

Trailer Technologies for Increased Heavy-Duty Vehicle Efficiency: Technical, Market, and Policy Considerations

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ABSTRACT

This paper reviews fuel-saving technologies for commercial trailers, provides an overview of the trailer market in the U.S., and explores options for policy measures at the federal level that can promote the development and deployment of trailers with improved efficiency. For trailer aerodynamics, there are many technologies that exist and are in development to target each of the three primary areas where drag occurs: 1) the tractor-trailer gap, 2) the side and underbody of the trailer, and 3) the rear end of the trailer. In addition, there are tire technologies and weight reduction opportunities for trailers, which can lead to reduced rolling resistance and inertial loss. As with the commercial vehicle sector, the trailer market is diverse, and there are a variety of sizes and configurations that are employed to meet a wide range of freight demands. Despite this great diversity, box-type vans represent more than two-thirds of the sales market and likely constitute a large percentage of total trailer miles traveled. In terms of manufacturing and sales, the trailer market is fairly consolidated, with the largest five companies accounting for nearly two-thirds of total sales. The van trailer market is even more consolidated, with the top five companies making up more than 90 percent of total sales. As policymakers in the United States and across North America weigh options for trailer policy measures, the authors recommend integration of trailers into the Phase 2 U.S. heavy-duty vehicle regulatory program, with emphasis on box trailers but inclusion of other types as well.

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INTRODUCTION

Worldwide, freight vehicles are a major and growing contributor to fuel consumption and climate change emissions in the on-road transportation sector. As shown in Figure 1 from the ICCT's Global Transportation Energy and Climate report, in the 2020 to 2030 time frame, heavy-duty vehicle emissions will become approximately equivalent to those of automobiles, currently the largest overall contributor to climate change within the transport sector [1]. In many regions around the world, the majority of goods that are transported by road are borne by heavy-duty combination tractor-trailers. As a result, tractor-trailers often account for the largest percentage of vehicle-miles traveled and thus fuel consumption and emissions from heavy-duty vehicles. For example, in the United States, tractor-trailers are estimated to represent roughly 60 percent of the total fuel use and greenhouse gas (GHG) emissions from

the on-road heavy-duty sector, which also encompasses construction vehicles, refuse haulers, buses, and other trucks including large pickups [2].

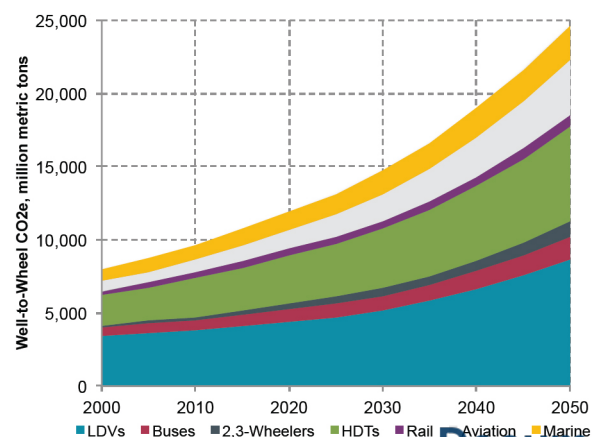


Figure 1. CO₂-equivalent emissions from global transportation

Achieving dramatic reductions in absolute heavy-duty vehicle energy use and GHG emissions, especially in light of widespread projections of increasing freight activity, has proved to be difficult in practice. Economic development has historically been linked to increased freight activity, so as populations and economies worldwide continue to expand, a key challenge in the coming decades will be curbing emissions and fuel use from the most energy-intensive of heavy-duty vehicles-combination tractor-trailers.

Categorically, the findings from literature indicate that there is a large portfolio of extant and emerging technologies for all the major heavy-duty vehicle segments. Vehicle makers and suppliers have been aggressively developing and beginning early deployment of these technologies. Specifically, there are a variety of engine, transmission, and overall vehicle technologies for tractor-trailers that can significantly and cost-effectively reduce fuel consumption.

In recent years, many governments around the world have begun to take targeted steps to promote these fuel-saving technologies within their heavy-duty vehicle fleets. The earliest such regulatory effort, in Japan, was promulgated in 2006 and requires engine efficiency improvements for new vehicles by 2015. The U.S. heavy-duty vehicle program was finalized in 2011; it specifies different GHG and efficiency standards for tractor-trailers, vocational vehicles, smaller pickups, and vans, as well as separate engine standards. California has been especially active in promoting heavy-duty vehicle efficiency by designing regulations aimed at end users. Specific to tractor-trailers, California first introduced a GHG regulatory program in 2008 that affects both California- and non-California-registered vehicles and has accelerated the adoption of many fuel-saving technologies for tractors and trailers. In 2012, China published standards for model-year 2015 vehicles that include full-vehicle testing to ensure the entire vehicle is encompassed in the regulatory program. In early 2013, Canada published standards for heavy-duty vehicles that are fully harmonized with the U.S. program in all significant aspects of regulatory design. In addition, Mexico and the governments of the European Union are actively developing policy measures to accelerate the adoption of fuel-saving technologies for commercial vehicle fleets.

