UMTRI-2014-27 NOVEMBER 2014

Reducing Truck Fuel Use and Emissions: Tires, Aerodynamics, Engine Efficiency, and Size and Weight Regulations

John Woodrooffe

UMTRI
University of Michigan
Transportation Research Institute

REDUCING TRUCK FUEL USE AND EMISSIONS: TIRES, AERODYNAMICS, ENGINE EFFICIENCY, AND SIZE AND WEIGHT REGULATIONS

John Woodrooffe

The University of Michigan
Transportation Research Institute
Ann Arbor, Michigan 48109-2150
U.S.A.

Report No. UMTRI-2014-27
November 2014

Technical Report Documentation Page

1. Report No. UMTRI-2014-27	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Reducing Truck Fuel Use and Emissions: Tires, Aerodynamics, Engine Efficiency, and Size and Weight Regulations		5. Report Date November 2014 6. Performing Organization Code 383818
7. Author(s) John Woodrooffe		8. Performing Organization Report No. UMTRI-2014-27
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute 2901 Baxter Road Ann Arbor, Michigan 48109-2150 U.S.A.		10. Work Unit no. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address The University of Michigan Sustainable Worldwide Transportation		13. Type of Report and Period Covered 14. Sponsoring Agency Code

15. Supplementary Notes
Information about Sustainable Worldwide Transportation is available at http://www.umich.edu/~umtriswt.

16. Abstract

This report explores ways in which the properties of trucks and regulations governing them might be modified to improve freight efficiency and reduce fuel use and emissions in the challenging world of transportation economics and environmental stewardship.

Trucks are the dominant mode of non-bulk commodity freight transport in the U.S. Compared to all other modes combined (rail + water + air + pipelines), trucks transport approximately twice the amount of freight by weight and approximately 1.8 times the amount of freight by value. Trucking has the most extensive distribution network of any transport mode, having access to over 3.9 million miles of roadways. Improvements in truck freight efficiency can be expected to show direct improvement of the nation's overall transportation system.

This study has identified four key focus areas that influence truck and truck freight efficiency.

1. Tire rolling resistance
2. Aerodynamics
3. Engine efficiency
4. Truck size and weight regulation

Each of the four focus areas are discussed in terms of past and present performance, along with projections to the future.

The final section of the report presents estimated potential realistic improvements for each of the four key focus areas, as well as the respective levels of technical challenge.

17. Key Words			18. Distribution Statement
Commercial vehicle, truck, fuel consumption, CO2 emissions, engine efficiency, tire rolling resistance, aerodynamics, size and weight regulations, societal value, sustainability			Unlimited
19. Security Classification (of this report) None	20. Security Classification (of this page) None	21. No. of Pages 39	22. Price

Contents

Introduction

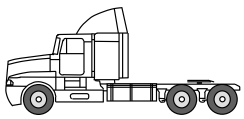
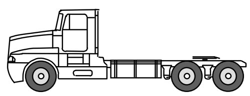
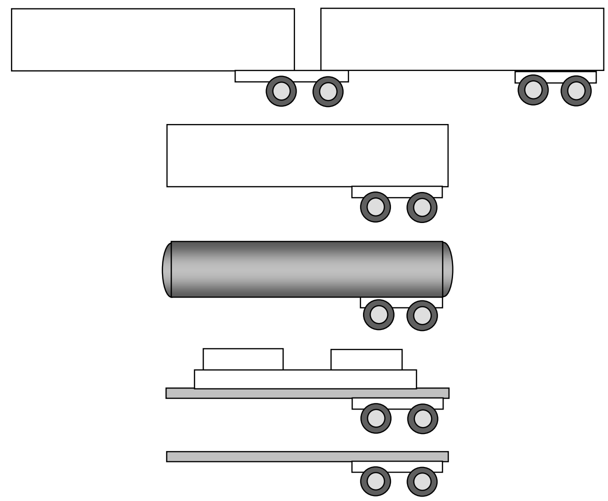
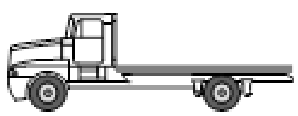
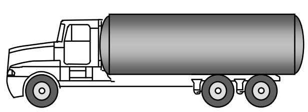
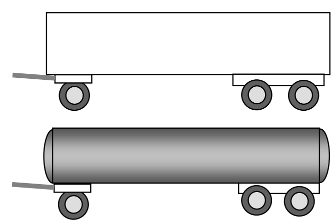
Trucks are hard to love. They are not sleek and stylish like passenger cars where emotion plays a big part in purchase decisions. Trucks are figuratively hewers of wood and drawers of water for society. They bring us food, shelter, clothing, all manner of items–even our cellphones, and they ask very little in return. Yet trucks are the Rodney Dangerfield of transportation modes–"they get no respect." Borrowing from an old Dangerfield gem, "a truck tells his psychiatrist that everyone hates him. The Doc says 'don't be ridiculous - everyone hasn't met you yet.'"

Perhaps this is the core of the problem. Too few people have been lucky enough to meet and understand trucks sufficiently to realize how important they are to our country, our economy, our society and the world at large. This report is intended to foster a deeper understanding of trucks so that the reader may more fully appreciate trucks for what they are, how they operate, and how we might reshape them so that they can realize their full potential in the very challenging world of transportation economics and environmental stewardship.

Background

Trucks are tools of industry and society. Their design is optimized for specific tasks requiring a truck manufacturing industry that is highly flexible and accommodating in terms of vehicle customization. For a given truck model, the purchaser can specify such basic attributes as wheelbase, the number of axles, the engine size, transmission characteristics, differential gear ratios, suspensions, the type of brake system, and cab features such as with and without sleepers. In this respect, when referring to a particular highway truck make and model, there can be no expectation of vehicle uniformity. This is very different from how passenger cars are characterized in the marketplace. To complicate things further, as illustrated in Table 1, trucks pull trailers of various shapes and sizes, which alter the total vehicle characteristic. These articulated vehicles are referred to as vehicle combinations.

Table 1
Illustration of a sample Class 8 truck and tractor with trailer combinations.

Power unit options	Cargo shape
 Long haul tractor with sleeper  Flat deck tractor	
 Flatbed truck  Tank truck	

Defining Truck Transportation Efficiency

Heavy truck fuel efficiency and emissions are influenced by several factors including vehicle design, vehicle size and weight regulation, zone of operation, driver technique and weather factors. Extending the definition of fuel efficiency to include a productivity measure such as "ton-mile of payload transported" presents a meaningful method for addressing the functional efficiency of the vehicle. The following list defines characteristics of commercial freight vehicles within the context of efficiency.

1. Commercial vehicles (trucks) exist to do work. Their worth and function are tied directly to tasks performed in exchange for money. (Very different from passenger cars.)

2. The tasks that commercial vehicles perform are highly varied. Trucks are purposefully designed to maximize their usefulness for a specific cargo or task. For example the tractor and trailer design will be very different if the task is to transport potato chips versus beer. The intended area of operation (e.g. movement of goods between cities or within urban areas) will also influence vehicle design.

3. Generally, competitive forces within the transport industry provide strong incentives to be reliable and efficient particularly with respect to fuel use and transport logistics.

4. Freight tasks vary, as do the weight and shape of cargo transported; therefore vehicles can change shape and weight significantly throughout a given day of work. (Very different from passenger cars.)

5. Tractor semi-trailers are the most common, large, commercial vehicle travelling the Interstate. The most frequently used semi-trailer is the van trailer, which is built to standard height and width dimensions. Most semi-trailers are 53 ft (16.2 m) long, but there are many 28 ft (8.5 m) long trailers used for double- and triple-trailer configurations. Semi-trailers are often owned by a third party, not necessarily by the company that owns the tractor. In general, there are approximately three trailers for every highway tractor.

6. Truck cargo can be volume limited or mass limited depending on the nature of goods transported. Volume-limited freight tends to be lower density, such as potato chips, whereby the cubic capacity of the trailer is fully occupied before the allowable gross vehicle weight (GVW) is reached. Mass-limited freight is higher density cargo such as heavy building materials resulting in the GVW being reached before the cubic capacity of the trailer is fully occupied. The distinction is important, as volume-limited freight efficiency benefits from longer or multiple trailers, while mass-limited fright benefits from higher allowable GVW through the use of more axles on the vehicle.

The Numbers

Federal Motor Carrier Safety Administration provides statistics on commercial vehicles. The 2014 Pocket Guide to Large Truck and Bus Statistics reports that as of December 2013 there were 539,033 motor carriers with recent activity operating in the U.S. There are 10,659,380 large commercial trucks (greater than 10,000 lb or 4,545 kg) in operation, collectively travelling approximately 268 billion miles annually. Of these, 8,190,286 were single-unit trucks and 2,469,286 were combination trucks (tractor semitrailers).

The U.S. Department of Transportation, Federal Highway Administration oversees the national highway system and provides data on all manner of transportation activity and infrastructure details (roads and bridges).

