Transformational Trucks: Determining the Energy Efficiency Limits of a Class-8 Tractor-Trailer

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Abstract

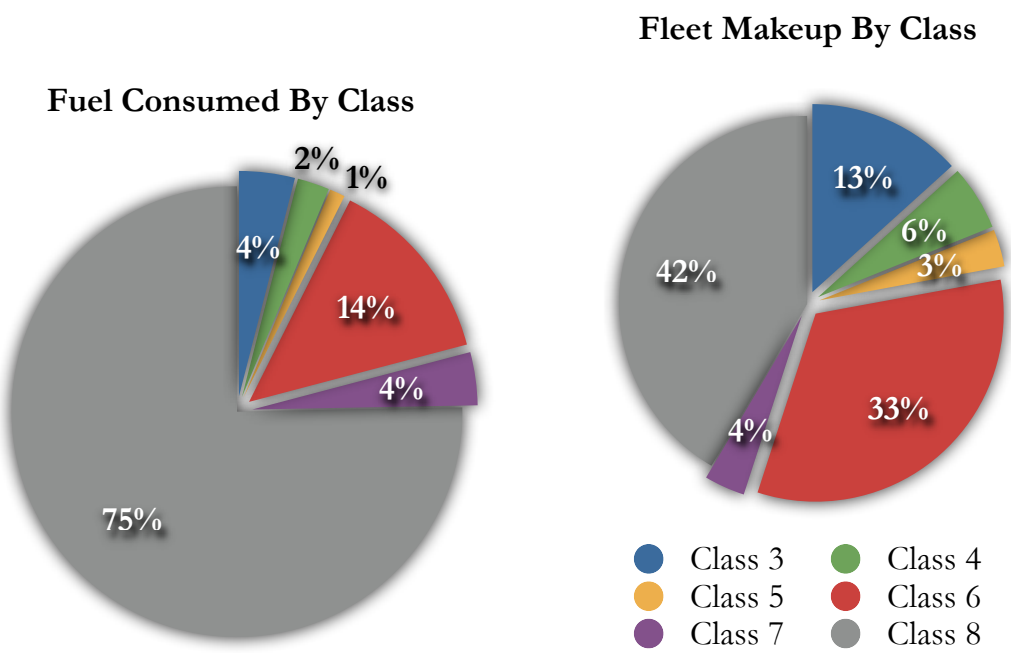
Feasible technological improvements in vehicle efficiency, combined with “long combination vehicles” (which raise productivity by connecting multiple trailers), can potentially raise the ton-mile efficiency of long-haul heavy tractor-trailers by a factor ~2.5 with respect to a baseline of 130 ton-miles/gal. Within existing technological and logistical constraints, these innovations (which don’t include such further opportunities as hybrid-electric powertrains or auxiliary power units to displace idling) could thus cut the average fuel used to move each ton of freight by ~64 percent. This would annually save the current U.S. Class 8 fleet about four billion gallons of diesel fuel and 45 million tonnes of carbon dioxide emissions. The authors’ next paper will quantify these improve-ments’ apparently attractive economics. Further benefits would include lower shipping costs, bigger profits for trucking companies, fewer tractor-trailers on the road, and fewer fatal accidents involving them. Thus transformational, not incremental, redesign of tractors, trailers, and (especially) both as in integrated system can broadly benefit economic prosperity, public health, energy security, and environmental quality.

Introduction

High fuel prices are taking a toll on the trucking industry. In 2007, when diesel fuel cost American truckers an average of $2.89/gallon , the U.S. Energy Information Administration predicted it would average $3.21 a gallon in 2008 [1, 2]. In fact, the average price in January 2008 already exceeded this prediction at $3.31/gal and it has only risen since, passing $4.71 in June 2008 [1]. Fuel prices are slashing or reversing fleet owners' profits; many smaller operators are going broke [3]. The ATA estimates that the trucking industry's fuel bill will rise from $103.3 billion in 2006 to over $110 billion in 2007 [4]. Class 8 truck sales are falling [5]. Regulatory pressure is meanwhile mounting to cut fine-particulates, carbon-dioxide, and other emissions. Slower driving, equipment retrofits, and fuel surcharges to customers aren't fully covering operators' increased costs [6].
No matter how higher fuel prices are split between operators and customers, ultimately they decrease national wealth. Moreover, wasted fuel increases oil dependence and depletion, harms energy security, transfers wealth abroad, and destabilizes the economy. Yet correcting fuel inefficiency is typically profitable, both in general and for trucking [7, 8]. Its life-cycle profits offer adopters a competitive advantage, and can cut freight transportation costs for all.