Within the U.S. heavy-duty vehicle GHG program, a range of technologies will be deployed to comply with the Phase 1 performance-based standards that affect model-year (MY) 2014 to 2018 vehicles. Prominent among the technologies will be refinements to fuel injection systems, turbocharger efficiency, engine improvements, and auxiliary system adjustments. In addition, the program will promote full-tractor-body advances such as aerodynamic improvements from roof deflectors, fairings, and bumpers; low rolling resistance tires; mass reduction through the use of lightweight materials; and idling control technologies.

Critically, the initial U.S. heavy-duty vehicle scheme delayed the incorporation of trailers within the rulemaking owing to a number of constraints at the time. As a result, the program does not acknowledge and credit trailer improvements already available that would reduce GHG emissions and fuel consumption, nor does it further the development and deployment of new trailer technologies.

The omission of trailers from the first phase of the U.S. heavy-duty vehicle regulation prompted this investigation of the potential of trailer technologies to increase tractor-trailer efficiency. In their analysis of regulatory alternatives for Phase 1, the U.S. Environmental Protection Agency and the National Highway Traffic Safety Administration considered an option in which dry and refrigerated van trailers would be subject to standards. In that alternative, the average fuel consumption of a MY 2017 tractor-trailer was estimated to be roughly 17 percent lower than the baseline MY 2010 vehicle. In the vehicle program as actually instituted, not taking into consideration trailer improvements, the average fuel consumption of a MY 2017 tractor-trailer was estimated to be about 13 percent lower than the MY 2010 baseline.

This paper is narrowly focused on updating the discussion of the technical, market, and policy dimensions of trailers themselves and the prospects for improving tractor-trailer efficiency through regulation. Although it concentrates on the regulatory context of the United States, the implications of the work are broader. The governments of Canada, Mexico, the European Union, Japan, China, and other nations grapple with similar policy questions and similar demands to increase tractor-trailer efficiency.

The paper seeks to inform policymakers on the question about how best to support trailer technologies that can offer cost-effective GHG emission and fuel consumption reductions. These are its primary objectives:

- Cataloging the technologies and approaches for reducing aerodynamic drag and rolling resistance in trailers
- Providing an overview of the dynamics of the U.S. trailer market as relating to technology adoption and potential policy implications
- Examining policy options for accelerating the deployment of cost-effective trailer technologies.

TECHNICAL BASIS FOR TRAILER-BASED EFFICIENCY IMPROVEMENTS

Fundamental physics dictates that the aerodynamic drag, the rolling resistance between tires and the road, and the inertial acceleration needed because of the weight of a trailer all present forces that must be overcome to propel a heavy-duty tractor-trailer. This section investigates the fundamental characteristics of the aerodynamics of trailers, with a focus on conditions at highway speeds. Also, the section explores the

rolling resistance and opportunities for mass reduction and describes the technologies that are available in each of these areas for diminishing drag and increasing efficiency.

Energy Balance of a Tractor-Trailer

Looking at a rough approximation of the energy balance of a tractor-trailer operating at a constant 65 mph for one hour with no grade (see Figure 2, whose values come from the U.S. Department of Energy 21st Century Truck Partnership Roadmap [3]), energy losses in the engine, amounting to 240 kilowatt hours (kWh), account for roughly 60 percent of the total energy used during an hour of constant-speed highway driving. The energy to move the tractor-trailer includes energy losses associated with aerodynamic and rolling resistance, the drivetrain, and auxiliary loads, which collectively represent the remaining 40 percent of the total energy expended. Focusing on non-engine losses, aerodynamic drag and rolling resistance account for approximately 85 percent (i.e., $[85 \text{ kWh} + 51 \text{ kWh}] / [85 \text{ kWh} + 51 \text{ kWh} + 15 \text{ kWh} + 9 \text{ kWh}]$) of the energy required to move the vehicle. Auxiliary loads (e.g., ventilation and climate control, lighting, compressor, fans) and losses in the drivetrain make up the remaining 15 percent. Rolling resistance and aerodynamic drag are usually similar in magnitude at freeway speeds. At constant highway speeds (roughly 60–65 mph), a percentage point reduction in aerodynamic drag (C_d) and rolling resistance (C_{RR}) yields roughly a half percent and a one-third percent reduction, respectively, in overall fuel consumption. Using the energy balance assumptions of [3] for a tractor-trailer driving at 65 mph, a 10 percent decrease in aerodynamic drag would result in roughly a 5 percent reduction in overall fuel consumption, assuming that engine efficiency is unaffected by load. For rolling resistance, a 10 percent reduction would result in a 3 percent decline in fuel use.