As shown in Table 2, the public road system is by far the most dominant infrastructure asset within the U.S. The public road distance is roughly 30 times that of railroads and 360 times greater than navigable channels of the inland waterways system. If we compare National Highway System (NHS) roads with Class 1 railway infrastructure, the road network is 1.7 times greater. These data suggest that NHS roads and rail "main line" networks are more closely aligned in terms of miles of infrastructure than are secondary and tertiary routes, which are dominated by roads. The ability to access these diverse secondary and tertiary roads makes trucking an attractive mode of transportation particularly with respect to the final destination of freight.

Table 2
Miles of infrastructure in the U.S. by transportation mode: 2011 (DOT, 2014).

Infrastructure Category	Miles
Public roads, route miles	**3,929,425**
National Highway System (NHS)	163,741
Interstates	46,960
Other NHS	116,781
Other	3,765,684
Strategic Highway Corridor Network (STRAHNET)[1]	63,887
Interstate	46,960
Non-Interstate	16,927
Railroad[2]	**138,518**
Class I	95,387
Regional	10,355
Local	32,776
Inland waterways	
Navigable channels	11,000
Great Lakes-St. Lawrence Seaway	2,342
Pipelines	
Oil	178,809
Gas	1,563,527

1. The Strategic Highway Corridor Network (STRAHNET) is the total minimum public highway network necessary to support deployment needs of the U.S. Department of Defense.
2. Class I railroads have annual carrier operating revenue of $433.2 million or more. Regional (Class II) railroads have annual carrier operating revenue greater than $20.5 million and less than $433.2 million. Local (Class III) railroads have annual carrier operating revenue below $20.5 million.

Table 3 compares the total annual weight of shipment by transport mode. In 2012, trucks transported a total of 13,182 million tons of cargo compared with 2,018 tons by rail. Trucks transported approximately 6.5 times the amount of cargo by weight than railways. Compared to all other modes combined, trucks transport approximately twice the amount of freight by weight. However, considering freight movements on a weight distance metric, the ranking is rail 39.5%, truck 28.6%, pipeline 19.6%, water 12.0%, air

0.3%. This metric of freight transport illustrates that rail is very effective in long distance freight haulage for commodities such as grain and coal in rail cars and consumer goods in containers or truck semitrailers called intermodal traffic (FRA, 2014).

Table 3
Weight of shipments by transportation mode: 2012 (DOT, 2014).

Mode	Millions of tons			
	Total	Domestic	Exports[2]	Imports[2]
Total	19,662	17,523	901	1,238
Truck	13,182	12,973	118	92
Rail	2,018	1,855	82	82
Water	975	542	95	338
Air, air & truck	15	3	5	7
Multiple modes & mail[1]	1,588	453	540	595
Pipeline[1]	1,546	1,421	13	112
Other & unknown	338	277	47	14

1. 2007 total and domestic numbers for the multiple modes & mail and the pipeline categories were revised as a result of Freight Analysis Framework database.
2. Data do not include imports and exports that pass through the United States from a foreign origin to a foreign destination by any mode.

Table 4 examines the total annual value of goods shipped by various modes during the year 2012. Trucks moved goods valued at $11,130 billion compared with $551 billion by rail, which means that trucks move 20 times more goods by value than rail. Compared to all other modes combined (rail + water + air + pipelines), trucks transport approximately 1.8 times the amount of freight by value.

The large difference between the weight of goods shipped and the value of goods shipped by truck and rail mode is likely tied to the fact that railways are very good at moving large quantities of dense raw materials long distances, which often are transported from the extraction source or centralized bulk storage facilities to ports and primary manufacturing plants. Trucks, on the other hand, tend to be best at taking the finished products from factories and delivering them to a widely dispersed set of destinations facilitated by the extensive secondary and tertiary road network.

Table 4
Value of shipments by transportation mode: 2012 (DOT, 2014).

Mode	Billions of 2007 dollars			
	Total	Domestic	Exports[2]	Imports[2]
Total	17,352	13,927	1,392	2,033
Truck	11,130	10,531	309	289
Rail	551	400	55	96
Water	339	170	21	148
Air, air & truck	1,182	163	470	549
Multiple modes	3,023	1,697	478	848
Pipeline[1]	768	699	9	61
Other & unknown	359	267	51	41

The data above clearly show that trucks perform a dominant role in non-bulk commodity freight transportation within the U.S., and the ability for trucks to travel on the existing road system makes them indispensable. No other mode of transportation matches or exceeds the amount of freight moved by trucks in terms of weight or value. It follows, therefore, that future solutions for substantive transportation improvement will need to consider improvements in truck transportation efficiency given their dominant role in the transportation network.

Energy Use

Examining the recent past and projecting forward, global transportation consumed about 43 million barrels of fuel per day in 2005, or about 52 percent of the total liquid fuels consumed. As shown in Figure 1, by 2030 the share of liquid fuels estimated to be consumed for transportation is expected to rise to 60 percent, while the share consumed by others sectors is expected to fall marginally (EIA, 2011).

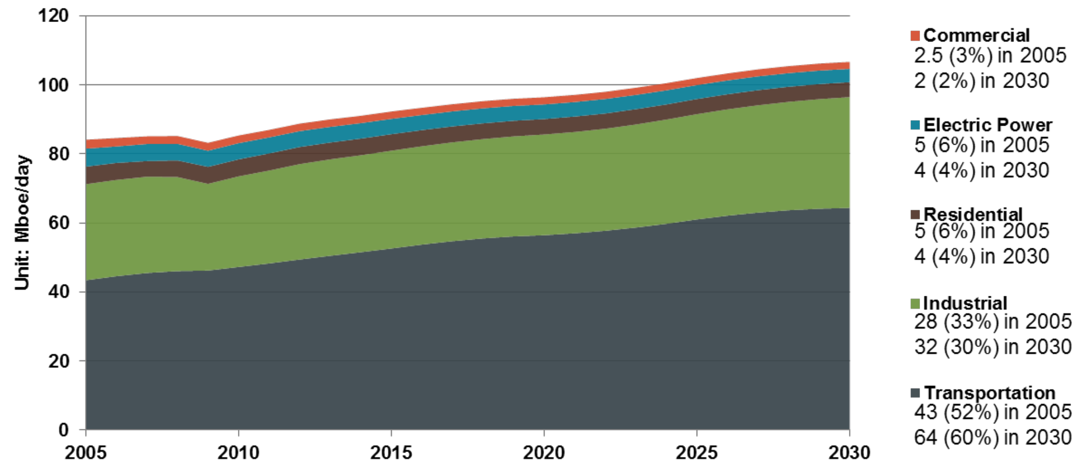


Figure 1. Consumption of liquid fuels by sector (ICCT, 2014).

Considering the amount of energy used in the transportation sector by mode or vehicle type, Figure 2 shows that fuel consumption by all modes is growing, and that light-duty vehicles (LVD) and trucks combined consume 66 percent of energy used for transportation (average share over the 30 year period 2000 to 2030) (ICCT, 2014).

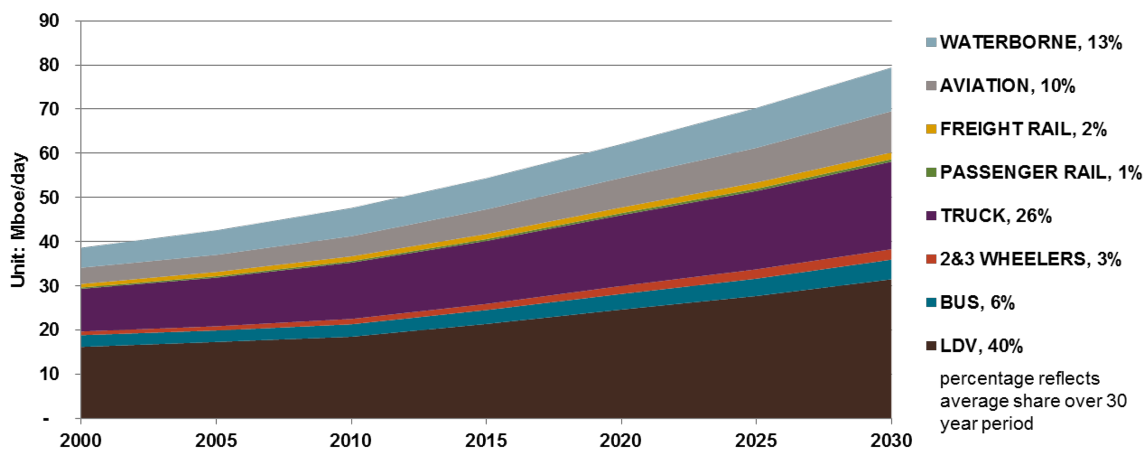


Figure 2. Share of energy consumption by transportation mode (vehicle sector) (ICCT, 2014).