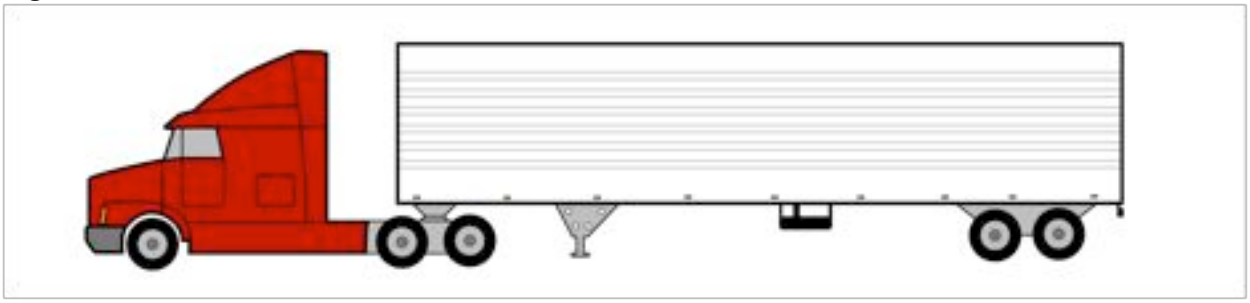
In the United States, transportation uses about two-thirds of all oil. Of total U.S. oil use, Class 7 and 8 trucks used 11.3% in 2000, projected in 2004 to rise to 12.3% by 2025 [9]. This study focuses on Class-8 tractor-trailers, which use 75 percent of the fuel consumed by all U.S. Class 3–8 trucks, as shown in Figure 1 [10].

Figure 1: Class-8 Trucks Account for the Majority (75 percent) of Trucking Fuel Consumed [10]



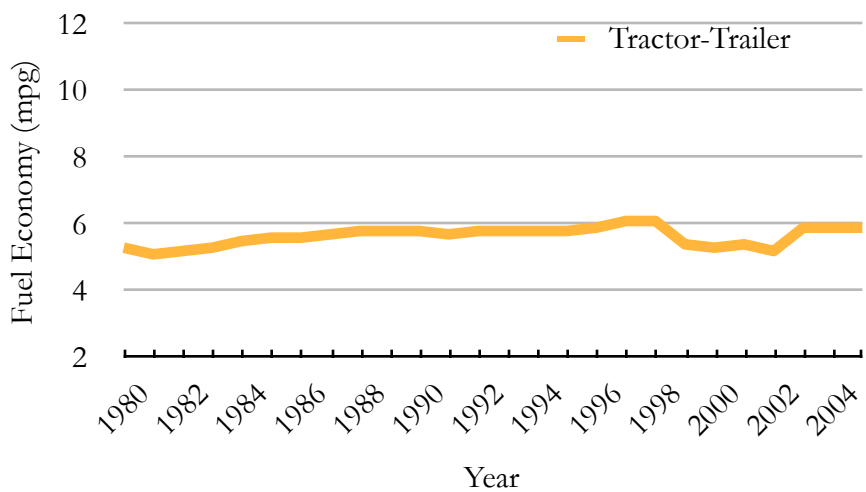
Averaged over its entire lifetime, through many owners and uses, the US Department of Energy finds that a typical U.S. Class-8 tractor-trailer (Figure 2) travels 45,739 miles/y (73,610 km/y) at 5.7 mpg (41.3 l/100 km) [10]. When new, however, it often travels between 100,000 and 150,000 miles/y [11,12]. Our analysis conservatively assumes 100,000 miles/y for efficient new units. The typical tractor-trailer has a 400-hp engine, an aerodynamic drag coefficient C_d of 0.6, dual tires with a rolling resistance coefficient of 0.0073, and an empty weight of 30,000 lb (13,608 kg).

Figure 2: RMI Baseline Tractor-Trailer, C_d = 0.6



From 1970 to 2005, U.S. tractor-trailer fuel economy increased by only 0.6 percent per year (Figure 3) [13]. In December 2007, President Bush signed the Energy Independence and Security Act, which sets the first U.S. fuel economy standards for medium- and heavy-duty trucks [14]. This has increased interest in energy efficiency opportunities in heavy-duty vehicles (HDVs). A heavy-duty truck is over 8,500 pounds in the federal jurisdiction and over 14,000 pounds in California [15]. Specifically we will be focusing on Class 8 tractor-trailers.

