
- Actual road surfaces vs. test track or ideal surface assumptions
- Instantaneous Road Grade changes vs. flat or oval banked track testing
- Actual tractor and trailer configuration vs. selected test vehicle configuration.
- Actual vehicle maintenance level vs. just serviced test vehicle.
- Actual vehicle state of assembly vs. just manufactured test vehicle - tolerances on assembly and reassembly.
- Rain, snow, ice, mud accumulation vs. clean test vehicle
- Actual driving profile vs. assigned standard test duty cycles.
- Actual traffic conditions vs. single vehicle tests or limited on-road tests
- Actual vehicle and component age vs. relatively new test vehicle
- Actual driver skill and habits vs. controlled test conditions such as cruise-control only test
- Measurement system precision realities.

An example of the difference between real world and controlled tests cited by NACFE is that the difference between a SmartWay modified SAE J1321 test result and a fleet's real world experience can be one third (1/3) to one half (1/2) of the controlled test values. It is not that one of these values is "wrong," but that each is correct in the context of the assessment methodology [21].

Context includes the details of the vehicles being compared. Vehicles in Canada, the U.S., Europe, Japan and China all operate under significantly different rules and conditions. The "typical vehicle" in each region differs, for example, where the common U.S. transport is a three axle tractor pulling a 53 foot (16.15m) two axle van trailer, a common European unit has a two axle tractor and three axle 13.65m (44.8 ft) trailer. Canadian operations can see A-Train doubles using two 53 foot doubles and significantly greater weights than the U.S. Allowable speeds differ as well by region, with European units limited to 85-90 kph (52.8 - 55.9 mph) and U.S. units range from permitted highway speeds of 55 mph to as much as 85 mph, depending on state and specific roads. The tractor shapes vary significantly by region with cab-overs used in some and conventionals used in others, depending on various length rules and market preferences. The new engineer should take care in drawing conclusions on fuel economy reported in different regions by clarifying the specific configurations of the vehicles and their operational conditions. [46][48][62][125].

Opportunities exist for new engineers to improve use of fuel efficiency test data by evaluating and documenting the differences between the controlled test and the real world user. Correlation and conversion factors are common in engineering to permit application of bench test results to real world, such as in electrical devices where the term “derating” for various conditions is common [63][64]. Yet in today’s world of heavy truck fuel use reporting, these qualifiers and conversion factors can be lacking, leading to questioning the credibility of results.

Multiple Methods of Gauging Fuel Economy Performance

The new engineer embarking on fuel economy evaluation encounters a plethora of relevant standards and test methodologies. A sample list of twenty-seven (27) of these were assembled by NACFE and reviewed in their 2016 Confidence Report: Determining Efficiency white paper [21].

In addition to these published standards, fleets, research groups and test agencies have developed internal, proprietary methodologies customized for their specific use. At the corporate level, annual financial reporting continues to provide data that can be used to assess in the aggregate, the general trends of fuel economy and freight efficiency for companies. Even the individual truck driver has tools for assessing fuel economy, including dash gages presenting data from the Engine Control Modules (ECM), his own record of trips, weights and fuel purchased, and data collected by fleet management software. The multitude of fuel use methodologies reinforces that there are many possible answers to the question, “what is the fuel economy of that vehicle?”

Assuming that each method has some foundation in reason and experience, and that each method, when applied with due diligence has some level of statistical precision, then differing results could imply that each method may have unique contexts and application.

This is the challenge in today’s world, as fuel economy results are often presented in short snippets without inclusion of the qualifiers, details, motives, conflicts of interest, or purpose. Public, industry and government users of information often do not comprehend the fine print that should but often does not accompany any statements on fuel economy. As originally stated, fuel economy should be simple, but the sheer volume of current methods should support the conclusion that it is more complex than simply miles driven divided by fuel used. Yet it may be human nature to want simplicity where physics, marketing, regulation and competition can seem to complicate. An example of this can be found in a common experience of buying a car in the United States.

Government, public and the automotive industry encountered issues with the EPA Corporate Average Fuel Economy (CAFE) Standard introduced in 1975 and reported for city and highway cycles on every new car with the ubiquitous MPG rating posted on the dealership cars as shown in Figure 26 [65][66].



Figure 26. Automotive mpg labeling [66]*

The fine print in Figure 26 flagged as item 10 of this label states “Actual results will vary for many reasons, including driving conditions and how you drive and maintain your vehicle.” Yet it is not uncommon for consumers to have concern when their own fuel economy does not match these stated values. It is also possible that manufacturers have manipulated test conditions such that these posted results are not reflective of EPA’s intended test protocols [67][68].

Heavy truck fuel economy has significantly more variables than automotive. There is greater opportunity for confusion and/or manipulation. The new engineer should take care to investigate and understand the fine details of the assessment methodology, and summarize the context and qualifiers when reporting results for consumption by others.

Overview of the Multiple Performance Assessment Methods

The complexity of truck fuel economy assessment has resulted in a range of test methodologies. Each, when diligently applied, can produce results that have some level of precision, but the results are directly relevant to the specifics of the test protocol and specific tested vehicles at the specific time and location of the testing. As the actual real-world use varies from that vehicle and test condition, the applicability of the test results may differ. Mihelic qualitatively presents this as a bell curve comparing test validity versus real world conditions as affected by a variety of factors in the 2016 NACFE Determining Efficiency whitepaper as shown in Figure 27 [21].

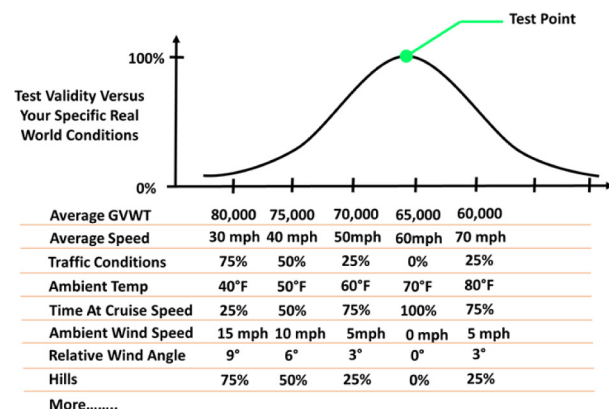


Figure 27. Different operating conditions will give different results [21]

In keeping with a systems perspective, engineers attempt to allocate the top level fuel economy performance to constituent parts. Inherent in this decomposition is a bias that the constituents are independent variables. The previous equation example from SAE J2263 partitions coastdown drag forces into three distinct components, mechanical, aerodynamic and gravitational [59].

$$-(M_e)(dV/dt) = D_{\text{mech}} + D_{\text{aero}} + D_{\text{grav}}$$

The objective in this partitioning is to use sound engineering judgement to apply known, estimated and/or measured values to attempt to quantify unknown ones. In this case, the unknown is the aerodynamic factor. However, these factors are not necessarily independent, “known” values, may not actually be representative of the specific test, and measurement and estimation methods include confidence intervals and require statistical evaluation.

The new engineer should embrace that fuel economy is the net contribution of constituent parts and the energy balance requires including all of the component factors. Each of the following methods may involve interpretations of how to divide or assess the constituent parts. The new engineers should recognize and be able to explain to end users of their test information that comparison between methods requires conversion factors to adjust for any differences in vehicles, procedures, assumptions, simplifications, precision and contexts as they are not measuring the same thing in the same way. An example of this is detailed by the EPA in their GHG Phase 2 RIA, describing “In general, while coastdown tests are used to determine the aerodynamic drag, the procedure itself is a road load procedure, not an aerodynamic one. That is, the measured or calculated forces represent the total road load from which the aerodynamic forces must be calculated or inferred; they are not measured directly. As a result, all analysis methods that are used in conjunction with coastdowns must calculate or infer aerodynamic forces” [23].

Fuel economy as a term itself is somewhat misleading, originating in history from primary use of petrochemical energy sources for vehicle propulsion, but as technology is evolving into hybrid and zero emission vehicles, perhaps the correct term should be energy economy, or more correctly, energy efficiency. Uniform energy use performance comparisons between vehicles with different energy sources requires a system level evaluation, as stated in SAE 1634, Battery Electric Vehicle Energy Consumption and Range Test Procedure, “Evaluations are based on the total vehicle system’s performance and not on subsystems apart from the vehicle [69]:” Some evaluations go further describing “well to wheel” evaluations, implying the true net efficiency should define the system as including the production of the fuel itself, transport, etc. in addition to the vehicle.” A parallel metric to this can be described as net cost of ownership, implying the system costs include not just cradle to grave considerations, but perhaps conception to grave ones. The new engineer may be exposed to a reality of having to choose an appropriate definition of system to permit progress to occur, or he may be mandated with a manager’s direction of one, then working with an appropriate test method for that system definition.