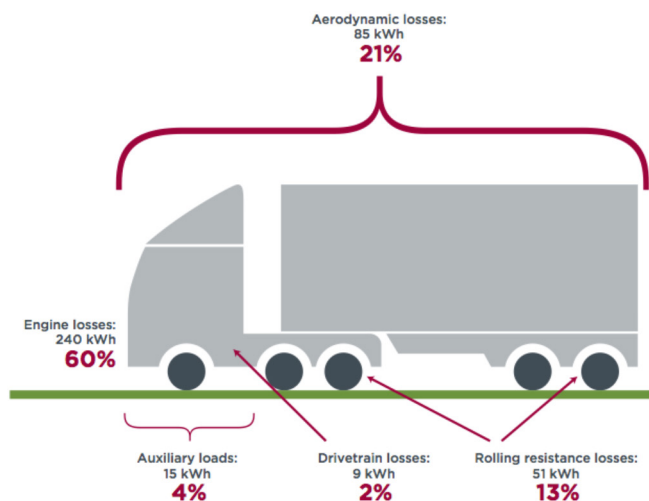


Figure 2. Energy audit of a fully loaded (80,000 lbs. GVWR) tractor-trailer traveling at 65 mph for one hour

In examining the energy expenditures (adapted from Table 3.1 in [3]), it is important to note that the payload carried in the trailer has important ramifications for the loss percentages, particularly for aerodynamics and rolling resistance. As payload

decreases, the force on the tires—and thus the rolling resistance—is reduced. As a result, aerodynamics make up a greater percentage of the losses compared with rolling resistance in cases where tractor-trailer is operating at less than the maximum gross vehicle weight rating (GVWR) of 80,000 lbs. According to an MJ Bradley & Associates analysis [4], only 30 percent of tractor-trailer miles traveled take place with weights of 80,000 lbs. or more, while the remainder of such trips are either volume restricted (i.e., “cube-out,” for payloads that are intrinsically light, maximum volume is reached before maximum weight), are carrying less than full loads, or are “dead heading” with an empty trailer.

A North American tractor with a dry-van or refrigerated trailer has a frontal area of about 100 square feet. At 65 mph, the tractor-trailer's frontal area displaces around 40,000 lbs. of air every minute. That figure approaches the standing empty weight of the tractor-trailer itself. This air must be accelerated to make way for the tractor-trailer. It then passes across the top and the sides of the vehicle, with the disrupted air streams merging again in the vehicle's wake. Aerodynamic improvement allows more of the energy required to displace the air to be recovered as the air decelerates in its wake.

Consider a cube as a very simple representation of this truck, moving through air, with the leading face perpendicular to its axis of motion. The cube displaces air in front of itself, and the air streams flow down the top and sides of the cube and merge again behind the cube. As shown in Figure 3, there are two separate contributions to drag force on the cube. First, the pressure in front of the cube is higher than the pressure behind it, leading to a net retarding force (sometimes called a suction force) in the axial direction. Second, there are shear forces on the four sides (including top and bottom) that are parallel to the flow. These shear forces are associated with a velocity gradient that arises because the air at the surface of the cube has the same velocity as the cube, whereas the air far from the moving cube is either still or moving at the prevailing wind speed.

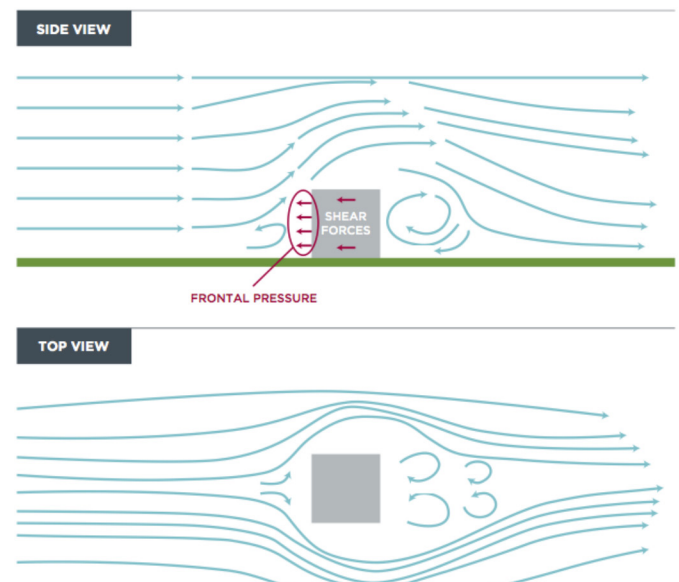


Figure 3. Side and top view of airflow around a cube

When air is accelerated to the traveling velocity, to move out of the way of the cube, some of the air's static pressure is translated into dynamic pressure. The static pressure can be restored only if the air decelerates again without developing eddies. The deceleration in the cube wake does not raise the static pressure appreciably, so the pressure on the back of the cube is lower than the pressure at the front, representing net frontal drag.