Figure 3: Fuel Economy, 1980–2005 [13]



We analyze those opportunities in two stages: Step 1 explores available technological efficiency gains, while Step 2 examines the complementary benefits of increasing volume and load capacity, requiring important regulatory changes we explore. Integrating both steps into a whole-system design yields benefits greater than the sum of the parts—if the parts are properly combined through more collaborative design of both tractors and trailers, making conveniently available both new or retrofit efficiency packages that are designed to work optimally together.

Efficiency is measured in Step 1 largely by miles per gallon, but in Step 2, by ton-miles (or, for lighter and bulkier cargoes, “cube”-miles) per gallon. The purpose of a truck is to deliver tons or “cubes” of freight, so raw mpg is an inadequate and sometimes misleading metric: Step 2 can reduce mpg but can haul so much more freight per tractor-trailer that ton- or cube-miles per gallon increase.

Step 1 includes aggressive but achievable improvements in air drag and tire rolling resistance, weight, and engine efficiency, while modestly increasing volume and weight capacity—all known to be technologically and economically feasible. We first reduce the energy needed to move the

tractor-trailer, and then shrink the powertrain to match the reduced load and adopt more advanced powertrain technologies.

Step 2 investigates hauling two 48-foot (14.6 m) trailers instead of one and increasing maximum gross vehicle weight rating (GWVR) from 80,000 pounds to 120,000 pounds, so each tractor becomes far more productive when part of a "long combination vehicle" (LCV) or (as the American Trucking Association calls it) "high productivity vehicle" (HPV).

Certain assumptions in Step 1 require a fresh approach—a redesign with no preconceived notions—to accommodate the aerodynamics and tractor-trailer interfaces, but our approach leaves unchanged the truck's basic geometry. We assume that trailers will stay the same length they've been for many years—48 to 53 feet (14.6–16.2 meters)—and that tractor-trailers will remain articulated much as they are now—to ensure both "backward" and "forward" compatibility, so new equipment can be coupled with old. We don't assume radical changes to the standard height, width, and load-floor height common in today's trailers because these would require excessive changes to existing infrastructure (roads, bridges, loading docks, etc.).

Step 1: Improving Platform Efficiency of a Class 8 Long-Haul Tractor-Trailer

Class-8 highway trucks continuously require more than 180 horsepower (hp) (137 kW) to drive at 60 miles per hour (mph) (97 km/h) along a level, windless highway. [20] (Our analysis adopts this speed as typical because such trucks typically spend three-fourths of their operating time at highway speeds.) This power is not the engine power, but is the power required at the wheels after being created by the engine and passed through the transmission and axle, often called "tractive load." Of this tractive load, approximately 100 hp (75 kW), is needed to move the air out of the way, while the other 80 hp (60 kW), is needed just to roll the tires of a loaded tractor-trailer. Available technologies can dramatically reduce both these needs. Their relative importance shifts at different driving speeds because the power to overcome aerodynamic drag rises as the cube of speed.

Since this analysis deals with highway (over-the-road) fuel economy, it considers energy savings only in highway driving, not in driving cycles that also include low-speed operation and stops. Thus two important energy-saving options not counted in this paper are reducing idling time and hybridizing the powertrain. Auxiliary power units (APUs), which provide services like comfort and communica-tions to drivers while the main engine is off, are taken to be standard in the future truck industry, and typically save 8 percent of the total fuel used by a conventionally designed tractor-trailer in long-haul use where an average truck not only drives 100,000 miles/y but also idles overnight 1400 hours/y.