Caution should be taken as each method generally permits or requires some level of customization, or tailoring, such that results on the same vehicle tested under the same banner method by different agencies may have differing results. Also be aware that each procedure goes through some iteration over time, with possible refinements through revisions and updates so that results on the same vehicle under the same banner test method taken under different vintages of the procedure may differ. Properly prepared test reports should adequately document and rationalize these qualifiers. This tailoring of the specification is exemplified by the EPA Interim Test Method for Verifying Fuel Savings Components for SmartWay: Modifications to SAE J1321 and in EPA GHG Phase 1 adaptation of SAE J1263 and J2263 automotive specification for coastdown testing to create a methodology for the EPA/NHTSA regulations [70][71].

The assessment methods relevant to net vehicle fuel economy and its constituent factors can be categorized into five segments as suggested in NACFE’s Confidence Report: Determining Efficiency [21]:

- Computer Modeling
- Wind Tunnel Testing
- Track Testing
- On-Road Testing
- Fleet Composite

Mihelic also outlined in this paper that tests can be grouped by primary measurement method, with an understanding of knowns, unknowns and test data end user considerations as follows [21]:

For tests that measure fuel economy:

What is known:

- fuel use for a specific set of conditions
- confidence interval for the test

What is unknown:

- sensitivity of the vehicle or device being tested to changes in geometry, weight, powertrain, weather, terrain, etc.
- the associated confidence intervals for each sensitivity parameter

What end users should consider:

- their own vehicle operating conditions and performance values for the tested operating conditions
- confidence interval for their own vehicle data

For tests that measure aerodynamic drag:

What is known:

- aerodynamic data for a specific set of conditions
- confidence interval for the test

What is unknown:

- aerodynamic values for the full scale vehicle version of the wind tunnel test article in free air operation
- confidence interval for the approx./conversion data
- conversion criteria for aerodynamic to fuel economy conversion of test data
- the associated confidence interval for those conversions
- sensitivity of the vehicle or device being tested for changes in geometry, weight, powertrain, weather, terrain, etc.
- the associated confidence intervals for each sensitivity parameter

What end users should consider:

- their vehicle operating conditions and performance values for the tested operating conditions
- confidence interval for their own vehicle data

For tests that measure load (dynamometers, torque or coastdown):

What is known:

- torques or deceleration rates for a specific set of conditions
- confidence interval for the test

What is unknown:

- sensitivity of the vehicle or device being tested for changes in geometry, weight, powertrain, weather, terrain, etc.
- the associated confidence intervals for each sensitivity parameter

What end users should consider:

- their vehicle operating conditions and performance values for the tested operating conditions
- confidence interval for their own vehicle data

Grouping assessment methods and guides in this paper is by responsible organization, and by author's recommended priority for new engineer familiarization.

- Society of Automotive Engineers SAE
- American Trucking Association / Truck Maintenance & Technology Council (ATA/TMA)
- U.S. Environmental Protection Agency (EPA) & National Highway Traffic Safety Administration (NHTSA) Green House Gas and SmartWay
- U.S. Department of Energy (DOE)
- Other North American
- Software Vendors
- International
- Fleets

Appendix A presents overviews or selected excerpts from each of more than sixty fuel economy or relevant guides or methods. The new engineer will find there are thousands of pages of methods, regulations, guides, evaluations, comments, etc. For example the GHG Phase 1 rules, Phase 1 RIA, Phase 1 GHG Emissions Model (GEM) documentation, peer reviews, National Academy of Sciences (NAS) Reviews of the program, non-government organizations (NGO) reviews of the rules, Phase 1 submitted comments, testimony from public hearings, etc. conservatively exceed 3000 pages. It is somewhat daunting to the new engineer to be thrust into the middle of a fuel economy evaluation without the experience and required background. Appendix A has been assembled to assist the reader locating relevant information - it is not intended as a truly comprehensive collection, but is the author's recommendation of starting points for the new engineer.



Figure 28. Thousands of pages of fuel economy assessment methodology, guides, evaluations and comments exist.

SAE Methods & Relevant Guides

- SAE J1321 Fuel Consumption Test Procedure Type II - (2012) [72].
- SAE J1526 Fuel Consumption Test Procedure (Engineering Method) - (2015) [73].
- SAE J1264 Joint RCCC/SAE Fuel Consumption Test Procedure (Short Term In-Service Vehicle) - (Stabilized 2011) [74].
- SAE J2971 Aerodynamic Device and Concept Terminology - (2013) [75].
- SAE J2966 Guidelines For Aero Assessment Using CFD - (2013) - [76].
- SAE J1252 Wind Tunnel Test Procedure for Trucks & Buses - (2012) [77].
- SAE J3015 Reynolds Number Simulation Guidelines and Methods - (Work-In-Process - On going SAE Task Force since 2012) [79].
- SAE Jxxxx Constant Speed Test Task Force - (Work-In-Process - On-going SAE Task Force since 2014) -Possible insight to this method is described by Graz University's Hausberger, et. al, in the 2012 report Reduction and Testing of Greenhouse Gas Emissions from Heavy Duty Vehicles - LOT 2 with basic principles [81] and EPA's Phase 2 proposed rules and RIA [23] [53].
- SAE J2978 Road Load Measurement Using Coastdown Techniques - (Work-In-Process - "On-going SAE Task Force since 2014) [82].

- SAE J1263 Road Load Measurement Using Coastdown - (2010) [60].
- SAE J2263 Road Load Measurement Using Anemometry and Coastdown (2008) [59].
- SAE J2711 Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid-Electric and Conventional Heavy-Duty Vehicles - (2002) [83].
- SAE J1711 Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles, Including Plug-in Hybrid Vehicles - (2010) [84].
- SAE J2047 Tire Performance Terminology - (2013) [85].
- SAE J1269 Rolling Resistance Measurement Procedure for Passenger Car, Light Truck, and Highway Truck and Bus Tires - (2006) [86].
- SAE J1634 Battery Electric Vehicle Energy Consumption and Range Test Procedure - (2012) [69].
- SAE J2071 Aerodynamic Testing of Road Vehicles-Open Throat Wind Tunnel Adjustment - (Work-In-Process - SAE since 2014) [87].

ATA/TMC Methods & Relevant Guides

- TMC RP 1102A, TMC In-Service Fuel Consumption Test Procedure-Type II [88].
- TMC RP 1109B, Type IV Fuel Economy Test Procedure [89].
- TMC RP 1103A, TMC In-Service Fuel Consumption Test Procedure-Type III [90].
- TMC RP1106A Evaluating Diesel Fuel Additives for Commercial Vehicles [91].
- TMC RP1111B Relationships Truck Components & Fuel Economy [92].
- TMC RP1118 Fuel Savings Calculator for Aerodynamic Devices [93].
- TMC RP1114A Driver Effects on Fuel Economy. [94].
- TMC RP1115 Guidelines for Qualifying Products Claiming a Fuel Economy Benefit [95].
- TMC RP1108 Analysis of Costs from Idling and Parasitic Devices for Heavy Duty Trucks [96].

EPA/NHTSA GHG & SmartWay Methods

- EPA Interim Test Methods for Verifying Fuel Savings Components for SmartWay [70].
- EPA/NHTSA 40 CFR§1037.521 Aerodynamic Measurements - GHG Phase 1 Revised Coastdown [71].
- EPA/NHTSA 40 CFR§1037.521 Aerodynamic Measurements - GHG Phase 1 Revised Wind Tunnel [71].
- EPA/NHTSA 40 CFR§1037.521 Aerodynamic Measurements - GHG Phase 1 Revised CFD [71].
- EPA/NHTSA 40 CFR§1066 Subpart D-Coastdown § 1066.301 Overview of coastdown procedures [71].
- EPA/NHTSA 40 CFR§1066 Subpart C-(Chassis) Dynamometer [71].
- EPA/NHTSA 40 CFR§1065.15 - (Engine) Dynamometer Specifications [71].