The net pressure on the cube is customarily described as being proportional to the square of the velocity, although it in fact varies in a more complex fashion with respect to velocity. The shear forces (skin friction) in simple theory vary in direct proportion to velocity, but this relationship is also approximate. It is cumbersome to describe the total force on the cube in terms of these two different effects, and thus they are usually lumped into an equation that mimics the pressure force. The drag force, F , on the cube, is therefore usually expressed as in Equation (1):

$$F = 0.5C_dAV^2 \quad (1)$$

where A is the frontal area of the cube, around which the air must flow, V is the velocity of the cube through the air, and C_d is a drag coefficient, which is empirically defined by this equation. The drag coefficient is not constant over a range of velocities because the actual flow is more complex than can be described by the simple equation. For this reason, it is always important to present the applicable frontal area and velocity when introducing a drag coefficient into a data set.

Now consider a box that is the size of two cubes placed one behind the other and touching. The frontal area A remains the same, but the side area doubles. This example is depicted in part A of Figure 4, where Cube 1 and 2 have identical dimensions. The value of the drag coefficient rises for the two-cube case. However, neither the force nor C_d doubles. The skin friction on the lead cube is higher than that on the following cube, and the pressure differential between front and back is not experienced twice. By similar example, a railroad train with 100 cars will have a higher drag coefficient than one with 50 cars, but it will not be twice as high.

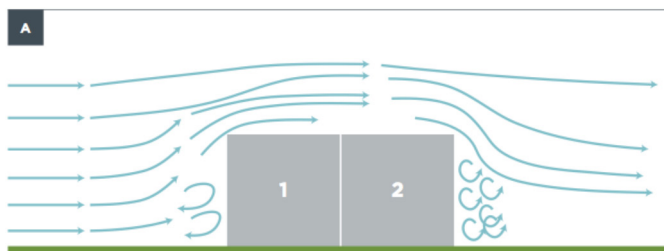


Figure 4.

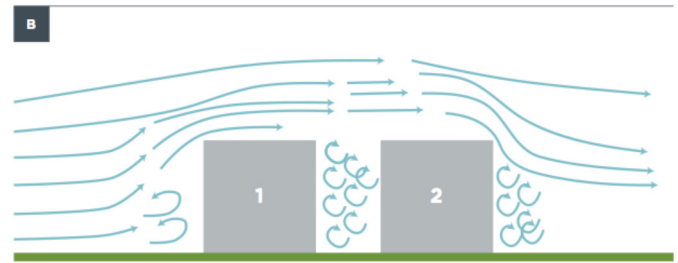


Figure 4. (cont.) Air flow around two cubes and the effect of a gap between the two bodies

However, if the two cubes move through air as one unit but are separated by a gap, C_d is greater than in the case where they are touching because the gap between them will disrupt the air flowing around the cube faces, or boundary layer, and this boundary layer will need to be re-established for the second cube. C_d increases with gap size. This case is shown in part B of Figure 4. These two cubes, separated by a gap, are symbolic of a road tractor and van trailer, and they illustrate the efficiency advantage of reducing the gap between tractor and trailer and keeping the flow in smooth transition from the trailing edge of the tractor to the leading edge of the trailer.

The two-cube arrangement also yields higher drag when the lead cube (i.e., the tractor) is smaller than the trailing cube (the trailer), even if they are arranged on the same center axis. This situation is illustrated in part A of Figure 5. To reduce the overall drag on this pair of cubes, a ramp, rather than a bluff front, is needed to deflect the air from the side surface of the smaller cube to the side surface of the larger cube as shown in part B of the figure. This conclusion has led to the adoption of sloping rooftop surfaces and gap fairings on tractors, as discussed below.

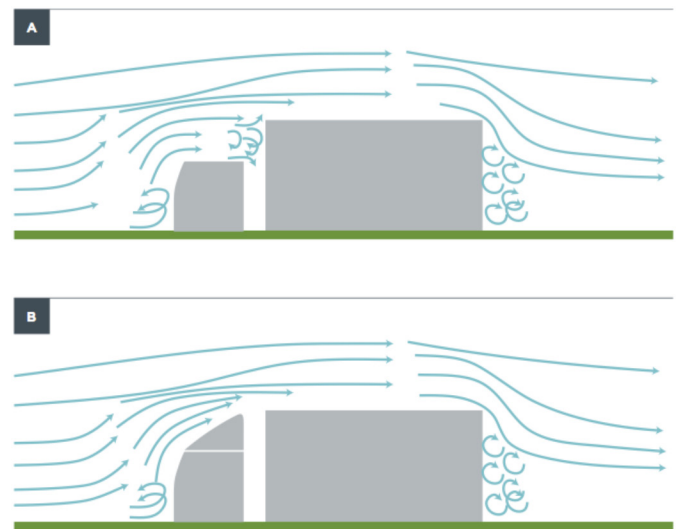


Figure 5. Conceptual diagram of the effect of a roof deflector fairing

If the cube is moving through air a set distance above a stationary surface (as with the underside of a truck above a roadway), some of the air encountered by the cube is accelerated and directed between the cube and the surface.