In order to influence improvements in fuel consumption and reduction in emissions, the U.S. enacted "Greenhouse Gas Emissions Standards and Fuel Efficiency

Standards for Medium- and Heavy-Duty Engines and Vehicles” in 2011 (EPA/NHTSA, 2011). The standard addressed both fuel use and greenhouse gas (GHG) emissions related to medium- and heavy-duty trucks. The complementary EPA and NHTSA standards that make up the Heavy-Duty National Program apply to combination tractors (semi-trucks), heavy-duty pickup trucks and vans, and vocational vehicles (including buses and refuse or utility trucks).

The standard has special consideration for heavy-duty combination tractors (highway tractors) that have various roof heights classified as low, mid, and high roof. Roof height is tied to the type of trucking operation or trailer type that a given tractor is connected to. For example, a high roof tractor would most likely be coupled to a van (box) trailer, while a low roof would be connected to a flatbed trailer. The differentiation of roof height influences the frontal projected area of trucks, which has first-order influence on aerodynamic drag. Therefore, the regulation accounts for these particular tractor shapes.

Truck Energy Balance

The U.S. truck fuel consumption standards are expressed in terms of gal/1,000 ton-mile of fuel used, thereby accounting for the amount of freight that trucks can move. The freight moved by a truck per unit of fuel consumption must be accounted for in order to incentivize freight efficiency. Without such consideration, it would be possible to have a truck with low fuel consumption that cannot move freight efficiently. For the purpose of regulation in the U.S., the fuel consumption of a given vehicle is evaluated through simulation using the Greenhouse Gas Emissions Model (GEM). Tire rolling resistance and aerodynamics are variables considered by the model. These variables, together with engine efficiency, will be discussed in separate sections of the report to follow.

Figure 3 is an illustration of approximate proportionate work energy loss for an 80,000 lb (36,290 kg) tractor semitrailer traveling on a level road at 65 mph (105 km/h). Given that the thermodynamic engine energy loss in the form of heat dominates, the percent energy loss depicted excludes thermodynamic engine energy loss. Engine loss is the result of the thermodynamic cycle characteristic of internal combustion engines, which are approximately 42 percent efficient. This means that 58 percent of the fuel energy is lost to heat most of which cannot practically be captured and converted to propulsion given technology currently available. However, there is promise that over the coming years, thermal efficiency of truck diesel engines may rise from the current 42 moving closer to 50 percent. When the vehicle is traveling at constant speed on a level road at 65 mph (105 km/h), aerodynamic loss is approximately 53 percent, and tire rolling resistance is approximately 32 percent. Aerodynamic loss is a function of vehicle speed, while tire rolling resistance is a function of vehicle mass.

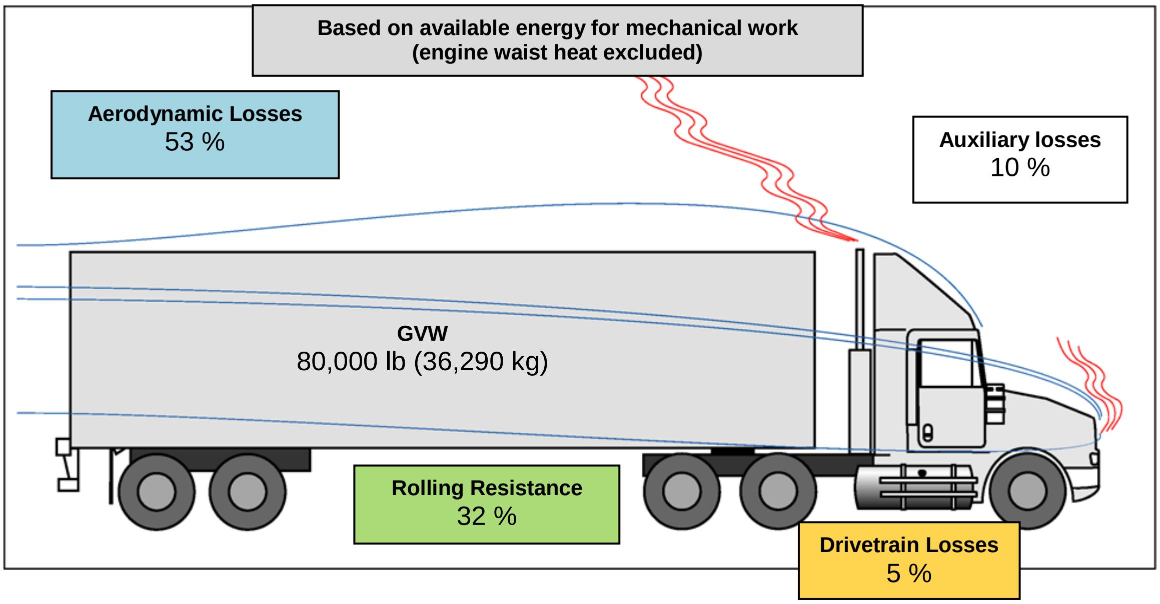


Figure 3. Approximate distribution of resistance loss for a tractor semitrailer on level road at 65 mph (105 km/h).

Tires

Truck tires are complex components in terms of construction, chemical content, and manufacturing process. The tire industry has developed products well suited to various road and weather conditions.

On tractor semitrailers operating in the U.S., single tires are used on the steer axle having a maximum axle load of 12,000 lb (5,450 kg). The tandem drive axles located at the back of the tractor and the tandem trailer axles both carry a combined maximum load of 34,000 lb (15,450 kg) for each tandem set and, therefore, are equipped with dual tires or new generation wide-base single tires as shown in Figure 4. Increasing the tire width on these heavier axles reduces the tire road contact pressure for the benefit of road life.

So-called super single tires were introduced to North America in the late 1980s and predated the new generation wide-base single tires, which were introduced in 2000. The new generation wide-base single tires are wider than the super single tires (super single tires 385/65: wide-base tires 445/50) and require approximately 30 percent less inflation pressure, resulting in a lower more uniform tire contact patch pressure distribution, which reduces pavement wear.

Figure 4. Comparison of dual tires and new generation wide-base single tires.

Tires consume energy when they are manufactured and also when they are in operation on a vehicle. It takes approximately 22 gallons (83 liters) of oil to manufacture one new truck tire. After a period of use when the tire tread has worn to the point of replacement (tread life), truck tires can be re-treaded using a process that consumes about

7 gallons (27 liters) of oil (Bandag, 2014). Truck owners are highly motivated by cost; therefore, they have a strong economic incentive to rebuild and reuse tires. Re-treading is a form of conservation that has significant energy savings and additional auxiliary savings with respect to tire disposal.

The ability to re-tread tires is conditional on two factors, both related to tire safety:

1. The used tire casing or carcass must be free of flaws that would negatively influence the integrity of the tire. All tires in the re-tread process go through a sophisticated multi-level inspection process that includes hands-on visual inspection, followed by non-destructive techniques such as shearography, ultrasound, and fluoroscopic X-rays, which can detect casing defects within the casing that are invisible during visual inspection (Woodrooffe, Page, Blower, and Green, 2008).
2. For low-severity categories of service, such as long haul for example, casings may commonly be retreaded up to 7 years from the date of original manufacture. However, many fleets establish their own set of criteria for retreads based on experience and type of application. Irrespective of age, there is a practical limit to the number of times a casing can be retreaded. (Special identification information is branded onto the side wall of retreaded tires each time the tire is retreaded, so that the history of the tire is known).

The tread life of the tire depends on how it is used. Long-haul trucking is relatively easy on tires because the vehicles travel on high-quality roads with few tight radius turns–tight radius curves are responsible for most truck tire wear. Quality tires in such applications can last between 350,000 to 400,000 miles (563,000 to 644,000 km) before retreading is required. Given that such trucks travel, on average, between 95,000 and 120,000 miles per year (153,000 and 193,000 km) (Delgado and Lutsey, 2014), the tires on such vehicles would likely only be retreadable twice. On the other hand, refuse trucks that operate in urban areas can be expected to require retreading perhaps twice a year and could be retreaded 5 to 7 times.

Tires consume energy in operation through flexing of the side walls, belts, and tread as the tire rotates and deforms in contact with the road. This energy loss is referred to as tire rolling resistance and accounts for approximately 15 percent of fuel used (or 32 percent of available work energy) at cruising speed. The tire industry has invested significant resources into producing tires with improved rolling resistance given the importance to the operating budget of truck owners. In addition, programs such as the Environmental Protection Agency's (EPA) SmartWay® help make the trucking industry aware of tire rolling resistance benefits and provide incentive mechanisms through program accreditation.

Government Initiatives Influencing Tire Acceptance

The EPA SmartWay® Program is a public-private initiative between EPA, large and small trucking companies, rail carriers, logistics companies, commercial manufacturers, retailers, and other federal and state agencies. Its purpose is to improve fuel efficiency and the environmental performance (reduction of both greenhouse gas emissions and particulate matter) of the goods movement supply chains. It has over 3,000 partners, and has resulted in $16.8 billion dollars in fuel costs saved, 51.6 million metric tons CO_2 reductions, 738,000 tons NOx reductions, and 37,000 tons PM reductions (EPA, 2014).