- EPA/NHTSA 40§ 1037.520 Modeling CO₂ emissions to show compliance [71].
- EPA's Greenhouse Gas Emissions Model (GEM) [98].
- EPA Motor Vehicle Emission Simulator -MOVES [99].
- GHG Proposed Phase 2 - EPA/NHTSA 40§ 1037.525 (a) General Provisions for Trailers [23][53].
- GHG Proposed Phase 2 - EPA/NHTSA 40§ 1037.525 (b) General Provisions for Tractors [23][53].
- GHG Proposed Phase 2 - EPA/NHTSA 40§ 1037.525 (d) Yaw Sweep Corrections [23][53].
- GHG Proposed Phase 2 - EPA/NHTSA § 1037.527 Coastdown procedures for calculating drag area (C_DA). [23][53].
- GHG Proposed Phase 2 - EPA/NHTSA § 1037.529 Wind-tunnel procedures for calculating drag area (C_DA) [23][53].
- GHG Proposed Phase 2 - EPA/NHTSA § 1037.531 Using Computational Fluid Dynamics to calculate drag area (C_DA) [23][53].
- GHG Proposed Phase 2 - EPA/NHTSA § 1037.533 EPA Phase 2 Road Load Measurement Using Constant Speed Torque - [23][53].
- GHG Proposed Phase 2 - EPA/NHTSA 40 CFR§1066 Subpart C-(Chassis) Dynamometer Specifications § 1066.210: Revise the dynamometer force [23][53].
- GHG Proposed Phase 2 - EPA/NHTSA 40 CFR§1065.Engine Testing Procedure [23][53].
- GHG Proposed Phase 2 - EPA/NHTSA CFR § 1065.680 - Adjusting emission levels to account for infrequently regenerating aftertreatment devices [23][53].

DOE Methods

- Argonne National Laboratory - Powertrain System Analysis Toolkit (PSAT) [100].
- Argonne National Laboratory Greenhouse Gases,, Regulated Emissions, and Energy use in Transportation - GREET program - [100]
- Argonne National Laboratory- Autonomie Program [101]

Other North American Methods

- CARB Tractor Trailer Greenhouse Gas Regulations - [102][103].
- CARB Approval of Modifications to SmartWay Verified Equipment - ARB mechanism for approval for California use where not previously tested by SmartWay [104].
- Environment Canada - Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations [105].
- National Research Council Canada - Fuel-Savings and Greenhouse-Gas-Reduction Analysis (one method detailed by Brian McAuliffe) [106].

Software Vendor System Modeling Methods

There are many methods for modeling both complete vehicle system performance and component or technology performance, including using special system evaluation software packages, including but not

limited to AVL Cruise™, MATLAB®, Simulink® and other MathWorks™ products, in addition to the government developed tools already mentioned. Readers should refer to various commercial sources for more information [107][108][109].

International Methods

- ISO 28580 Passenger car, truck and bus tyres - Methods of measuring rolling resistance - Single point test and correlation of measurement results - (2009) - [110]
- European Union - EU Climate Action - Reducing CO₂ emissions from Heavy-Duty Vehicles including VECTO system modeling software [113][114][115][116][117][118]
- Japan - Japanese Energy Conservation Standards including TRIAS system modeling software and testing. [113][115][116][117][118].
- China - China's Phase 2 heavy-duty vehicle fuel consumption standards [113][119].

Fleet Methods

Fleet methods are generally proprietary. One discussion of them is provided by NACFE in their 2016 Confidence Report: Determining Efficiency [21].

Summary of Fuel Economy Assessment Methods

There are a significant number of methods for assessing fuel economy and freight efficiency because the freight hauling industry is complex and the real world environment has a great deal of variables. Traditional testing tries to minimize variables to attain repeatability which defines precision of the measurements. This process produces context sensitive test results that need some level of adaptation to be applicable to the real world, this is accuracy. The trade-offs made between precision and accuracy can cause confusion for end users when the contexts of test results are not adequately explained. Industry has recognized deficiencies in fuel economy assessment and continuously works to improve understanding of complexity in measuring efficiency, refining test procedures as the body of knowledge evolves. The sheer volume of guides on fuel economy assessment can be daunting to new engineers, but it is critical that they learn the history of and current state-of-the-art in assessment methods so they can contribute to making further improvements.

MARKET DRIVEN FUEL ECONOMY IMPROVEMENT

What separates investment in a tractor/trailer or straight truck from consumers buying personal cars is that the commercial vehicle is an investment intended to produce business income. Trucks are tools subject to the need to attain positive returns on investment, to minimize operational costs, maximize residual values when disposed and sustain company profitability.

Consumer choice is a foundational element of North America's free-market economy. Successful vehicle manufacturers must provide customers with products that both comply with all government regulations and are commercially viable.

Regulations tend to level the commercial playing field, forcing manufacturers to concurrently meet common minimum requirements, often through adopting similar technology. This can be termed in industry as regulations that are "technology forcing" [23][120]. The technology does not need to be explicitly defined, but can be implicit as the only viable technical and economic alternatives available within a time frame. The adoption of selective catalytic reduction and introduction of Diesel Emission Fluid (DEF) to meet 2010 federal emissions regulations is one example where the industry consolidated around a particular technology to meet the standards, even though one manufacturer temporarily pursued an alternative technology that ultimately proved unviable [121].

Market competition, however, tends to drive innovation, as each OEM wrestles with tradeoffs and taking steps to produce entire vehicle systems that not only incorporate the technology required to meet regulations, but include offsetting ones to make the vehicles commercially competitive.

For example, every Model Year 2010 tractor had to be EPA 2010 engine compliant, but each manufacturer innovated to provide a competitive package that attempted to offset addition of weight for the requisite Selective Catalytic Reduction (SCR) and DEF systems to minimize potential freight reductions. Each OEM used a systems perspective to add or improve other technologies such as aerodynamics to offset any fuel economy performance issues so the new vehicles could perform at least as well as prior year ones. For every required new technology that adds weight or reduces performance, the OEM must find offsets in other vehicle areas to reduce weight and improve performance.

The economic reason for this is that OEMs' new models compete for sale in the market both with their competitors' new models, but also with the existing fleet of older vehicles [122]. In the near term, truck consumers can choose to extend the use of older vehicles rather than purchase new ones. They can choose to buy existing model year products rather than next year's technology, known in industry as a pre-buy [124]. The marketplace generally dictates that new OEM products must perform at least as well as the ones from prior years, and must perform substantially better to gain customer share. An example of this is discussed by James Miller in a 2002 Chicago Tribune article on the EPA's 2002 rules precipitating an industry pre-buy, stating "Based on data the EPA released in January, the new engines are expected to cost about \$4,000 or \$5,000 more than the current truck engines, which fetch about \$14,000. Fuel mileage, a matter of great concern for fleet operators, is expected to decline by about 2.5 percent. Whether they've been encouraged to or not, fleet owners have clearly been ordering trucks at a unusually rapid rate in recent months, as they scramble to get trucks with present-generation engines that don't incorporate the new emission-reducing technology" [123].

There is a misconception in some sectors that the trucking industry and OEM products have not improved fuel economy in decades. For example, one 2015 non-government organization (NGO) report states "lack of truck fuel economy progress," and another 2010 NGO report, "these vehicles currently average about 6 miles per gallon, and have made only modest gains in fuel economy over the past 30 years."

[125][126]. These judgements may be because of simplistic comparisons of current model year trucks to ones from a decade ago, as if they both are built to the same requirements, functions and standards. They are not. It may also be due to use of aggregated government data without factoring that trucks can stay in the population for 10 to 25 years or more, as shown for the U.S. in Figure 29, and Europe for Figure 30 [124][127]. Trailers similarly stay in the population [128].

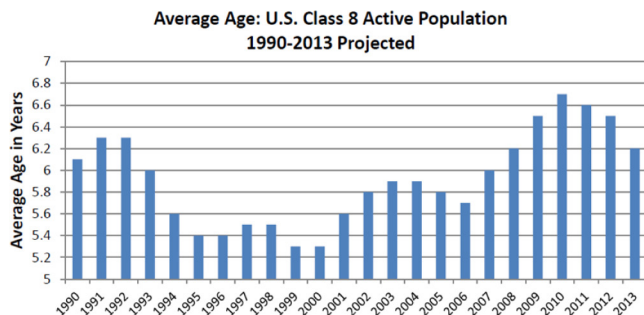


Figure 29. Average age of trucks in the U.S. [124]*

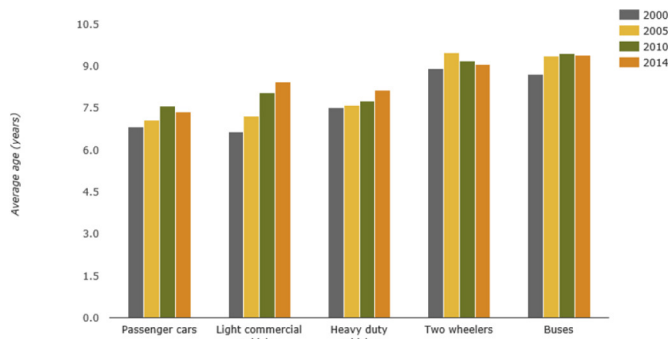


Figure 30. Average age of vehicles in Europe [127]*.