Between these two, the air creates a velocity gradient, which causes a drag force between the cube and the surface. The air flow still involves boundary layers, but it is affected by the distance between the cube and the stationary surface and develops differently from the layers on the other three parallel sides. Trucks are equipped with air dams (or low bumpers) to reduce the redirection of air into the gap between the truck body and the road. As shown in part B of Figure 6, where the front bumper deflects air away from the space between the tractor-trailer and road surface, the less air that is sucked into this zone, the less air must be accelerated.

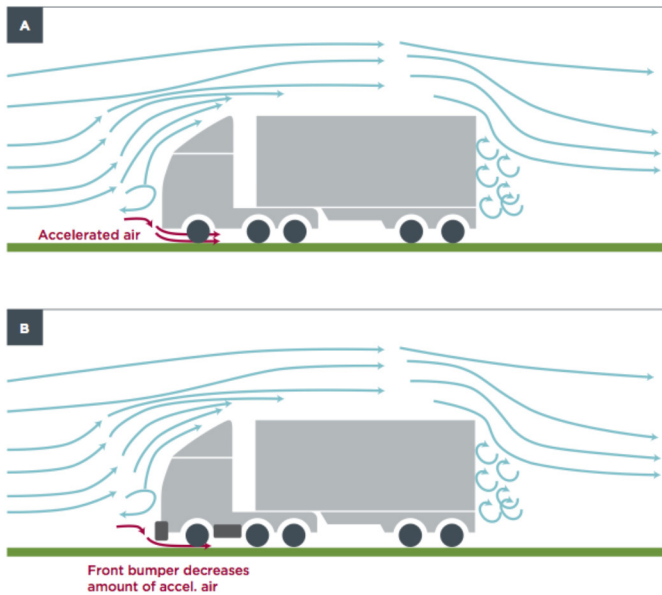


Figure 6. Front bumper reduces air flow between the tractor-trailer and the road surface

Other basic flow concepts are at play. It is well documented that the roughness of a surface can affect the boundary layer and hence the drag force. The boundary layer is thick over most of the length of a trailer, but protrusions such as vertical ribs will disrupt it, leading to more drag.

Aerodynamic drag can also be viewed from an energy perspective rather than through the inertia and force concepts presented above. The truck imparts kinetic energy to the air by accelerating the air to range of velocity values. This results in velocity gradients, which ultimately, due to viscosity of the air, translate into a loss of kinetic energy to heat. Eddies that form in the gap between the tractor and trailer, under the trailer, and in the wake, all decay and serve to create heat from kinetic energy through viscous dissipation.

A historical flow concept that can be used to envision energy expenditure and resistance is mixing length theory. If one takes a "packet" of still air and moves it into the vicinity of any truck surface, the truck has to accelerate that packet, which requires force (or energy) from the truck. When that packet moves away into the bulk of the air, it does not return that force to the truck or resupply the truck with kinetic energy. By this argument, any movement of air to and from the truck surface represents

added drag. This packet movement occurs when eddies of air are present near the truck. The mixing length concept also explains how crosswinds intensify resistance by bringing fresh packets of air near or under the truck. Since those packets have no forward velocity, they must be accelerated by the truck and trailer, leading to higher losses of energy. Simply put, the more that the air near the truck is stirred, mixed, and exchanged, the greater will be the drag.

Influence of Wind

When there is a prevailing headwind or tailwind, the relative velocity between the truck and the air will change. Regrettably, tailwinds and headwinds do not cancel out one another exactly over the operating life of a truck because the drag force is roughly proportional to the square of the relative speed. Thanks to the squared term in the equation, the intensification of drag from a headwind exceeds the lessening of drag from a tailwind of the same velocity.

Crosswinds, winds that buffet the truck from directions other than straight on or squarely behind, produce a yaw angle, which is the angle at which the relative velocities of the truck and the air are at a maximum differential. In Figure 7, the wind acts at an angle with respect to the longitudinal axis of the vehicle. The angular wind vector can be resolved into longitudinal (x-axis) and perpendicular (y-axis) components as shown in the figure. Crosswinds may have different effects on different parts of the trailer. They deliver a net force to one side of the tractor and trailer. This will result in variable stresses on the tires, causing them to slip in a distinct way, and the need to correct the truck direction by setting a steering angle. The resulting additional tire rolling resistance may be seen as an aerodynamic loss. In addition, high-frequency gusts will disrupt the truck's or trailer's boundary layer, increasing the drag.