Manufacturers of tires verify to SmartWay® requirements, and in doing so must balance wear, traction, durability, and rolling resistance in order to provide an optimum product with low rolling resistance characteristics. Tread thickness and design, casing construction, materials, rubber compounds, and manufacturing techniques all influence these tire attributes. Both regular and wide-base tires are available as low rolling resistance offerings, but the wide-base tire that replaces duals has the added benefit of two less sidewalls, and lower tire and rim mass, which provides benefits that dual tires cannot match.

The U.S. Department of Energy (DOE) SuperTruck program is a cost-shared, public private partnership that promotes precompetitive research and development to improve the freight-hauling efficiency of heavy-duty Class 8 long-haul, tractor-trailer trucks. This program aims to help accelerate the development of advanced efficiency technologies. A recent report by Delgado and Lutsey (2014) evaluated the SuperTruck program, noting that low rolling resistance tires in the form of wide-base single tires replacing dual tires can be expected to reduce tire and rim weight by 20 percent compared to dual tires and provide about 5 percent improvement in freight efficiency through lower rolling resistance and lighter tire and rim weight.

Industry Perspective on Tire Performance Measurement

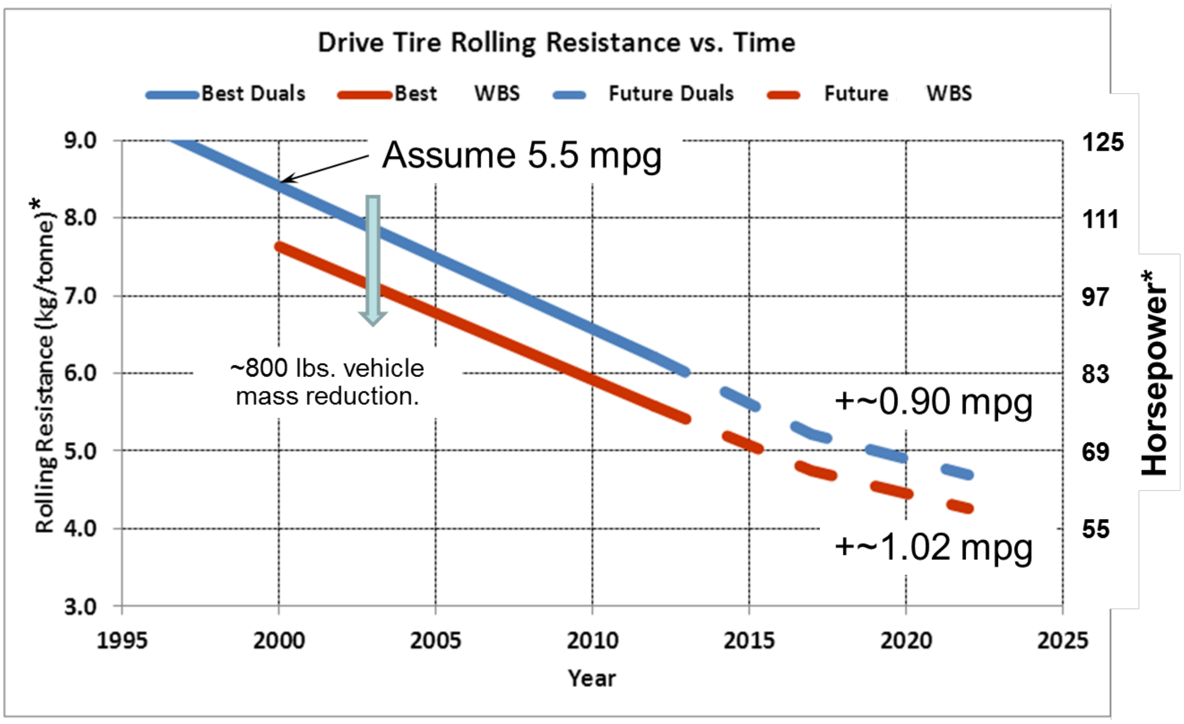
Commercial vehicle owners are interested in having an objective measure of tire rolling resistance performance so that they can make informed tire purchasing decisions. Truck tire manufacturers want to reduce error in the measurement process to improve the confidence in tire rolling resistance measurement. ISO 28580, "Standard passenger car, truck and bus tyres—Methods of measuring rolling resistance" provides a relevant test methodology. This standard, although not perfect, provides a means of assessing tire rolling resistance in a manner that is as close to representative of real-world performance as is practical given the difficulties of assessing tire rolling resistance. However, one of the main challenges facing tire rolling resistance measurement is that during testing it is necessary to measure small forces in the presence of much larger forces, which makes comparison of test results from various test facilities problematic. A feature of this standard incorporates a method for correlating measurement results to allow inter-laboratory comparisons. Unfortunately, despite the correlation methodology, variations in results remain. At present, each truck tire manufacturer conducts rolling resistance testing to measure the rolling resistance of their tires.

In the spirit of transparency and consistency of testing, it would be desirable if a single independent reference test laboratory could be established to measure and certify truck tire rolling resistance. Having confidence in the accuracy of the published rolling resistance performance data is a key requirement to ensure that the investment in research and development by the tire industry is rewarded in the marketplace.

Future Expectations for Tire Rolling Resistance

The effort to reduce tire rolling resistance has been ongoing in the industry for decades. Figure 5 illustrates the progress made in the development of dual and wide-base single truck drive tires in terms of rolling resistance and power required to overcome the resistance assuming a 5-axle 80,000 lb (36,290 kg) tractor semi-trailer common in the

U.S. It shows that wide-base singles consistently outperform dual tires and reduce the tare, or unladen weight, of the vehicle by about 800 lb (360 kg). This reduction in tare weight can be converted to additional cargo capacity, which improves the freight efficiency of the vehicle. Figure 5 also shows that in the past 15 years tire rolling resistance has been steadily reduced. Dual tires have improved from approximately 8.5 kg/tonne in the year 2000 to about 6.0 kg/tonne in 2014, while wide-base singles have improved from 7.6 to 5.4 kg/tonne during the same time period. Such improvements cannot be expected to continue at this rate indefinitely, and gains will likely diminish in the future, settling between 4.0 and 5.0 kg/tonne (C_{RR} between 0.004 and 0.005).



* Note: Values represent the evolution of the lowest rolling resistance long–haul drive tires. Other performance is assumed equivalent. Absolute values depend on test equipment and conditions. Actual values in the market will vary. Horsepower represents consumption due to tires at 65 mph, 80,000 lb total load.

Figure 5. Rolling resistance of new truck drive axle tires over time (Teeple, 2012).

In conclusion, low rolling resistance conventional or wide-base single tires for trucks offer significant fuel savings. Wide-base single tires offer distinct advantages in fuel saving and freight efficiency compared with dual tires because of tire and rim reduced weight and the reduction of sidewall energy loss. There is a need to establish a single independent test facility to measure and certify truck tire rolling resistance.

Aerodynamics

The general equation for aerodynamic drag below is instructive for understanding the relationship between vehicle speed and body design regarding energy loss related to overcoming air resistance.

$$P_d = \frac{1}{2} * \rho * C_D * A * V^3$$

P_d is the power required to overcome aerodynamic drag
C_D is the aerodynamic drag coefficient
A is the projected frontal area of the vehicle
V is the velocity of the vehicle
ρ is the air density

Since the power required to overcome aerodynamic drag force varies as the cube of velocity, vehicle speed is the crucial parameter for influencing vehicle fuel consumption. For example, any vehicle that reduces speed by 13 percent from 115 km/h (71 mph) to 100 km/h (62 mph) will reduce the power needed to overcome aerodynamic drag by 52 percent. Many trucks are now governed in the range of 100 to 105 km/h (62 to 65 mph) to take advantage of this considerable saving.

Further reductions in aerodynamic loss can be found through improvements in the drag coefficient C_D and a reduction in projected frontal area A. Air temperature and elevation also influence drag by altering air density.

- Drag coefficient is a numerical representation of the "slipperiness" of a vehicle. It is influenced by the shape of the vehicle that is exposed to the air stream, surface uniformity and various discrete obstructions such as side mirrors, tires and wheels.
- Projected frontal area is the total area visible from the front of the vehicle as if its shadow were cast on a screen (hence the word projected). Projected frontal area accounts for the area of the object that is presented to the wind. This is the parameter that required the U.S. fuel efficiency standards to consider roof height variations in the medium- and heavy-duty fuel consumption regulations.

- In cold climates, the aerodynamic drag in winter can be nearly 20 percent greater than at standard conditions, due to the increase in ambient air density (Patten, McAuliffe, Mayda, and Tanguay, 2012).