Companies had to redesign trucks to respond to significant introduction of environmental and safety regulations since the mid-1990's when EPA and industry, facilitated by the introduction of electronically controlled engines, to ratchet down emissions, with new levels every few years (2002, 2007, 2010, 2014, 2017). Each of these new standards added technology, weight and complexity to trucks, and generally did not improve fuel economy performance. Yet in that same time span, OEMs and industry managed to attain fuel economy and freight efficiency gains as illustrated in Figures 31 and 32 for the Federal Highway Administration (FHWA) data from 1975 to 2005 and in data presented by NACFE for the period 2003 to 2014 [9][55].

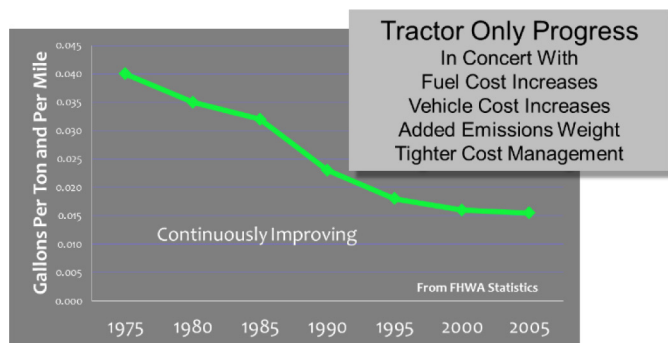


Figure 31. FHWA freight efficiency improvement to 2005 [55]*

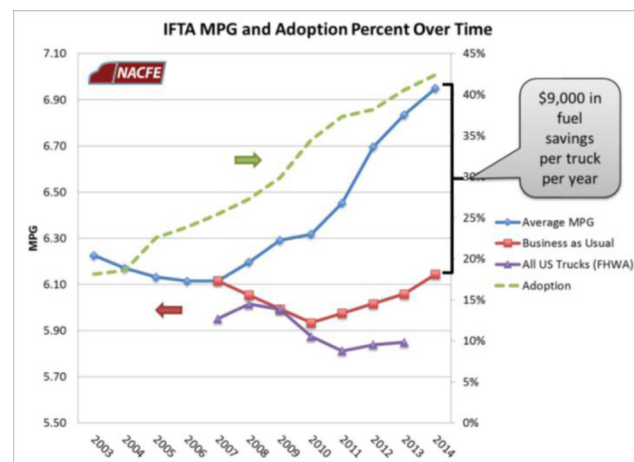


Figure 32. NACFE fuel savings per truck 2003 to 2014 [55]*

Non-mandated government programs, such as EPA SmartWay, have provided guidance to the marketplace, but the EPA SmartWay program since its introduction in 2004 has been a voluntary program for fleets and manufacturers. As of 2016, there are no U.S. national regulations mandating vehicle configurations comply with the program. This may change as part of future EPA GHG regulations, and California did mandate SmartWay configuration in-state, but since its 2004 creation, a major force behind adoption of SmartWay technologies has always included fundamental commercial business reasons to improve fuel economy and profitability.

A freight hauler's total cost of ownership is somewhat equally divided between the equipment (procurement and maintenance), the driver (salary and other) and the fuel (and now also DEF) used as previously shown in Figures 14, 15 and 16. The fuel economy metric is influenced by innovations related to all three factors, but how fleets prioritize or focus their efforts depends invariably on both the price and stability of fuel.

The price of diesel fuel over time is available from the U.S. Energy Information Administration (EIA) [130]. A 2016 summary of diesel fuel price data in is shown in Figure 34 [55]. The graph highlights that fuel costs were relatively stable in the period prior to the late 1990's, and then entered into significant increases and fluctuation.



Figure 34. Diesel fuel price over time [55]*

Fuel price stability pre-1990s may in part be due to economic conditions, adequate supply and corresponding demand. A factor in this stability was the 55 mph National Maximum Speed Limit introduced in 1973 in reaction to the Oil Embargo.

The increase in fuel costs placed greater emphasis on fuel economy improvement. Fleets with more fuel efficient operations saw improved profitability and greater flexibility in pricing services. Less efficient operations had thinner profit margins and less ability to compete on freight pricing. The late 1990's saw growth in the aerodynamic segment of truck sales versus the traditional vehicle market, and OEMs introduced a series of new models as reported by Mihelic in Figure 35 [54][55].



Figure 35. Late 1990's aerodynamic tractor launches - Ford HN80, Kenworth T2000, Freightliner Century, Volvo VN, Peterbilt 387 [54]*

Fuel price is the result of supply and demand market conditions along with interpretations of supply risks. The early 1990's saw war in the Middle East region that affected both oil supply and commodity pricing. In concert, demand increased as the U.S. economy improved in the late 1990's reflected by trucking with a growth in freight hauled. Compounding these two factors was the 1995 repeal of the National Maximum Speed Limit which returned full authority to set speed limits to the individual states [131]. Thirty-three states quickly upped their speed limits. As truck fuel use is directly related to speed, demand for diesel increased with increased highway speeds. Another contributing factor began in 1995 when EPA, CARB and OEMs reached agreement in a Statement of Principles on a plan for engine emissions reductions [132][133]. This plan was first codified in 1997's EPA regulations with an initial target implementation of 2004 [133][134]. The proposed rules imposed new technology on engines that were expected to degrade fuel economy, which would increase fuel demand. The planning included decreasing fuel sulfur content which was expected to raise fuel processing costs. These factors, along with likely many others, influenced the fuel market of the 1990's and illustrate the on-going complexity freight haulers face in predicting and managing fuel costs.

Market Driven Innovation Pertinent to Fuel Economy Improvement

Fuel economy and freight efficiency are system level metrics. As such, they are affected by multiple subsystems [135][136][137][138]. The vehicles equation of motion dictates that energy is required to keep a vehicle moving at a constant speed against opposing forces. Those opposing forces include gravity, aerodynamic drag, rolling resistance drag, accessory drag, other friction drag and losses such as related to engine energy conversion efficiency. Energy is expended in transient events as well, such as accelerating and braking events that directly impact fuel efficiency.

A systems level perspective on fuel economy should also consider equipment and driver utilization factors that can impact the percent of on-highway time seen by both. Regulations limit the number of hours a driver is available to operate a vehicle between rest periods. Actual freight operations involve some amount of driver down-time loading, unloading or waiting for loads. Routing may require transiting

congested traffic regions slowing the vehicle and encountering significant volume of braking and acceleration events. Trailers are not always loaded, so the fuel expended may not be accomplishing any freight transport. Maintenance and accident repair create both driver and vehicle down-time that reduces net miles driven per period. All of these factors impact the vehicle duty cycle, the average speed of the vehicle, both average and instantaneous fuel use and freight efficiency. These qualifying factors are often missing in considering results from steady state track tests for fuel economy, but they are significant factors in the real world evaluation of fuel economy and the market has inspired innovation in all of these areas.

The following is a partial list of technologies that contribute to improved fuel economy that were not originally specifically mandated by regulations and owe their origins to market forces such as business continual mission to reduce costs, increase equipment and employee utilization and eliminate waste to improve profitability.

- Electronic Engine Control
- Tractor Aerodynamic Packages
- Trailer Aerodynamic Packages
- Cruise Control
- Adaptive Cruise Control
- Predictive Cruise Control
- Real-Time Traffic Condition Reporting
- Route Planning Software
- Instantaneous and Average Fuel Economy In-Dash Gauge
- Automatic Transmissions
- Collision Avoidance Systems
- Automatic Braking Systems
- Low Rolling Resistance Tires
- Wide Base Tires
- Down-Speeding
- Weigh-in Motion Systems
- GPS Tractor & Trailer Tracking Systems

A number of agencies have published lists of possible fuel saving technologies. New engineers are encouraged to search at ICCT, NAS, NACFE, DOE, EPA, NHTSA, CARB, RMI, UCS, NRC, TMA, TMC, SAE, and industry OEMs and suppliers (for example [9][11][22][23][42][43][47][112][113][122][139][140]).

Challenges Moving Forward

Market forces will continue to drive innovation and adoption of new technologies that can improve fuel economy. A challenge is where regulation constrains the innovation by effectively mandating specific technologies rather than permitting the marketplace to drive natural selection. In systems engineering terms, requirements should be specified as "what" rather than "how". The technology developers are expected to define the "how". Regulators do not always show flexibility, and can mandate directly or indirectly, specific technologies to meet system performance requirements.