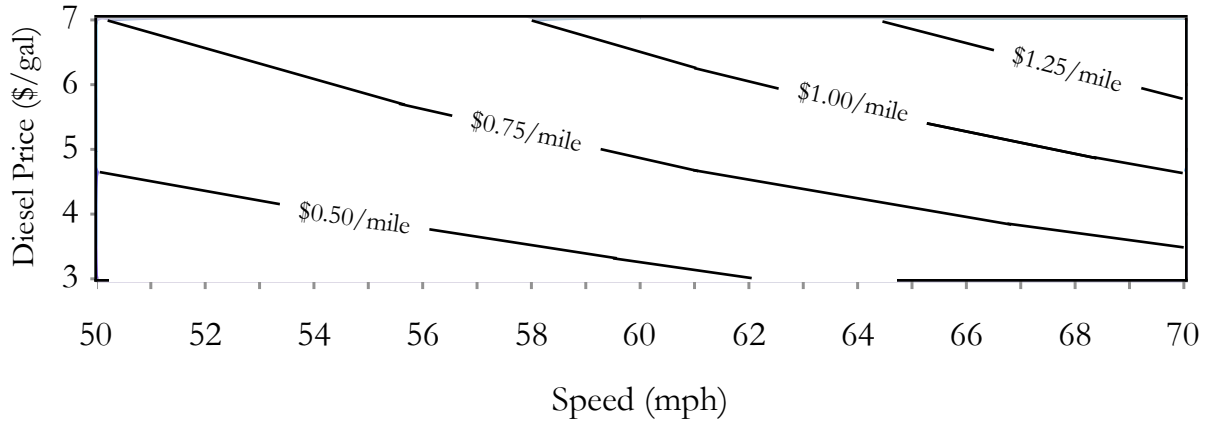
A Brief Look Back

In World War II, General George Patton remarked that "the truck is our most valuable weapon." Since then, the truck industry has seen rapid growth but the truck itself has seen relatively slow technological change. As freight mileage increased rapidly through the second half of the century, the industry was slow to adopt efficiency techniques like the cab roof air deflector. Even today some trucks operate cross-country without this simple device. In 1980 the truck industry was deregulated, leading to an increase in the number of carriers operating border to border, and, after the Surface Transportation Assistance Act of 1983, there was a gradual shift to 53-foot trailers. From 1984 to 2004, the EPA phased in regulations to control oxides of nitrogen (NOx) and particulate matter (PM). These regulations will bring PM and NOx to very low levels through a program that starts in 2007 and ends in 2010 [16]. The benefits to air quality and human health are clearly positive, but the changes represent a large technological challenge for makers of tractor-trailer' diesel engines.

The pressures to adopt APUs are economic and, increasingly, regulatory: in January 2008, the state of California—a leader in heavy-duty tractor emissions regulations—began limiting heavy-duty vehicles from idling for more than five minutes [18]. We also have not considered hybridization because it works best in stop-and-go driving, not in long-haul trucks. On certain urban delivery routes, Eaton and FedEx have achieved a 50 percent fuel efficiency improvement when using hybrid delivery trucks, while Eaton expects just a 3–5 percent fuel efficiency improvement in tractor-trailers in certain highway situations [19].

A final aspect not considered in this analysis is the effect that speed has on fuel economy. Decreasing vehicle speed from 65 mph to 60 mph can improve fuel economy 8%. [54] As diesel prices rise, a fleet operator can keep fuel costs constant by reducing the speed of their trucks. (Figure 4) By incorporating this with changes to logistics costs (delivery schedules, driver wages, etc) a fleet can re-calculate its optimal speed as fuel prices change.

Figure 4: Adjusting Speed to Maintain Fuel Costs[1]

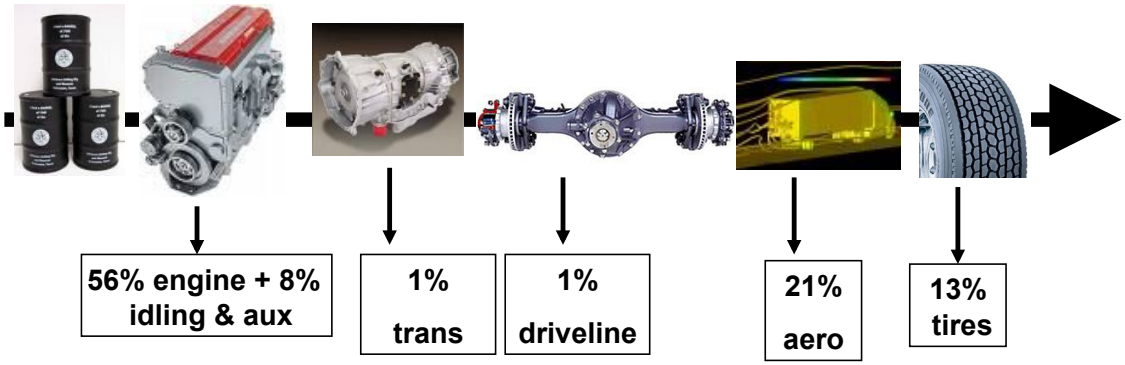


A critical but often overlooked aspect of energy efficiency strategy is the sequence of improvements. Energy efficiency in trucking is traditionally improved by wringing out energy losses from the components with the biggest losses—the engine, idling, and auxiliaries. The DOE's 21st Century Truck Partnership found that the engine's thermodynamic inefficiency wastes 57.9 percent of the energy that the truck uses, auxiliary loads use 3.9 percent, and inefficiencies in the drivetrain are responsible for another 2.4 percent (Figure 5)[20]. If, hypothetically, engine efficiency could be improved 10 percent, you could expect to save about 10 percent in fuel.