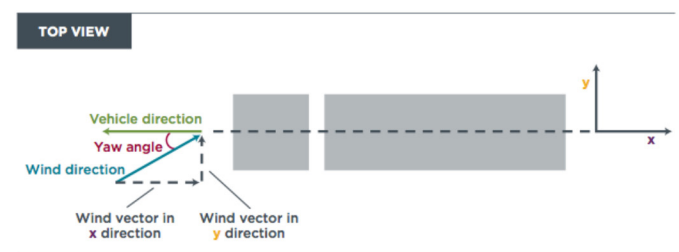


Figure 7. Yaw angle

Trailer-Tractor Interaction

This discussion examines aerodynamic drag on trailers, but the trailer cannot be isolated from the truck in any analysis. It is important to define trailer drag in some consistent fashion: consider that the trailer drag is the sum of the axial forces at the tractor fifth wheel and at the rear suspension. First, the truck dictates the upstream conditions and sets the airflow field that encounters the trailer. Trucks with substantially distinct aerodynamic designs or with varying gap separation from the trailer will affect the drag on the trailer differently while operating at steady speed. They may also affect the benefit

conferred by trailer aerodynamic devices. Second, it is important to note that some drag reduction devices, such as truck rooftop fairings, could, in theory, equally well be attached to the trailer. However, trucks have received greater attention because they are outnumbered substantially by trailers, because geometric constraints favor attachment of devices to the truck, and because some aerodynamic devices offer inside headroom in sleeper cabs. Third, it is not clear whether the truck or the trailer is responsible for the losses associated with the gap, but the consistent definition of trailer drag presented earlier in this paragraph can render this consideration redundant. The presence of the trailer, even when the drawbar pull is subtracted, will affect the truck's own drag force.

Available Designs and Devices

Sides and Underbody of the Trailer

The most common devices added to trailers are skirts, which extend below the trailer on each side between the rear of the tractor and the trailer axles. These may be parallel to the trailer axis, or angled outward to the rear, and they serve to limit flow of air between the underside of the trailer and the roadway on either side of the trailer. This reduces the transfer of momentum from the truck to the surrounding air and presumably also helps to reduce the delivery of air to the underside of a trailer by a cross-wind. Present-day devices usually consist of a flat composite or metal sheet, often with a flexible lower section to avoid road impact (break-over) or railroad crossing damage. Designs with a vertical or lateral bend also exist. The science of measuring or modeling trailer drag is sufficiently precise to allow the demonstration of the effectiveness of skirts but probably not the relative effectiveness of designs with subtle differences. Most of these devices are retrofit components, which do not fully seal the underside of the trailer and do not necessarily work in close conjunction with minimizing losses at the rear axles. Designs exist, particularly in Europe, where the side skirting is integrated and where the rear tires are housed within fenders, but these trailers differ fundamentally from the designs used in the U.S. market.

An underbody surface is a separate device that consists of a surface angled downward under the body of the trailer, directing the air beneath the axle tubes.

Wheel covers may be used on trailer wheel rims as well as on tractor rims. The addition offers modest improvements but is inexpensive. The air pocket in the rim is contained, reducing eddies that lead to losses.

Tractor-Trailer Gap

A trailer gap fairing is a rounded protrusion (or bent panel) at the leading edge of the top of the trailer, which may serve to offset losses associated with a truck with an aerodynamic contour that is not the full height of the trailer. It may also add to the benefit of a truck with a full-height aerodynamic profile by reducing the gap effect.

Various systems, some resembling accordion-like structures, have been devised and patented to close the gap fully while allowing angular change between the tractor and trailer. A curved gap has been proposed to reduce drag in the presence of crosswinds. These devices are not commercially available at this time.

Rear of the Trailer

Various devices exist to decelerate the air passing over the roof and sides of the trailer and to reduce losses in the wake. They serve to diminish the trailer's cross-section over a short distance but add to the overall trailer length. One of the simplest designs-trailer end fairing, tail fairing, or boat tail-offers two panels, positioned in a similar fashion to trailer doors that are three-quarters open, extending about three feet behind the trailer. The intent is to preserve the boundary layer attached to these fairings and to restore pressure by slowing the air to the rear of the trailer sides. An inflatable version exists, in which three panels resemble air mattresses. Additional panels for the roof or floor may be included, leading to a rectangular funnel shape when all four panels are deployed. Several total rear enclosure designs exist, all being "bubbles" or distorted hemispheres. All seek to reduce the tail diameter over three or four feet to the aft of the trailer doors. Where these devices are solid, there is a need to remove them or somehow collapse them for access to the rear doors. Some hemispherical designs are deployed by inflating air.

Rolling Resistance and Tire Technologies

When a tire rolls on the road, it deforms in shape to accommodate a moving "contact patch." The tire, composed of belts and elastomers, is not a fully elastic structure, and the deformation causes energy loss. The energy required to rotate the tire on the road causes tire heating. Generally, the higher the tire inflation, the smaller is the contact patch: deformation and energy loss are then reduced, but the need for traction and reasonable pavement pressure dictates a limit to inflation. The energy that is delivered to the tire can be interpreted as a force in the direction of vehicle motion, multiplied by the distance that the vehicle travels. Although the force exerted is a complex function of both vehicle load and speed, the force required to roll the tire is often approximated as proportional the load (weight) that the tire carries. The constant of proportionality is termed the coefficient of rolling resistance (C_{RR}) and is defined in [Equation 2](#):

$$C_{RR} = \frac{\text{resistive axial force, kilograms}}{\text{normal force, metric tons}}$$

(2)

Values for C_{RR} are typically less than 10, but virtually all current production tires for modern heavy-duty vehicles have a C_{RR} well below this value, typically between 4 and 8 [5].