As mentioned previously, the most common trailer in the U.S. is the van trailer. Since van trailers are wider and taller than the tractor, roof and side fairings are added to the tractor to help deflect the air flow so that it is less disturbed by the leading edges of the trailer. These fairings influence drag coefficient but not the projected area unless the trailer is of a different (smaller) type such as a tanker or flatbed trailer. Since van trailers dominate the projected area parameter, tractor manufacturers place increasing emphasis on reducing the drag coefficient of the tractor through shaping and adding aerodynamic treatments such as fairings on the roof and upper body, skirting at the tire level, and air dams below the front bumper of the tractor. Given that the tractor manufacturers control the integration of the body shape and aerodynamic treatments, the vehicle purchaser can be confident that the aerodynamic package is beneficial and that the approximate fuel savings attributed to it can be defined. Because truck manufactures have been actively improving the drag coefficient of tractors, it is likely that future improvements in total vehicle drag coefficient will come mostly from trailer aerodynamic treatment – perhaps 1/3 improvement from the tractor and 2/3 improvement from the trailer.

Trailers

Semitrailers are manufactured by the trailer industry, which is separate and distinct from the tractor manufacturing industry. There are approximately three trailers for every one tractor in operation, as trailers are standalone cargo containers made available to shippers and can be stationary for long periods of time. Tractors, on the other hand, must keep moving to be profitable.

In operation, a significant number of trailers are not owned by the tractor fleet, so there is little incentive for such trailer owners to adopt fuel conservation measures because, in many cases, the owner sees no return on investment for the aerodynamic treatments.

Nevertheless, in recent years, trailer owners and manufacturers have adopted several different aerodynamic treatments to reduce drag coefficient, as shown in Figure 6.

Many treatments are aftermarket products with claims of potential benefits that are difficult to quantify. As with low rolling resistance tires, the performance is difficult to measure accurately, as fuel savings provided by such devices are small compared to the sum of all losses experienced by the truck. Testing aerodynamic performance in most cases is done on open roads using standard procedures that control for air temperature, wind, and road vertical profile. As with tires, there is a need for independent testing with standardized vehicles to ensure that performance claims can be verified and compared fairly.

Figure 6. Aerodynamic side skirts and boat tails used to reduce aerodynamic drag (DOE, 2011).

Recent independent evaluation by the National Research Council of Canada (NRCC) (Patten, McAuliffe, Mayda, and Tanguay, 2012) and other research (Landman, Wood, Seay, and Bledsoe, 2009) found that the gap between the tractor-trailer begins to have a significant impact on vehicle drag once it is greater than about 0.45 m, with the drag increasing by about 2 percent for every 0.25 m of increased gap beyond approximately 0.75 m. Research has suggested that by completely addressing the tractor-trailer gap issue, drag savings on the order of about 6 percent could be achieved for a typical tractor-trailer. This would amount to an approximate 3 percent improvement in fuel consumption at 60 mph (98 km/h).

More advanced integrated aerodynamic systems have emerged from the SuperTruck program described earlier. Figure 7 illustrates an advanced, integrated vehicle design concept described by Oehlerking (2013). This design concept includes aerodynamic enhancements in different areas of the tractor and the trailer. Several aerodynamic scale models have been developed and evaluated in the wind tunnel. A 42 percent reduction in aerodynamic drag can be expected with changes to both the tractor and the trailer. For example, for the tractor, a rear-engine concept is under study that would allow moving the driver and windscreen forward, enabling an enhanced aerodynamic body shape (Oehlerking, 2013). To achieve a 42 percent reduction in drag requires a radical departure from traditional vehicle design and the practicality of doing so within the constraints of truck operations and tractor and trailer compatibility remains unlikely. A more realistic estimate for near-term aerodynamic benefits at highway speed is approximately 10 percent improvement in fuel efficiency (NRC, 2014).

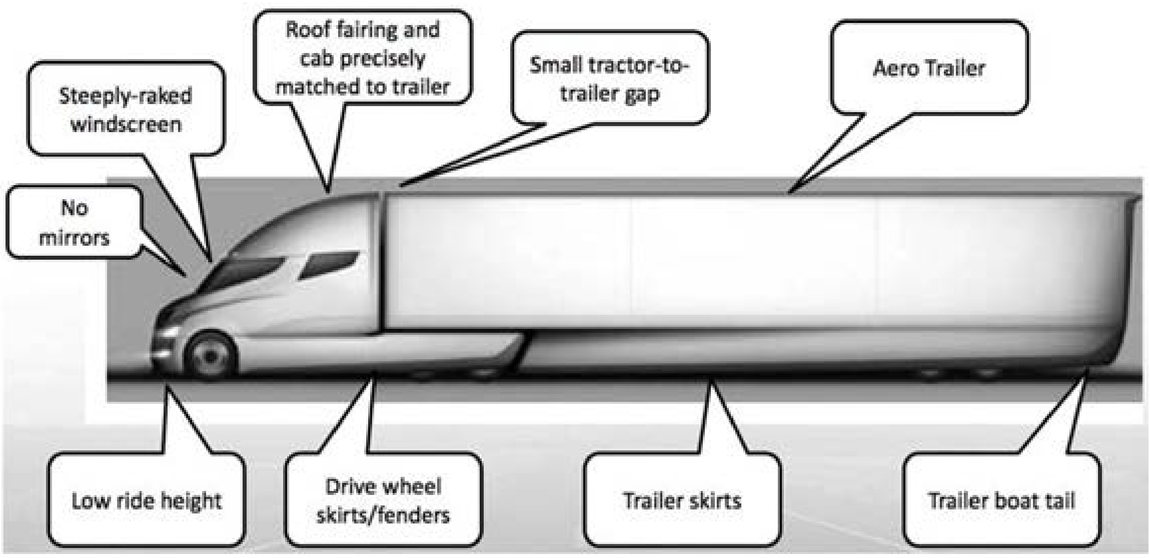


Figure 7. Aerodynamic concept presented by Oehlerking (2013).

Engine Efficiency

Diesel engines dominate the heavy-duty truck market because of their durability, high-torque characteristics and relatively high fuel efficiency. Engine thermal efficiency of truck engines is approximately 42 percent, meaning that only 42 percent of the fuel energy is converted to mechanical work (NRC, 2012), and 58 percent is rejected as heat. As shown in Figure 8, there has been good progress in thermal efficiency of truck diesel engines, increasing by approximately 40 percent during the period 1960 through 2003. However, the 8 percent drop in engine efficiency that occurred in the 2004 time period when new EPA emissions standards were implemented has taken almost 10 years to recover the gains lost. The benefits of the EPA regulation on emissions output are illustrated in Figure 9. For the time period from 1980 when regulations were first introduced to 2003, the NOx emissions fell from 16 to 4 g/bhp-hr. Between 2004 and 2010, NOx emissions were reduced to 0.2 g/bhp-hr. This remarkable improvement in emissions reduction came at considerable cost, not only in terms of fuel efficiency but also in terms of capital cost of engines. In 2003, a typical, heavy-duty truck engine cost approximately $9,000. Today the installed cost of a truck diesel engine with after-treatment (diesel exhaust filter and SCR system) and cooling system has risen to approximately $30,000 (Greszler, 2014). In 2010, with the addition of NOx after-treatment using selective catalytic reduction (SCR), manufacturers were able to increase the NOx out of the engine and recover much of the efficiency lost from 2004 to 2007.

The likelihood of improving truck diesel engine thermal efficiency beyond 50 percent in the foreseeable future seems very low, given that new engine architecture and/or the addition of secondary cycles with many more complex monitoring and control systems would likely be required.

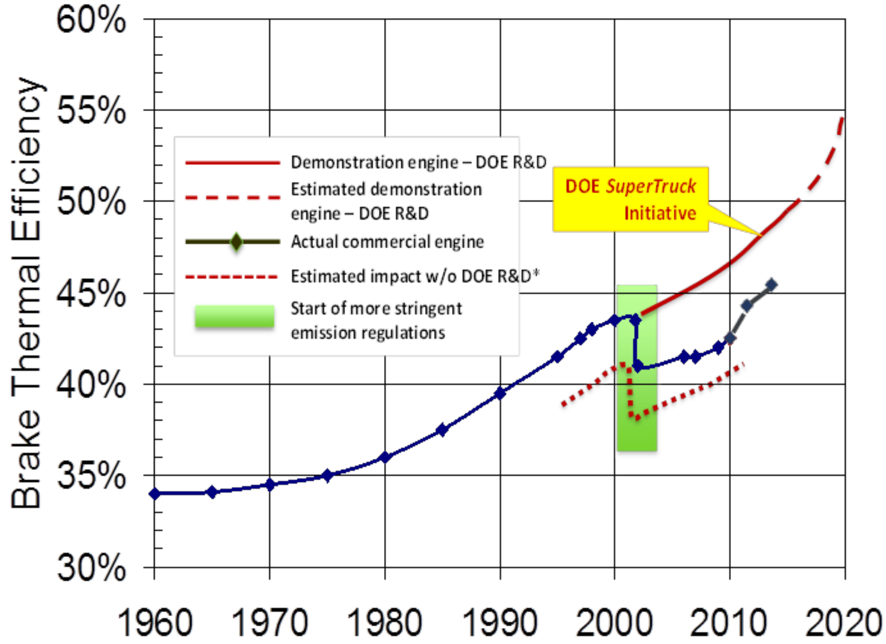


Figure 8. Historical trend in heavy-duty diesel engine efficiency (DOE, 2014).