A case in point is that the EPA GHG Phase 1 rules, and proposed Phase 2 rules, along with California ARB rules, which all focus manufacturers and industry on solutions for single 53' dry van and refrigerated trailers [53][71][102]. This artificial segmentation of the innovation envelope focuses development of solutions under these rules that effectively exclude consideration of longer combination vehicles as are used in Canada and used in many U.S. states under permit. These rules also do not incentivize innovation in multi-vehicle performance such as from platooning or use of dedicated truck highway lanes, as the metrics are primarily focused on individual vehicle measurements and analysis.

Market forces can be skewed by the unintended consequences of regulations. These can impact how the marketplace prioritizes and selects technology areas for innovation. An example of this is EPA GHG Phase 1 and California ARB rules which currently ignore containers and their carriers, Figure 36, as they technically are not legally defined as trailers [53][71][102]. This omission provides no regulatory incentive for improving containers and carriers. In fact, the omission tends to incentivize use of the containers over the regulated 53' van trailers, as the regulations have failed to level the playing field by requiring one to be SmartWay equipped and ignoring the other mode of on-highway freight transfer. Depending on price of fuel, cost of capital equipment, taxes, and many other factors, some operators may choose to operate containers in lieu of van trailers, effectively bypassing the regulators intentions.



Figure 36. Unintended consequences -containers are not trailers [14]

Another example of unintended consequences is use of SmartWay trailers combined with intermodal train transport as seen in Figure 37. The skirted trailers require extra care in loading on flat bed rail cars and the aerodynamic benefits intended for on-highway operations are not gained since the trailer is being hauled by train between major urban destinations, and likely sees only limited on-highway mileage for which the regulators expected the system to operate.



Figure 37. Unintended consequences -SmartWay trailers used on rail cars [14]

Legislation can also mislead the marketplace, emphasizing confusing metrics. An example is mandating aerodynamics for tractor/trailers as in California with implication that fuel savings projections apply to that one complete unit, when in practice, freight haulers operate with a ratio of trailers to tractors such that for a single tractor to attain its projected fuel economy, perhaps three or more trailers must be equipped with skirts. More challenging is that there is no guarantee which trailer will be mated to the tractor at any time such that attaining the stated fuel economy requires the entire tractor and trailer fleet to be equally equipped. Compounding this confusion further is that some trailers are used primarily for on-site warehouse storage and get few if any on-highway miles, yet rules may require they be configured with skirts [21][55]. Figure 38 emphasizes that while tractors may be in motion, many trailers are not.



Figure 38. MPG confusion in regulations - fuel economy estimates depend on tractor/trailer ratio and how trailers are actually used [14][21].

Regulations evolve from different groups in federal, state and local governments. These are not always synchronized efforts. This can impact the solution space available for the market to drive innovation. For example, the 55mph National Highway Speed Limit, when repealed in the 1990s led to many states adopting 65, 75, even 85 mph limits on some routes [21]. These increases in permissible state truck highway speeds were in parallel with implementing the EPA's federal rules focused on reducing fuel use and emissions, seemingly working at cross purposes.

A more recent example seen in 2014-2016 is the mandatory use of truck speed limiters and required settings proposed as new federal rules and sent to OMB in 2015 by DOT FMCSA and NHTSA. This is occurring in parallel with national review of the 2015 proposed EPA/NHTSA Phase 2 GHG rules [141][142]. The two rules inherently affect each other by impacting duty cycles used in savings projections and will affect applicability of technology choices that are speed related, yet there has been little public discussion of the ramifications each has on the other as they originate from different groups in the government.

Summary of Market Driven Fuel Economy Improvement

The natural forces inherent in the market place have played a significant role in the evolution of technology for improving fuel economy, and in demanding greater accuracy and precision in assessment. The new engineer should be open to the concept that market forces work in parallel with regulatory ones, helping describe the solution space for innovation and motivating continuous improvement in performance. Opportunities exist to better synchronize legislation with market forces to facilitate innovation while concurrently achieving regulatory needs.

Innovation in fuel economy and assessment requires investment in research and development. Significant government and industry focus on fuel economy and assessment methodology originates from the DOE 21st Century Truck Program (21st CTP) [42]. This “Government-Industry Partnership” began in 2000 as described in the Technology Roadmap for the 21st CTP as “a gathering of U.S. truck and supporting industries, concerned environmentalists, and federal agency representatives [42]. The program’s goals and research objectives are to:

- improve fuel efficiency
- reduce emissions
- enhance safety
- reduce total owning and operating costs
- maintain or enhance performance” [42]

The group recognized the complexity of these objectives stating “Making progress in each of these goals simultaneously is a major challenge. The federal government and the trucking and supporting industries will work actively together to develop a balanced portfolio of research aimed at achieving all these goals, coordinate their research activities as appropriate, and making effective use of the nation’s research universities and national laboratories. Proprietary research agreements between individual companies and federal agencies, which cannot be shared with industrial competitors, will continue to be appropriately funded” [42].

They further detailed specific system level objectives for the effort - “This research partnership will support research aimed at developing production prototype vehicles that achieve all of the following objectives:

- Improve fuel efficiency of heavy-duty trucks and buses, specifically, by 2010
 - double the Class 8 line-haul truck fuel efficiency on a ton-miles-per-gallon basis,
 - triple the Class 2b and 6 truck (delivery van) fuel efficiency on a ton-miles-per-gallon basis, and
 - triple the fuel efficiency of heavy-duty transit buses on a miles-per-gallon basis.

- Reduce emissions:
 - throughout the Program, meet prevailing standards for oxides of nitrogen, particulate matter, carbon monoxide, and hydrocarbons.
- Enhance safety:
 - In 1998, truck-related crashes resulted in 5,374 fatalities and 127,000 injuries. The U.S. Department of Transportation is committed to reducing truck-related fatalities by 50% by 2010. The 21st CTP will contribute to the goal of improving truck and bus safety by fostering advancements in vehicle design and performance.
- Enhance affordability:
 - maintain or enhance performance.

A central goal of this initiative is to develop cost-effective, heavy-duty vehicles for truck operators that are fully competitive in prevailing markets” [42].

The National Academy of Sciences has monitored and documented progress of the 21st CTP as an official program auditor for the U.S. government. The NAS has released three comprehensive progress reports in 2008, 2012 and 2015 [17][143][144]. Additionally, program participants have issued reports and done conference presentations over this period (for example, [43]). Combined, these provide a wealth of information for new engineers to mine on fuel economy, assessment and areas for innovation.

The program realized in their Roadmap that a systems engineering perspective was required with respect to performance, stating “Analysis of the truck as a system will allow a comprehensive evaluation of how the various components and subsystems relate and interact with each other, and how improvements in the efficiency of various components lead to overall efficiency improvement of the whole system. Synergisms among the various subsystems can be exploited so that the overall improvement can potentially be larger than the product of the improvements of the individual subsystems. Systems analysis will be used to investigate various technology pathways to achieving the aggressive goals of the 21st CTP and to provide guidance in the direction of R&D” [42].

A major accomplishment of this effort is raised awareness that fuel economy and freight efficiency are context sensitive metrics. In the initial Roadmap, the heavy truck fuel economy and freight efficiency objective was clarified as “The goal of the 21st CTP with respect to Class 8 trucks is to develop, by 2010, enabling technology for line-haul trucks that (1) will have a fuel efficiency of 2× ton-mpg at 65 mph, fully loaded on a level road, and (2) will meet prevailing emission standards using petroleum-based diesel fuel.” [42].

This restatement of the program goal of “double the Class 8 line-haul truck fuel efficiency on a ton-miles-per-gallon basis” expanded to specify a constant speed of 65mph, requiring level road, stating freight conditions that the vehicle is fully loaded defined as 80,000 lb

Gross Vehicle Weight and that the future truck would meet the prevailing emissions standards using petroleum based fuel. Additionally, the Roadmap states “Highway” driving has been approximated as steady-speed interstate driving at 65 and 70 mph. Grades and speed variations due to traffic have been ignored.” Over time, the research spawned by the 21st CTP and parallel commercial and other government and private efforts have highlighted a number of significant additional details, contexts, tradeoffs and perspectives are needed to accurately set goals for fuel economy.

In no particular order, missing from this early definition is clarification of the baseline comparison vehicles actual configurations and functionality, environmental conditions, vehicle age/mileage used for testing, what specific test specification and version was to be used, whether straight road or some percentage of flat curves, how flat is the road, etc. etc. The “flat road” objective seems to eliminate banked oval tracks and many highway segments. No definition of the freight weight, only GVW.