Procedures to measure C_{RR} are becoming standardized, but they may not reflect the actual in-use values owing to the slight speed and load dependence of the parameter and the dependence of C_{RR} on the type of road surface and tire pressure. During a truck coast-down procedure, the deceleration at low speeds is dominated by tire rolling resistance, but brake drag and losses resulting from bearings, the driveshaft, and the rear of the transmission imply that the coefficient obtained from coast-down overestimates C_{RR} . Values of C_{RR} change when tires are steering and cornering, or when they experience a side thrust while rolling. A truck driving in a crosswind is likely to incur greater rolling resistance because of steering angle and side thrust, and this contributes additional aerodynamic losses to the energy accounting. Also, when the tires are delivering propulsion torque, they complete more revolutions per unit distance of vehicle travel, and when they are delivering braking torque, they complete fewer revolutions. This "longitudinal slip" is expressed as apparent change in C_{RR} . Although basic theory can contend with many of these subtleties, comprehensive data are not available, and most models for C_{RR} are thus deficient in that they are overly simplified.

The energy losses occur both in the tread area and the tire sidewalls. Both the tread area and the sidewalls can be designed to absorb less energy, thereby reducing C_{RR} . This may include the choice of elastomers, arrangement of belts and reinforcement, or tread design. As a result, there are "low rolling resistance" tires in the marketplace. Since some advantage may come from the tread design, the advantage of the low rolling resistance tire relative to a conventional tire may shrink as the tread wears [6]. One of the potential downsides that must be balanced in tire design is the reduced traction, useful life, and braking performance that is associated with lowering rolling resistance.

Further reductions in tire rolling resistance may be obtained by using wide-base single (WBS) tires. A WBS tire can carry a high load and can be substituted for a dual tire set: there are only two sidewalls to flex rather than four, and the energy associated with deformation is reduced. In addition, the rotational inertia is reduced by use of a wide-base tire (and only one rim), leading to reduced energy loss to friction braking in highly transient driving conditions. WBS tires may be unsuited to operations involving a great deal of tight cornering because of scrubbing by the wide contact patch and the imposition of different velocities on the widely spaced sidewalls. Standard dual tires can accommodate cornering more readily by having opposing longitudinal slip on the two separate tires.

Beyond improved tire designs, automatic tire inflation and air pressure monitoring systems can also lower the rolling resistance by helping drivers maintain their tires at optimum pressure. Rolling resistance is strongly related to the air pressure in the tire, increasingly steadily as tire pressure declines below the manufacturer's recommendation. According

to Goodyear, the approximate relationship is that every 10 pounds per square inch (psi) underinflation results in 1 percent poorer fuel economy [6].

The U.S. Environmental Protection Agency's SmartWay program presents a list of accepted low rolling resistance (LRR) tires and retread technologies for Class 8 long-haul tractor-trailers on its website. It is difficult to set up a baseline for conventional tires because their values for C_{RR} vary widely and because values for C_{RR} have been reduced over time. However, based on its testing program, the EPA established the values show in Table 1 [7] as the threshold for designation as an LRR tire for trailers. The EPA site states that fuel savings of 3 percent or more are possible by adopting LRR tires or retreads, which would reasonably correspond to a 10 percent reduction in C_{RR} for long-haul operation.

Table 1. Target values for SmartWay-certified low rolling resistance tires

Test Procedure	C_{RR}
J1269 Application Test Point (1.7-meter drum)	0.0055
J1269 Test Point 2 (1.7-meter drum)	0.0055
J1269 5 point average (1.7-meter drum)	0.0056
ISO 28580 (2-meter drum)	0.0051

Rolling resistance forces are generally greater than aerodynamic forces at lower speeds, and the opposite is true at higher speeds. In describing how the forces acting on a tractor-trailer are a function of vehicle speed, Bernard Tanguay [8] presents an example for a typical tractor-trailer in which the rolling resistance forces dominate until roughly 90 kilometers/hour (~ 55 mph); at higher speeds, aerodynamic drag is the largest force. Therefore, tires with lower rolling resistance typically offer the greatest fuel savings (as a percentage) at low and medium speeds. However, due to the fact that in-use operations can vary considerably in terms of payloads, altitude, grade, temperature, and other ambient conditions, the aforementioned relationship between aerodynamic and rolling resistance drag versus vehicle speed is a simplification should not be taken as valid in all situations.

Mass Reduction Technologies

From a fundamental physics perspective, decreasing the weight of a vehicle reduces the forces needed to accelerate or decelerate the vehicle as well as the forces needed to overcome rolling resistance, which, as described the section above, are approximately proportional the load on the tires. In both tractors and trailers, manufacturers have commercialized and continue to develop products that utilize alternative materials such as aluminum and composites that lower the curb weight (weight with an empty payload) of the vehicle.