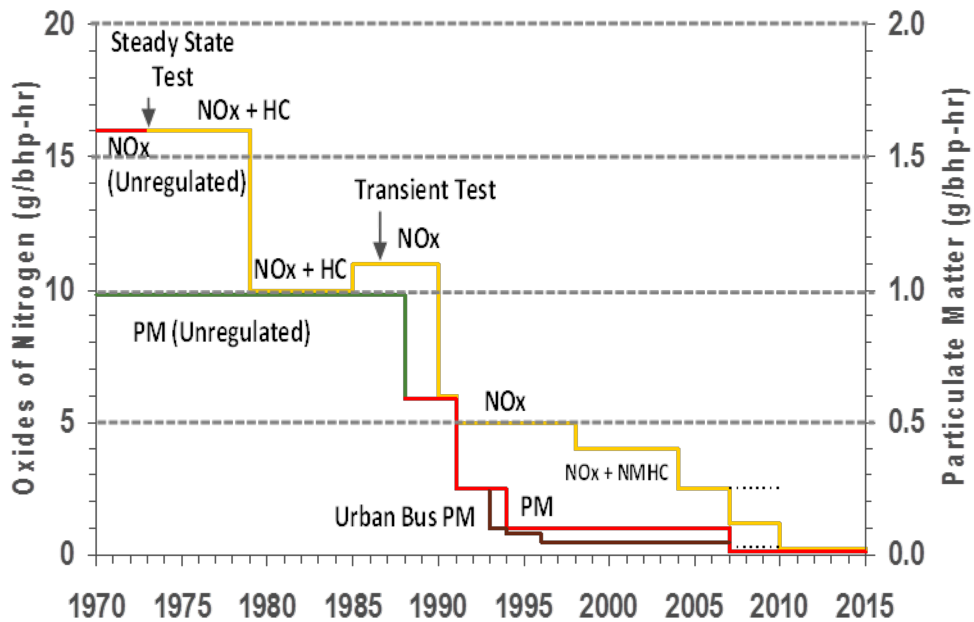


Figure 9. Historical trend in emissions from heavy-duty diesel engines (DOE, 2014).

Size and Weight Regulation

Truck size and weight policy was enacted to preserve the infrastructure and ensure that heavy vehicles could operate on the road system within the load carrying capacity of roads and bridges. It also ensured that vehicle size was controlled to allow operation within geometrical constraints dictated by bridge height, lane widths, and curve radius constraints, which limit vehicle maneuverability.

The Surface Transportation Assistance Act (STAA) of 1982 set restrictions on tractor-trailer combinations and twin trailer combinations operating on the U.S. National Truck Network. Current Federal regulations continue the ISTEA freeze (1991) on enforcement of longer combination vehicles (LCV) and limit the gross weight of all trucks to 80,000 lb (36,290 kg). LCV operation is only permitted on a relatively small proportion of the Interstate System and other highways, mostly confined to western states.

The 1982 size and weight freeze was enacted at a time when there was great uncertainty regarding size and weight policy reform, and legislators were understandably cautious. However, since then other countries have judiciously moved size and weight policy to balance infrastructure consumption with vehicle productivity and safety, resulting in substantial improvements in transportation efficiency. In many countries, safety performance was improved through vehicle design requirements that were part of policy reform.

Size and weight policy is not uniform throughout the country on all roads. Both the federal and state governments have their own policies. This patchwork of truck size and weight limits presents challenges for interstate trucking operations as well as for public regulation of the trucking industry.

The outcome of the stagnant policy has resulted in the U.S trailing all developed nations in terms of mass freight efficiency per vehicle unit (Woodrooffe, Bereni, Germanchev, Eady, Glaeser, Jacob, and Nordengen, 2010). As shown in Table 5 within the context of the NAFFTA region, both Canadian and Mexican tractor semitrailers are, by cargo mass, more freight efficient than the 80,000 lb (36,360 kg) U.S. vehicle by 44 and 53 percent respectively.

Table 5
Comparison of legal axle load limits, GVW and vehicle productivity for semi-trailers in NAFTA region (Woodrooffe, Bereni, Germanchev, Eady, Glaeser, Jacob, and Nordengen, 2010).

Country	Steer lb (kg)	Drive lb (kg)	Tridem lb (kg)	GVW lb (kg)	Productivity advantage relative to 5-axle*
Mexico	14,300 (6,500)	39,600** (18,000)	49,500** 22,500	103,400 (47,000)	53 %
Canada	12,100 (5,500)	37,400 (17,000)	52,800 (24,000)	102,300 (46,500)	44 %
USA	12,000 (5,460)	34,000 (15,460)	34,000 (15,460) tandem	80,000 (36,360)	----
Assumed empty weight 36,300 lb for 6-axle and 34,100 lb for US 5-axle. Only 5-axle tractor semitrailers are on the National Highway System. * Compared to the US 80,000 lb ** Axle weights estimated from bridge formula					

In the mid-1980s, Canada reformed its truck size and weight policy. This was accomplished through implementation of a scientifically-structured size and weight research program (TAC, 1986), which included full-scale testing of vehicles and pavements and computer simulation analysis of vehicle dynamic performance. Through this process, it was recognized that vehicle configuration type, axle layout, and the characteristics of the load profoundly influence vehicle stability and control characteristics as well as the compatibility of the vehicle with highway geometry. To objectively assess various truck size and weight policy options, a set of “Performance Based Standards” (PBS) was created. Using the PBS and the results of a sensitivity analysis, Canada developed truck size and weight policy consisting of a number of “vehicle envelopes” that provide flexibility in design for various vehicle classes, while ensuring that the vehicles would have desirable performance attributes. The envelope concept reduced the burden of compliance evaluation when small variations in vehicle design were required.

Regulating Vehicles Designed for High-Density Freight

One of the vehicles that emerged from the Canadian study mentioned above (TAC, 1986) was the B-train, shown in Figure 10. It is a double trailer combination with a special coupling system between trailers that provides roll coupling and eliminates one point of articulation, giving it superior vehicle dynamic characteristics. The B-Train can travel on the full road network in Canada. As shown in Tables 6 and 7, the B-train can transport twice the amount of cargo by mass with 68 percent less fuel and emissions compared with the 80,000 lb U.S. tractor semitrailer.

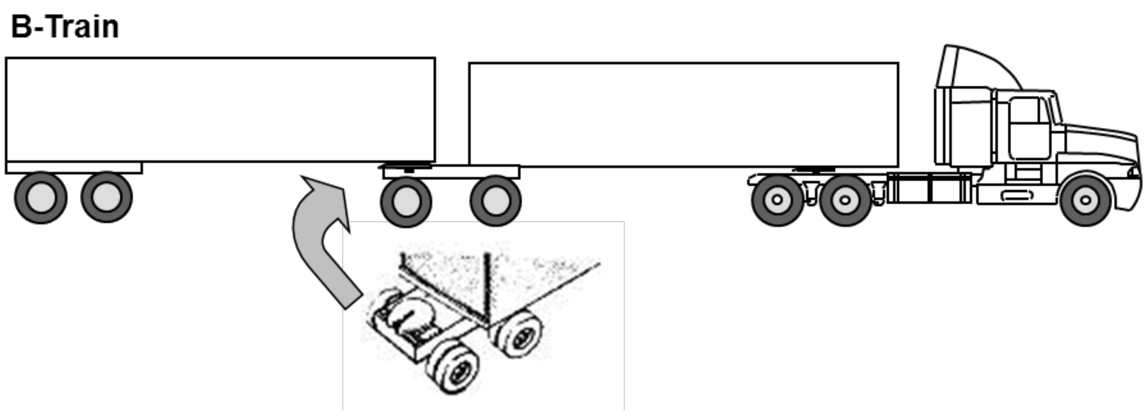


Figure 10. Illustration of Canadian B-train configuration (TAC, 1986).

Table 6
Comparison of mass productivity of the Canadian B-Train to the US 80,000 lb tractor semitrailer.

Country & vehicle	GVW	Number of axles	Payload	Productivity advantage
Canada 8-axle B-train	137,500 lb (62,500 kg)	8	93,060 lb (42,300 kg)	Factor of 2
US tractor semi	80,000 lb (36,360 kg)	5	46,600 lb (21,180 kg)	-

Table 7
Comparison of fuel consumption and emissions output for the Canadian B-Train to the US 80,000 lb tractor semitrailer.

Country & vehicle	Cargo unit fuel (liter/tonne-km)	Cargo unit CO_2 (g CO_2/tonne-km)	Fuel and GHG advantage per unit cargo
Canada B-train	0.037	98.79	68 %
US tractor semi	0.063	165.9	-

Note: Evaluated assuming 105 km/h constant speed, level road.