While they foresaw that emission requirements were evolving such that a future vehicle would have different emissions requirements, they did not specifically address in fuel economy assessment that the composition and chemistry of the fuel itself would actually change so that fuel used in a baseline vehicle would be different than that used in a future vehicle, although they did recognize EPA had plans in place that would impact the fuel sulfur content and that would impact engine designs. They did not forecast any need to value DEF use as part of fuel economy evaluations, although they foresaw SCR Engines were one of the future technologies in prime consideration to meet emissions standards. No adjustment in fuel economy assessment was discussed due to adding equipment for future emissions requirements [42]. The objectives also focused on petroleum based energy to the exclusion of alternatives.

The Roadmap highlighted technologies to improve safety. As with emissions requirements that introduced new fuel, DEF and SCR engines, the Safety technologies were not addressed in terms of their impact to making fuel economy comparisons between baseline and future vehicles. For example, no adjustment in fuel economy was discussed due to adding equipment due to future revised safety requirements. Conversely, they did clarify that “no safety performance measure would be reduced as a result of design changes related to energy savings” [42].

These omissions and oversights with regards to emissions and safety requirements that fundamentally change the baseline definition of a vehicle are factors in actual vehicle fuel economy comparisons, but this initial Roadmap had yet to include them as factors. The Program surfaced these types of issues over time. One example where the Program clarified focus over time is stating the fuel efficiency in terms of a “fully loaded” unit at 80,000 lb GVW. The 2015 NAS third progress report on the 21st CTP showed an actual fleet bimodal weight distribution in Figure 39, highlighting that each vehicle may differ substantially in freight and that only a small percentage of vehicles actually operate at the max 80,000 lb GVW [17].

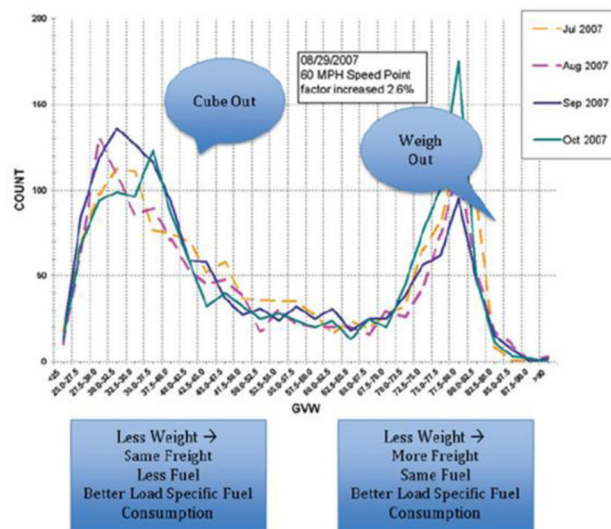


Figure 39. Bimodal distribution of truck gross vehicle weight for five axle vehicles from Weigh-in-Motion data (source Quinley) [17]*.

The NAS published two similar vehicle actual weight graphs in their 2010 report Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles shown in Figures 40 and 41 [9].

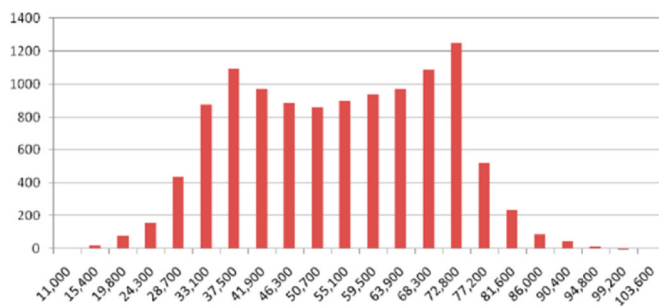


Figure 40. Truck weight distribution from 2008 weigh-in-motion (New West Technologies) [9]*.

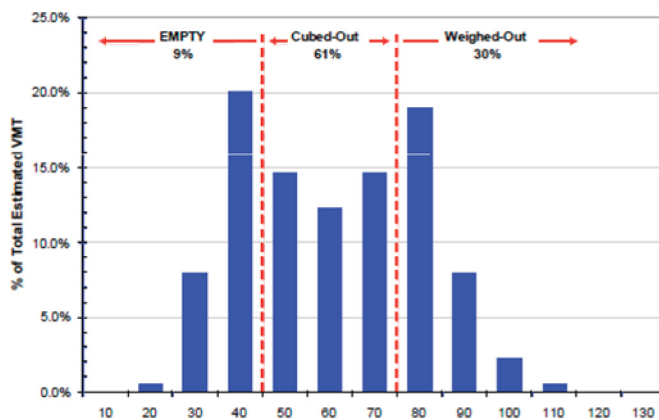


Figure 41. Truck weight distribution from 2009 (M.J. Bradley & Associates) [9]*.

These three vehicle weight graphs came into the fuel economy body of knowledge as a result of the 21st CTP and parallel government and industry efforts to better understand fuel economy and its relationship of weight centered on U.S. Census Bureau voluntary survey.

information in the periodic Vehicle Inventory & Use Survey (VIUS) that ceased in 2002 [9]. Fuel economy and freight efficiency are both tied directly to weight. This data has been beneficial to industry in applying controlled fuel economy assessment results to real world operations. Some fuel economy test methods were revised from 80,000 lb to lower weights to more closely reflect real world distributions, such as the target weight for the DOE SuperTruck Program as representative [41]. NAS reported that tests by NESCCA/ICCT in 2009 showed a 65,000 lb GVW tractor/trailer had 5.96 mpg in an on-highway duty cycle with some grade change. When run at 80,000 lb GVW, the unit had 5.4 mpg. The NAS listed several reported results for weight sensitivity for fuel economy varying from 0.1% per 1000 lb to 2.4% depending on grades, speeds, traffic, etc. [9]. In the same time period, TMC in RP 1112 used 0.0375 mpg per 1,000 lb [145]. Publication of these details and differences benefit industry by better quantifying relationships to fuel economy and highlighting opportunity to clarify and improve methods and guides.

As a starting point, the 21st CTP Roadmap team did an admirable job extensively documenting the current state of technology, future challenges, and outlining paths to success to achieve their desired doubling of freight efficiency by 2010 goal. This foundational work greatly reinforced future efforts to identify and improve understanding of fuel economy and assessment. The more open environment fostered by the 21st CTP team members, shown in Figure 42, greatly facilitated subsequent public dissemination of test information, active discussion of results and identification of opportunities for improvement in fuel economy assessment [144]. Figure 42 could be expanded to include the extended NGO and other parties that have cited 21st CTP program data in producing additional studies and reports. This spectrum of participants and extended parties has provided the public with a diversity of information and perspectives fundamental to improving discourse on fuel economy and assessment science.

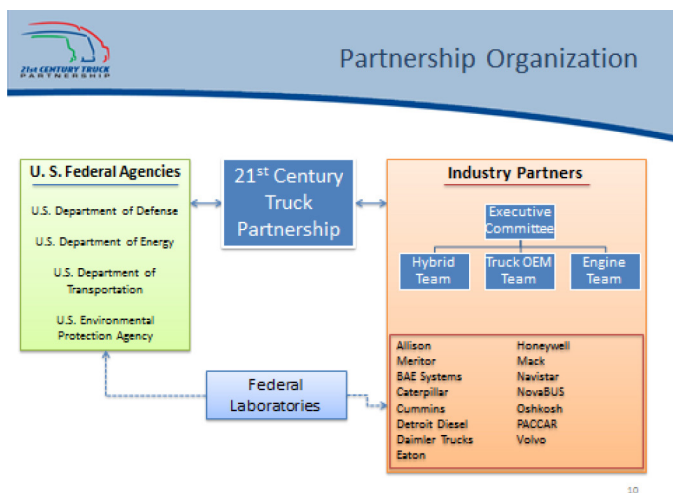


Figure 42. 21st CTP team members and structure [144]*.

The 21st CTP created the foundation for the 2009 Department of Energy SuperTruck program. It has served as one outlet for reporting progress on fuel economy improvement technology and assessment methods [41][143][144]. This SuperTruck program, as discussed in a later section, has provided an outlet for OEMs to demonstrate the feasibility of significantly improved technology and assessment methods through the various successful program prototypes between 2009 and 2016.

The 21st CTP is providing similar utility to the Phase II SuperTruck efforts announced in 2016 [146].

The 21st CTP has brought together OEM and supplier competitors, regulators, laboratories, independent researchers, NGOs covering a broad range of interests, and the public helping to improve the credibility, depth and applicability of heavy truck vehicle fuel economy research over a 15 year period. It promises to continue to do so in the future.