Based on analysis done in support of the Phase 1 heavy-duty vehicle regulation, roughly 30 percent of the total miles driven by tractor-trailers in the United States are done at the

permissible weight limit ("weighing-out"), while the remaining 70 percent of miles are driven when the trailer is at its volumetric limit ("cube-out"), carrying a partial load, or empty ("deadheading") [4]. In the case where a vehicle weighs out, reduced curb weight gives the operator the opportunity to increase the payload, thus decreasing the payload-specific fuel consumption, which is the amount of energy (or equivalent emissions) required to move a unit of payload over a unit distance (i.e., gallons or grams per ton-mile). Returning to the example in Figure 2, for a fully loaded (80,000 lbs. GVWR) tractor-trailer traveling at constant highway speeds, reducing the tractor-trailer empty weight by 1,000 lbs. and substituting an equivalent payload would yield approximately a 2 percent reduction in payload-specific fuel consumption [5]. In the case where a tractor-trailer cubes out, the use of lightweight materials makes the loaded vehicle weigh less than it otherwise would, and so less energy is required to accelerate the vehicle and overcome rolling resistance forces. Further, for both weigh-out and cube-out conditions, the use of lightweight materials can help to offset in the additional mass that may be imposed by aerodynamic devices or other fuel-saving technologies.

The development and deployment of lightweight materials in tractors are not discussed in detail in this paper. However, vehicle manufacturers are currently offering lightweight alternatives for a number of structural and body components in commercial products. Moreover, research in this area is driving advancements, many of which are highlighted in the U.S. Department of Energy (DOE) SuperTruck Program, which will be discussed in more detail below. To recognize and promote the commercial availability of lightweight materials in tractors, the U.S. Phase 1 fuel efficiency and GHG regulation credits the use of certain substitute materials as a compliance mechanism for the tractor standard.

For many different types of trailers, there are models currently available that make use of lightweight materials for various components, and customers have options for additional lightweight features or packages. As is discussed in the following section, the van trailer market is dominated by three manufacturers, which together account for more than 80 percent of sales [9]. These manufacturers have employed composites or aluminum in place of plywood lining and steel sheet metal for side wall panels and rear doors in their premium dry-freight van product lines, as summarized in Table 2 [10, 11, 12]. Aluminum wheels and wide-base tires are common optional features for both van and non-van trailers. The use of aluminum in place of steel in wheels provides a weight savings of roughly 30 pounds per wheel, which for a van trailer with eight standard dual tires is a total reduction of 240 pounds [5]. For WBS tires, the approximate weight savings is 175 pounds per axle, or 350 pounds total for a standard two-axle trailer [13].

Table 2. Examples of commercially available dry-van trailers using lightweight materials

Manufacturer	Product Name	Materials	
		Side Walls	Rear Doors
Wabash National	DuaPlate XD-35	Composite	Composite
Great Dane	Champion SE	Aluminum	Steel
Utility Trailer	4000D-X Composite	Composite	Steel

The U.S. DOE's SuperTruck Program is a collaborative research and development program aimed at bettering the efficiency of tractor-trailers. The program is split into four distinctive research projects, which are lead by Cummins, Daimler Trucks North America, Navistar, and Volvo. One of the principal goals of the SuperTruck program is to develop a tractor-trailer that can achieve 50 percent greater freight efficiency (payload tons per gallon) over a defined drive cycle as compared to a model-year 2009 baseline. An additional target that was set by an individual SuperTruck participant is to improve freight efficiency by 68 percent over a defined 24-hour real-world cycle that is meant to represent typical long-haul operations. The project began in 2010, and the teams are on schedule to complete the demonstrations and analysis in 2014/2015 (though it should be noted that all of the SuperTruck teams are on unique schedules with different end dates).

All four SuperTruck teams have a comprehensive research and development approach that includes improvements to virtually every technology area, including the engine, drivetrain, powertrain integration, aerodynamics, rolling resistance, idling reduction, and vehicle frame lightening. Looking specifically at mass reduction strategies, all of the teams are employing lightweight materials in the tractor design. From the latest SuperTruck project review, two of the teams have highlighted the weight savings that are specific to the trailer. The lead for the Cummins team on trailer technologies is Peterbilt. Utility Trailer, which is also a partner on the Cummins team, has cut out roughly 2,500 pounds through the use of lightweight materials and advanced design concepts. The team estimates that this reduction in the trailer curb weight and the corresponding expansion in payload results in an overall increase in freight efficiency of nearly 8 percent. Looking at the tractor-trailer in its entirety, the net weight reduction after accounting for the additional bulk of the aerodynamic and idling management equipment yields a greater than 3 percent improvement in freight efficiency. The trailer manufacturer project partner for the Navistar team is Wabash, which reports that trailer lightening results in roughly 1,200 pounds saved for payload capacity. To put these weight reduction values in context, a conventional trailer weighs about 14,000 pounds.