Regulating Vehicles Designed for Low-Density Freight

The transportation of low-density freight benefits from longer trucks with multiple trailers (LCVs). Examples of typical LCV combinations are a tractor pulling two 53 ft (16.2 m) trailers or three 28 ft (8.5 m) trailers. Because of their length, these vehicles are often restricted to certain road classes having geometric design characteristics that are compatible with LCVs. In some jurisdictions, LCVs operate under a special permit program governed by strict operating conditions. The structure and enforcement mechanisms of the policy engender a level of safety consciousness within the LCV fleet that far exceeds that found in other vehicle classes (Woodrooffe, 2001; Montufar, Regehr, and Rempel, 2006). The principal motivating factor for heightened safety performance is related to the special safety requirements and to the influence of the special permit privilege that can be revoked for safety performance failure. The LCVs operating in Alberta were found to have significant benefits as shown in Table 8.

Table 8
Benefits of the Alberta LCV program (Woodrooffe, et al., 2001).

System category	Benefit Estimate
Improved productivity	44 %
Improved safety	2.5 to 5 times*
Reduced fuel consumption	32 %
Reduced emissions	32 %
Reduced infrastructure consumption	40 %
Reduced truck travel	44 %
Reduced shipper cost	29 %

* The improvements in safety are attributed to the strict policies enacted to govern the operation of LCVs. Without such policies, the safety benefits would not be as significant.

The benefits of coupling trailers together come from the elimination of one tractor for double trailers and two tractors for triples, aerodynamic benefits that the second or third trailer have travelling in the slip stream of the lead trailer. The infrastructure benefits come from lengthening the vehicle and elimination of the tractor(s).

Conclusions

Trucks are the dominant mode of non-bulk commodity freight transport in the U.S. Compared to all other modes combined (rail + water + air + pipelines) trucks transport approximately twice the amount of freight by weight and approximately 1.8 times the amount of freight by value. Trucking has the most extensive distribution network of any mode, having access to over 3.9 million miles of roadways. Improvements in truck freight efficiency can be expected to show direct improvement of the nation's overall transportation system.

Truck fuel consumption and emissions are directly related to freight efficiency as are the size and weight regulations that define the mass and volumetric capacity of commercial vehicles. This study has identified four key focus areas that influence truck freight efficiency.

1. Tire rolling resistance
2. Aerodynamics
3. Engine efficiency
4. Truck size and weight regulation

Each of the four focus areas will have conditional elements that influence their practical contribution to fuel, emissions, and freight efficiency.

Tires

Tire rolling resistance varies slightly with vehicle speed while aerodynamic varies exponentially with speed. While tire rolling resistance may be lower than aerodynamic drag at higher speeds, as the vehicle slows and aerodynamic losses diminish, tire rolling resistance surpasses aerodynamics as shown in Table 9. This means that in varying speed conditions the relative contribution of aerodynamic loss and tire rolling resistance loses will change. It also means that tire losses are relatively constant and present at all times, while aerodynamic losses diminish with speed, implying that the benefits of improved tire rolling resistance will be realized during all operating speeds.

Table 9
Comparing aerodynamic with tire rolling resistance including auxiliary loads (Patten, McAuliffe, Mayda, and Tanguay, 2012).

Vehicle Speed	Aerodynamic	Rolling & Accessories
113 km/h (70 mph)	70 %	30 %
105 km/h (65 mph)	67 %	33 %
96 km/h (60 mph)	62 %	38 %
80 km/h (50 mph)	50 %	50 %
64 km (40 mph)	36 %	64 %
53 km/h (33 mph)	33 %	66 %
32 km/h (20 mph)	28 %	72 %

New generation wide-base singles consistently outperform dual tires in terms of rolling resistance and they also reduce tare weight of a conventional 5-axle tractor semitrailer by about 800 lb (360 kg). This reduction in tare weight can be converted to additional cargo capacity, which improves the freight efficiency of the vehicle.

During the past 15 years, tire rolling resistance has been steadily reduced. Dual tires improved from 8.5 kg/tonne in the year 2000 to about 6.0 kg/tonne in 2014, and wide-base singles have improved from 7.6 to 5.4 kg/tonne during the same time period. It is expected that the rate of improvement will likely diminish in the foreseeable future, settling between 4.0 and 5.0 kg/tonne (CRR between 0.004 and 0.005).

Aerodynamics

The exponential relationship between drag and vehicle speed accounts for the disparity in the aerodynamic influence on power consumption between urban and highway environments. Aerodynamic losses increase exponentially with vehicle speed; therefore, improvements in drag performance are most notable at higher speeds. For example, at 80 km/h, a 20 percent reduction in drag coefficient will contribute to about a 10 percent reduction in fuel consumption for a tractor semitrailer. At 120 km/h the reduction would be approximately 15 percent (Patten, McAuliffe, Mayda, and Tanguay, 2012).

A 42 percent reduction in theoretical aerodynamic drag is possible with radical changes to both the truck and the trailer. These changes would require a redesign of the tractor and trailer fleet, which seems unlikely in the short-to-medium time frame. Nevertheless, by improving the shape of the tractor and adding aerodynamic treatments to existing trailers in the form of advanced side skirts, advanced trailer end fairings and a reduction in tractor trailer gap, a 10 percent improvement in fuel efficiency can be expected (Oehlerking, 2013; NRC, 2014).

Given that aerodynamic losses diminish with speed, not all vehicles can economically benefit from aerodynamic treatments due to slower speed operating conditions such as in urban environments. However, even at slower speeds, some aerodynamic benefits can be achieved. For vehicles that can benefit from aerodynamic improvements, one of the most effective strategies is to govern the speed of the vehicle to approximately 60 mph (100 km/h) on the open highway.

Engine Efficiency

Truck diesel engine efficiency has risen from about 34 percent in 1960 to about 42 percent at present, meaning that only 42 percent of the fuel energy is converted to mechanical work. The likelihood of improving truck diesel engine thermal efficiency beyond 50 percent in the foreseeable future is low, given that new engine architecture and/or the addition of secondary cycles with many more complex monitoring and control systems would likely be required. Any improvement in engine efficiency will benefit freight efficiency in all operating conditions.

Truck Size and Weight Regulation

U.S. federal truck size and weight policy has been frozen since 1982. Meanwhile, other countries have reformed their policies, yielding improved freight efficiency and resulting in substantial fuel emission reductions for a given freight task. The potential gains in freight efficiency for freight that could make use of vehicle weight increases matching our NAFTA partners Canada and Mexico are 44 and 53 percent, respectively. The potential gains for LCVs, as demonstrated by the Alberta experience, is approximately 44 percent. While these numbers are large, not all freight can take advantage of these more efficient vehicles because of freight logistics and load ratios.

It is generally accepted that in the U.S. the ratio of mass-limited to volume-limited tractor semitrailers ranges from about 50/50 (NRC, 2010) to 40/60. However, in a survey of private carriers (Woodrooffe, Belzowski, Reece, and Sweatman, 2009) it was found that for out-bound freight, 56 percent of the companies' shipments were mass limited and 34 percent were volume limited. The remaining 10 percent were optimum loads. There was no information available on return trip ratios, which likely have lower mass content, because some significant portion of trailers from private fleets return in an empty or lightly loaded state due to backhaul uncertainty. If these data are representative of the national fleet, then there appears to be an opportunity to achieve gains in mass-limited freight for outbound movements than convention suggests and conversely a volume-limited freight opportunity for return travel. This suggests that a possible strategy for the future is to accommodate heavier 53 ft trailers for the outbound trip and then incorporate these trailers as LCVs for the return trip.

Finally, the amount of weight increase required to achieve gains in freight efficiency is a point worthy of discussion. Woodrooffe, Belzowski, Reece, and Sweatman (2009), in an examination of three trucking companies, found that increasing the GVW from 80,000 lb to 91,000 lb (36,360 kg to 41,360 kg) would achieve approximately 70 percent of the freight improvement that would occur if the limit were raised to 97,000 lb (44,090 kg). While these data may not be nationally representative, it does suggest even moderate weight increases can provide significant improvements in freight efficiency.

Size and weight regulatory reform offers a unique opportunity for the U.S. to reset commercial vehicle efficiency closer to that of other nations, and by doing so, to achieve freight efficiency gains that are significant in magnitude. These gains are achievable through policy reform without the need for technical development. However, there is longstanding political resistance to changing Federal truck size and weight regulations. Public perception of trucks is poor, likely because to some, these large vehicles appear to be intimidating and consequently unsafe. Safety is paramount in the truck size and weight debate. Policies that ensure improvements in truck safety performance are critical to size and weight reform, which holds great potential for national freight efficiency gains both economically and environmentally.

Other countries, most notably Canada and Australia, have demonstrated that advanced policies can achieve substantial gains in both freight efficiency and safety. One possible means of improving truck safety and productivity in the U.S. is to require heavier and longer trucks be equipped with proven crash-avoidance technologies, such as disk brakes, electronic stability control, and forward-collision warning and mitigation systems, thereby ensuring that safety technology adoption is tied to policy reform. The use of vehicle performance measures (Woodrooffe, Bereni, Germanchev, Eady, Glaeser, Jacob, and Nordengen, 2010) provides regulators with an engineering method for assessing potential candidate vehicle configurations.