Challenges Moving Forward

A challenge facing the 21st CTP program is to maintain a sense of relevance to society and the heavy truck marketplace. The program constantly faces the task of culling out technologies and efforts that have demonstrated diminishing returns. The program team needs to concentrate research on significant new opportunities and support innovation, not just in technology itself, but in the bureaucratic realm of regulations and standards development. These two areas can move at seemingly glacial speeds with respect to prioritizing opportunities. An example reported by John Woodrooffe at the 2015 Commercial Vehicle Outlook Conference, Figure 43, and by Rick Mihelic in 2015 at the SAE COMVEC Aerodynamics Plenary, as illustrated in Figure 44, by ships, planes and trains is the lack of any significant progress increasing the freight carried per heavy truck vehicle. This utilization factor has not changed significantly since the Surface Transportation Assistance Act STAA of 1982 [147][148]. Other modes of freight transport have successfully improved the freight carried per vehicle and freight carried per crew over the decades, where U.S. trucking has seen no significant change.

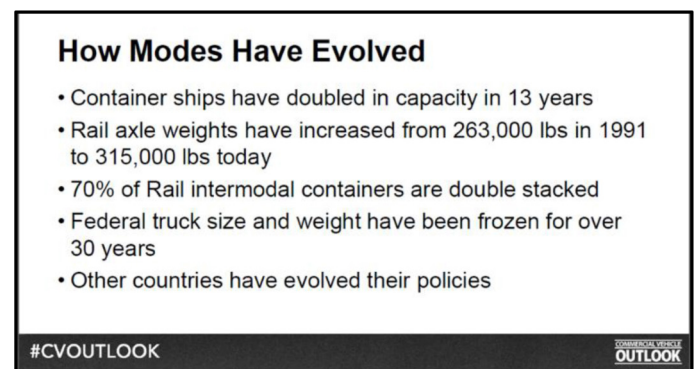


Figure 43. Freight utilization improvement by mode - Woodrooffe [144].

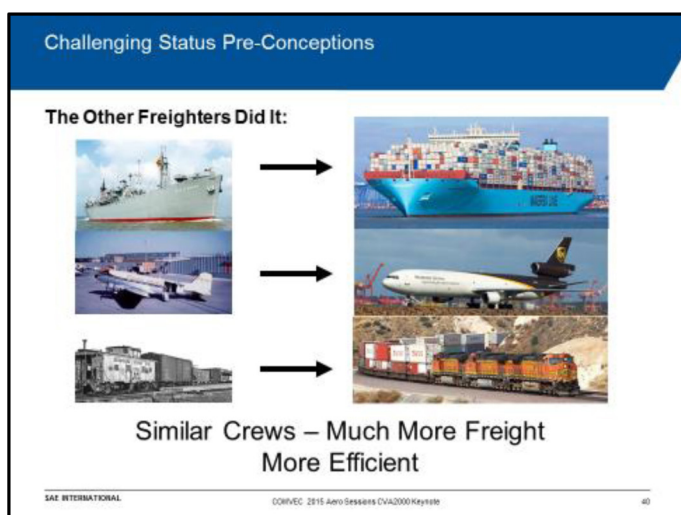


Figure 44. Freight efficiency per vehicle increases - Mihelic [144].

The 21st CTP was notified by NAS in the 2012 21st CTP progress review that “Some very large fuel savings are possible if regulatory barriers to the appropriate use of HPVs (High Productivity Vehicles) are removed” [144]. NAS highlighted finding for 21st CTP that “High-productivity vehicles, known as HPVs or LCVs, as currently configured and using current technology, can reduce fuel consumption by up to 28 percent. In addition, HPVs can reduce greenhouse gas emissions, truck vehicle miles traveled, congestion, shipper costs, truck highway accidents, road damage, and truck driver shortages.” NAS lamented that “As far as the committee can determine, no action on the (recommendations) has been considered by Congress” [144].

The review by the Federal Highway Administration of the national vehicle size and weight standards requested by Congress under the “Moving Ahead for Progress in the 21st Century Act” (MAP-21) effort, made no recommendations on LCV’s, stating “Several configurations not selected by DOT for inclusion in the MAP-21 study were of significant interest to stakeholders. Configurations of interest to stakeholders, but not assessed in this study, include Longer Combination Vehicles (LCV) such as the Rocky Mountain doubles (48’ trailer and 28’ trailer) and turnpike doubles (twin 48’ trailers); short-wheelbase trucks (dump trucks, concrete mixers, etc.); and specialized equipment. Some of these configurations have been examined in past studies and would be worthy of consideration in future work as the impacts are likely to vary noticeably from those of truck configurations considered in this Study.” The DOT made no recommendations, stating “The Study was designed to be responsive to the requirements of Section 32801 of MAP-21 but did not seek to satisfy the policy question as to whether a change in allowable truck sizes or weights would yield positive impacts that could outweigh negative impacts.” [149][150].

The Rocky Mountain Institute highlighted in a 2008 whitepaper the potential for LCV’s to significantly improve freight efficiency and reduce industry fuel use concluding LCV’s “...require new regulations for longer, heavier, but safer and less road-wearing Long

Combination Vehicles that could raise individual-vehicle ton-miles per gallon to 335, while reducing the number of trucks on the road by roughly 30% versus our baseline in a fleet scenario” [151].

Data from Idaho, Oregon and Canada on actual LCV operations show benefits and provide data on effects to infrastructure and safety. Mihelic summarized factors which differ between running two 53’ tractor/trailer units individually versus running one tractor pulling two 53’ trailers in Figure 45 and SAE paper, 2015-01-2897, Aerodynamic Comparison of Tractor-Trailer Platooning and A-Train Configuration [46]. The qualitative evaluation on these factors highlights advantages for the LCV, while the aerodynamic drag evaluation confirms net drag reduction for the double versus even platooning units. For example the National Research Council of Canada, NRC, stated from a 2012 study that one LCV burns approximately 23,200 fewer litres (6,129 gal) of fuel compared to two conventional vehicles operating the same distances and speeds [46].

Possible Comparison Factors		
- Equivalent Freight Weight and Delivery Route - Number of Tractors - Number of Tires and Axles - Number of Drivers - Net Tractor Mileage - Maintenance - Yard Time - Insurance - Taxes - Available Technology - Compliant Regulations - Driver Availability - Driver Training - Emissions - Fuel & Def - Service Items - Down Time - Safety - Etc. Etc.		
Net Capital	More	Less
Net Operating Costs	More	Less

Figure 45. Advantages to LCV double trailer use [46]*.

The improvement in freight carried per unit is a clear opportunity area for the 21st CTP to challenge the status quo and support innovation in the regulatory arena, not just the technical one.

Summary of 21st Century Truck Program

The 21st CTP built a constructive consortium of manufacturers, fleets and government agencies for the purposes of improving economic and environmental impacts of freight hauling in the U.S. The 21st CTP encouraged open sharing of fuel economy research for the benefit of the entire industry, overcoming to some extent the commercial tendency to keep this type of information proprietary. The consortium has provided a forum for cross fertilization of ideas that has benefitted the science of fuel economy assessment. The effort has sponsored valuable dialogue between competitors where none may have existed and created repositories of valuable science. The effort has provided an avenue for significant funding of research in fuel economy by both government and industry groups. The 21st CTP provides vision to research programs. It is in this role that future 21st CTP directions need to expand to include not only technology innovation, but a focus on opportunities for regulatory innovation that can take advantage of existing technologies to dramatically improve freight efficiency performance.

THE SMARTWAY PROGRAM

As the 21st CTP was ramping up, and EPA's 2002 and 2004 emissions rules were coming into play on engines, government and industry realized that tractor engine emissions and fuel efficiency improvements alone would limit improvement potential. While the tractor held the fuel and engine, it alone was only a portion of the fuel economy opportunity. At between 16,000 lb and 20,000 lb, the tractor represented perhaps 1/3rd to 1/4th of the vehicle weight. The tractors 10 wheels represented simplistically 55% of the tire rolling resistance drag. The tractor represented approximately 10% of the vehicle length and its portion of vehicle surface area is even less. While the tractor is the critical leading edge of the vehicle and does have a significant role on overall aerodynamic drag, as aerodynamic tractors became more refined, it became clear that performance of the ubiquitous 53' van trailer also needed to be addressed for the entire system to make aerodynamic improvements. The 2000 21st CTP Road Map energy audit, shown in Figure 46, highlights the Pareto rank ordering for energy use improvement opportunities [42].

- Engine Losses - 240 kW/h
- Aerodynamic Losses - 85 kW/h
- Rolling Resistance - 51 kW/h
- Auxiliary Loads - 15 kW/h
- Drivetrain - 9 kW/h

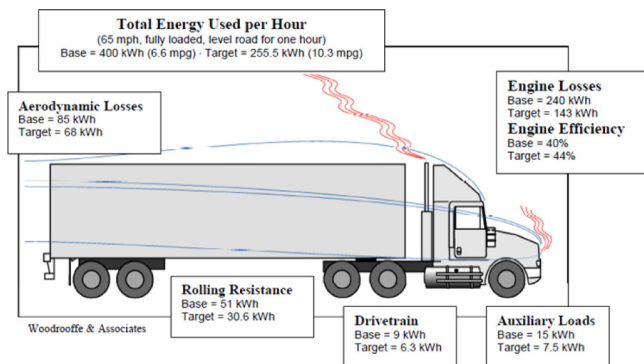


Figure 46. 21st CTP Road Map energy audit [42]*.

Per EPA, "EPA first engaged with industry stakeholders in 2001 to explore ideas for a new, public-private collaboration focused specifically on the freight sector and goods movement. Discussions centered on developing a voluntary, market based initiative that would achieve multiple goals: (1) Reduce harmful greenhouse gas emissions and other pollutants from goods movement by; (2) Accelerate the adoption of fuel and cost saving technologies and strategies; (3) Create recognition and visibility for freight sustainability achievements by industry leaders; and (4) Enhance the working relationship between EPA and the transportation sector. Working closely with the American Trucking Associations and Business for Social Responsibility, a Charter Partner group of business leaders was created in 2003 to kick off this effort. These 15 Charter Partners advised EPA on the creation of SmartWay, including the development of the partnership structure and program design, the performance benchmarking tools and methods, technologies and best

practices, and the SmartWay brand. Other companies were invited to participate and the program was launched on February 9, 2004 with 50 Partners from the trucking, rail and shipper sectors" [152].

The SmartWay Program deployed in 2005 a Technology Verification program adapting SAE J1321 Fuel Economy methods. The Program identified the attributes of a fuel efficient heavy truck and now included 53 foot van trailer recommendations.

The initial program defined the basic specifications for a U.S. EPA Certified SmartWay tractor:

- "Model Year 2007 or later engine;
- Integrated cab-high roof fairing;
- Tractor-mounted side fairing gap reducers;
- Tractor fuel-tank side fairings;
- Aerodynamic bumper and mirrors;
- Options for eliminating periods of extended engine idling (auxiliary power units, auxiliary cooling units, battery pack with start/stop system, bunk heater units); and
- Options for low-rolling resistance tires (single wide or dual) mounted on aluminum wheels" [153].

The initial Program defined the basic specifications for a U.S. EPA Certified SmartWay trailer stating "New long-haul van trailers can be ordered, and existing trailers can be upgraded, to qualify as a U.S. EPA Certified SmartWay trailer provided that they are equipped with:

- Side skirts;
- Weight-saving technologies;
- Gap reducer on the front or trailer tails (either extenders or boat tails); and
- Options for low-rolling resistance tires (single wide or dual) mounted on aluminum wheels" [153].

OEMs provided EPA with the definition of the initial SmartWay approved tractor models. EPA provided two methods for dealing with future new models either as a "replacement" for a current SmartWay vehicle or as an "addition". A "replacement" must be proven to be equal to or better than the current product. There was allowed a phase in period where both could be offered. An "addition" could be made for a new model, but the new model must have been proven better than the company's best current SmartWay model.

Over time, EPA SmartWay has refined test protocols, and evolved requirements based on new product introductions, experience, market feedback, and industry research and evaluation, for example SAE updated the SAE J1252, J1321, J1526, J2966, J2971 and other procedures [77][72][73][76][75].

EPA SmartWay, from its inception, has been a voluntary, market based effort. To entice involvement by OEMs and Fleets, SmartWay participation has been marketed as an OEM product and fleet differentiator as described in 2010 by Cheryl Bynum in Figure 47 [154]. As such, a significant element of SmartWay is its marketing, with extensive advertising ramifications for the government, fleets

and OEMs. Fleet participants in the SmartWay program have significant record keeping and reporting requirements to maintain or improve their SmartWay standing. EPA stated in 2014 “To encourage continuous improvement in freight efficiency, SmartWay provides incentives and recognition for top performers, including use of the SmartWay brand as a mark of cleaner more sustainable transportation, and an annual awards program. SmartWay’s three-thousand partners include large and small firms, dozens of Fortune 500 companies and represent major economic sectors such as retail, food & beverage, manufacturing, chemicals, paper & lumber, consumer goods, and others. Since 2004, SmartWay partners have eliminated over 51 million metric tons of CO₂, saved over 120 million barrels of oil and \$16 billion in fuel costs, and reduced 738,000 tons of NOx and 37,000 tons of PM” [152].

How Does The Partnership Work?

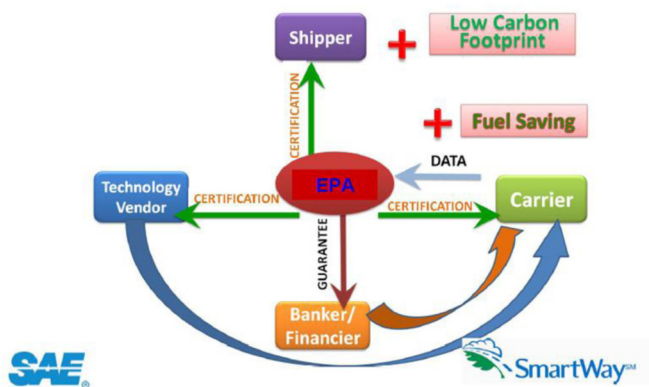


Figure 47. EPA SmartWay partnership overview [154].

As a publicly funded effort through Congress, EPA must appeal to congressional and administration EPA budget managers, and ultimately the U.S. tax payers including freight operators, so positive image and on-going beneficial results are important to the program’s future. As with voluntary market-based efforts, SmartWay, since its inception in 2004, has had to demonstrate to its various stake holders a return on investment to the country.

EPA SmartWay has migrated from voluntary program to a mandated-by-regulation one in California and aspects of the program may be part of future EPA Green House Gas Phase 2 regulations and other U.S. and Canadian state, province and federal rules, as discussed in later sections of this paper.

Major Accomplishments

A fundamental of continuous improvement in business and engineering is that improvement requires a measurement system, an ability to gauge progress in quantifiable terms.

Prior to 2004, there were no common, publicly accessible databases on heavy truck fuel economy performance. OEMs had their own proprietary data on their own products versus competitors. These could be used selectively in proprietary discussions with potential customers and occasionally surfaced in media. Publicly traded fleets might report data in financial reports that provided aggregated fuel

economy performance. Internally, they had proprietary data from their own evaluations, both quantitative and qualitative. This information might occasionally surface in media reporting.

What information was available in public lacked broad consensus on credibility to permit comparison across similar product lines [17][42]. The joint public/private SmartWay effort has evolved at a national level as the de facto industry benchmark ranking system for fuel economy improvement potential.

While there are proponents and detractors of SmartWay testing methods, the industry has transitioned from 2003’s not having a national truck fuel economy performance ranking system, to current discussion of how best to improve the existing SmartWay one to be more representative of real world [152].

SmartWay initially had a simple bidirectional ranking system - tractors and trailers were either SmartWay, or not. Technology such as tires, APU’s, etc. were either SmartWay or not. Aerodynamic devices for trailer’s could be added in multiple ways, the combinations were essentially worse, good, and better, presented as 0, X or Y% improvement per SmartWay’s interpretation of vendor supplied test data and SmartWay’s methodologies.

This fledgling ranking system required a level of test data to be provided to EPA, and EPA acceptance of it. While initial SmartWay tractors had to meet attribute based configuration requirements grandfathered into the program as a necessary starting point, subsequent vehicles had to provide OEM test data and analyses. Fleets that used the EPA approved technologies in the prescribed manner were designated as SmartWay compliant.

In the process of evolving since 2004, the EPA SmartWay Program has become in effect a national certification agency with responsibility for publication and maintenance of common evaluation methodology. The program has assumed authority and industry has effectively ceded it to them to certify, or more recently, “designate” configurations and performance to minimum levels. Fleets reporting under SmartWay have shared performance details to a national database that permit a level of common company performance evaluation.

2015 and 2016 have seen EPA SmartWay introduce improved methods migrating away from attribute based evaluations to measurement based ones. SmartWay has also added greater granularity in ranking technologies. 2010’s codification of SmartWay in California regulations has added to EPA’s implicit ownership of this national performance ranking system, since California trailers migrate beyond their border in national fleet operations. EPA’s role has evolved into a national moderator for performance assessment discussion.

Evaluating metrics like fuel economy progress requires standardized measurement systems. EPA’s SmartWay Program has made substantial progress in establishing a national performance ranking system where none previously existed. Its existence permits the forces of continuous improvement to work, educating, refining methods, procedures, definitions and application of the system for public use.