Anticipated Gains in Fuel Efficiency and the Consequent Societal Benefits

To provide comparative context to the influence of low rolling resistance tires, aerodynamics, engine efficiency, and truck size and weight policy on fuel use and CO_2 emissions, Table 10 provides an estimate of realistic potential that each of these options has in the foreseeable future. (This table provides estimates for each of the four aspects independently. The combined effects would be smaller than the sum of the individual effects.) The level of technical challenge to achieve these gains has been included as well. Improvements in aerodynamics and low rolling resistance tires include countermeasures that are currently available but not yet in common use plus benefit estimates from future development. The baseline used for these two options is an 80,000 lb (36,360 kg), 5-axle, tractor semitrailer with standard tires and no trailer aerodynamic features.

Table 10
Estimated potential realistic improvement in fuel efficiency and CO_2 emission reduction (assuming 65 mph [105 km/h] level cruise).

Aspect	Realistic gain in fuel efficiency and CO_2 reduction	Level of technical challenge	Technical timeframe and comments
Tires	13 %[1]	Moderate	Much of this benefit currently available—remaining benefit expected 5 to 10 years
Aerodynamics	10 %[2]	Easy	Much of this benefit currently available—development ongoing
Engine efficiency	16 %	Difficult	Very challenging and costly to achieve—15 to 20 years, would likely require regulation
Size & weight regulation	20 %[2, 3, 4]	Easy	Not limited by technology or development time. Requires policy change only. Politically sensitive.

1. Based on standard tire rolling resistance performance of 6.5 kg/metric ton.
2. NRC (2014).
3. Not all carriers can benefit, therefore projected improvement has been reduced to account for this (Woodrooffe, Belzowski, Reece, and Sweatman, 2009).
4. Applies to the U.S. assuming STAA freeze is lifted, GVW increased, and LCVs permitted.

Note: This table provides estimates for each of the four aspects independently. The combined effects would be smaller than the sum of the individual effects.

In the U.S., single unit trucks consume approximately 54.1 billion liters of diesel fuel and produce approximately 144 million metric tons of CO2 annually. Articulated vehicles, largely 5-tractor semitrailers, use approximately 106 billion liters of fuel/year and generate approximately 283 Million metric tons CO2/year (RITA, 2014). Across these two vehicle platforms each 10% improvement in fuel saving will translate to a saving of 16.0 billion liters of fuel/year and 42.7 million metric tons CO2 /year. The value of these savings are $15.8 billion for fuel based on $0.99/liter and $1.03 billion for CO2 based on a cost of $24/metric ton CO2 (White House, 2010).

Furthermore, it is likely that improvements in truck fuel efficiency in any of the four areas examined would result in net cost savings to the society given that trucking accounts for approximately 4.25% of GDP. This is the case because the cost of fuel saved would likely be greater than the cost of the needed countermeasures. Finally, changes in size and weight regulation would likely have an added net safety benefit because the reduced amount of truck travel through improved truck cargo capacity would likely dominate negative safety consequences per distance traveled associated with increased size and weight.

References

Bandag. (2014). *The Next Generation of FuelSmart Retreads*. Available at: http://www.ecopiatrucktires.com/files/Product/Specs/FuelTechBrochureSheet.pdf.

Delgado, O. and Lutsey, N. (2014). *The U.S. SuperTruck program: Expediting the development of advanced heavy-duty vehicle efficiency technologies*. Available at: http://www.theicct.org/sites/default/files/publications/ICCT_SuperTruck-program_20140610.pdf

DOE [U.S. Department of Energy]. (2014). *Twenty-First Century Truck Review*. Presented at the National Academy of Sciences.

DOE [U.S. Department of Energy]. (2011). *Vehicle and Systems Simulation and Testing*. Available at: http://energy.gov/sites/prod/files/2014/03/f8/2011_vsst_report.pdf.

DOT [U.S. Department of Transportation]. (2014). *Freight Facts and Figures 2013*. Available at: http://www.ops.fhwa.dot.gov/freight/freight_analysis/nat_freight_stats/docs/13factsfigures/pdfs/fff2013_highres.pdf.

EIA [U.S. Energy Information Administration]. (2011). *International Energy Outlook 2011*. Available at: http://www.eia.gov/forecasts/archive/ieo11/.

EPA [Environmental Protection Agency]. (2014). *About SmartWay*. Available at: http://www.epa.gov/OTAQ/smartway/about/index.htm.

EPA/NHTSA [Environmental Protection Agency and National Highway Traffic Safety Administration]. (2011). *Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles; Final Rule*. 49 CFR Parts 523, 534, and 535. Available at: http://www.gpo.gov/fdsys/pkg/FR-2011-09-15/pdf/2011-20740.pdf.

FRA [Federal Railroad administration]. (2014). *Freight Rail Today*. Available at: https://www.fra.dot.gov/Page/P0362.

Greszler, A. (2014). *VP Government and Industry Relations Volvo Group Truck Technology, personal communication*.

ICCT [International Council on Clean Transportation]. (2014). *Global Transportation Roadmap Model*. Available at: http://www.theicct.org/global-transportation-roadmap-model.

Landman, D., Wood, R., Seay, W., and Bledsoe, J. (2009). *Understanding practical limits to heavy truck drag reduction* (SAE Technical Paper No. 2009-01-2890). Warrendale, PA: Society of Automotive Engineers.

Montufar, J., Regehr, J., and Rempel, G. (2007). *Long combination vehicle (LCV) safety performance in Alberta 1999-2005*. Alberta, Canada: Alberta Transportation. Available at: http://www.transportation.alberta.ca/content/doctype61/production/lcvfinalreport2005.pdf.

NRC [National Research Council]. (2010). Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles. Available at: http://www.nap.edu/catalog.php?record_id=12845.

NRC [National Research Council]. (2012). *Review of the 21st Century Truck Partnership, second report*. Available at: http://www.nap.edu/catalog.php?record_id=13288.

NRC [National Research Council]. (2014). *Reducing the fuel consumption and greenhouse gas emissions of medium- and heavy-duty vehicles, phase two*. Available at: http://www.nap.edu/catalog.php?record_id=18736.

Oehlerking, D. (2013). *SuperTruck – Development and demonstration of a fuel-efficient Class 8 tractor and trailer*. Presented at the U.S. Department of Energy Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting, Washington, D.C., May 2013. Available at: http://www4.eere.energy.gov/vehiclesandfuels/resources/merit-review/sites/default/files/vss064_oehlerking_2013_o.pdf.

Patten, P., McAuliffe, B., Mayda, W., and Tanguay B. (2012). *Review of aerodynamic drag reduction devices for heavy trucks and buses* (Technical Report No. CSTT-HVC-TR-205). Available at: https://www.tc.gc.ca/media/documents/programs/AERODYNAMICS_REPORT-MAY_2012.pdf

RITA [Research and Innovative Technology Administration]. 2014, *Table 4-5: Fuel Consumption by Mode of Transportation in Physical Units.* Available at: http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_04_05.html.

TAC [Transportation Association of Canada]. (1986). *Canadian vehicle weights and dimensions study, vol. 1-14*. Ottawa, Canada: Authors. Available at: http://www.comt.ca/english/programs/trucking/TSC.pdf

Teeple, V. (2012). *North American Truck Tire State-of-the-Art and Vision*. Presented at the Commercial Vehicle Megatrends USA Symposium, June 13, 2012, Dearborn, MI. Available at: http://www.automotiveworld.com/img/slides/Van%20Teeple%20-%20Michelin.pdf.

White House (2010)"Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866" Interagency Working Group on Social Cost of Carbon, United States Government. Available at http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-update-social-cost-of-carbon-for-regulator-impact-analysis.pdf

Woodrooffe, J. (2001). *Long combination vehicle (LCV) safety performance in Alberta 1995-1998*. Alberta, Canada: Alberta Transportation. Available at: http://www.transportation.alberta.ca/Content/docType61/production/LCVSafetyPerformanceReport.pdf.

Woodrooffe, J., Belzowski, B.M., Reece, J., and Sweatman, P.F. (2009). *Analysis of the potential benefits of larger trucks for U.S. businesses operating private fleets* (Technical Report No. UMTRI-2009-11). Washington, D.C.: National Private Truck Council. Available at: http://deepblue.lib.umich.edu/handle/2027.42/65000.

Woodrooffe, J., Bereni, M., Germanchev, A., Eady, P., Glaeser, K.-P., Jacob, B., and Nordengen, P. (2010). *Safety, productivity, infrastructure wear, fuel use and emissions assessment of the international truck fleet; A comparative analysis*. Available at: http://www.internationaltransportforum.org/jtrc/infrastructure/heavyveh/TruckBenchmarking.pdf.

Woodrooffe, J., Page, O., Blower, D., and Green, P.E. (2008). *Commercial medium tire debris study* (Report No. DOT HS 811 060). Available at: http://deepblue.lib.umich.edu/handle/2027.42/61517.