This strategy is conventional, straightforward, but suboptimal. A more fruitful approach is to start at the right-hand end of Figure 5, with the energy losses from aerodynamic drag (21 percent) and the tires' rolling resistance (13 percent). Why? Because every unit of energy saved at the wheels, by reducing these two components of "tractive load" (energy required at the wheels to move the vehicle), saves an additional 3 units of energy that needn't be wasted getting it to the wheels. This leverage makes energy-saving efforts most effective at the "downstream" end of Figure 5. Moreover, lower tractive loads don't just save torque and the fuel consumed to produce it, but also make the required propulsion systems smaller, hence cheaper and lighter-weight.

1 A physics-based road load equation was used to derive the fuel economies for producing this contour plot. Assumptions included in this equation represent an average U.S. highway truck which serves as the baseline for this study: Cd = 0.6, Crr = 0.0073, m = 32,000 kg, ρair = 1.2 kg/m3, engine efficiency of 42%, transmission efficiency of 98%, and axle efficiency of 98%.

Figure 5: Energy Use in a Typical Tractor-Trailer [20]



Modestly improving freight-hauling capacity is an even further-downstream improvement than cutting aero and tire drag. We therefore begin with this opportunity, then analyze the main opportunities to reduce tractive load per unit of cargo hauled, then finally examine the upstream opportunities in the powertrain. The much larger capacity increases from Step 2 are considered later.

Design for Reduced Weight and Increased Cubic Capacity

Lighter vehicles save fuel. A typical car weighs roughly 20 times as much as its driver, just 13% of the fuel energy reaches the wheels, and only 6% of the fuel energy accelerates the car (the other 7% is lost to aerodynamic drag and rolling resistance), so only about 1/20th of that 6%, or 0.3%, of the fuel energy end up moving the driver. Fortunately, three-fourths of the tractive load is caused by the car's weight, and energy saved at the wheels leverages sevenfold-greater energy savings at the fuel tank. In contrast, a Class 8 tractor-trailer can haul ~1.5 times its own weight in cargo, and ~34% of the fuel energy reaches the wheels, so about 20% of the fuel energy ends up moving the cargo. Only about two-fifths of the laden gross weight is the empty tractor-trailer itself, vs. ≥95% for the car, but weight saved by lightening the tractor-trailer increases its load-carrying capacity. Thus lightening the truck has less benefit for mpg than in a car, but raises productivity when carrying the ~21% of U.S. cargoes that are limited by weight before volume (i.e., the cargo "weighs out" before it "cubes out").

A tractor's powertrain can be lightened by reducing its required power output (through reduced tractive load or more efficient accessory and auxiliary loads) or by choosing lighter components to deliver a given torque. Combining both methods saves about 3,000 lb (1,361 kg):

- We'll show below that reduced tractive load can provide the same hauling ability up a 2% grade with a smaller and ~1,000 pounds (454 kg) lighter engine
- We'll also show how wide-base tires' lower weight (a benefit additional to their lower rolling resistance) can save approximately 200 pounds (91 kg) per axle, or 800 lb (363 kg) for our baseline truck with four non-steering axles and dual tires.
- Absent extreme conditions, trucks do not require two drive axles. Replacing one drive axle with a non-driven "tag axle" can eliminate two differentials, saving 500 pounds (227 kg).
- Commercially available lighter-weight trailers can save an additional 700 pounds (318 kg).

The slight extra weight of added aerodynamic devices (Table 1) reduces the tractor-trailer's net weight savings from 10 percent to about 7 percent, enabling the tractor-trailer to carry about 7 percent more cargo on the ~21 percent of delivery trips that are done with the vehicle at maximum vehicle weight.

Table 1: Weight change for each modification.

Tractor-Trailer Modification	Weight Change (lbs)
Engine downsize	–1,000 (454 kg)
Rims/tires	–800 (363 kg)
Tag axle	–500 (227 kg)
Lighter trailer	–700 (318 kg)
Subtotal of weight reductions	**–3,000 (1,361 kg)**
Gap seal	+100 (45 kg)
Side skirts	+200 (91 kg)
Rear drag device	+250 (113 kg)
Turbocompounding	+150 (68 kg)
Subtotal of weight additions	**+700 (318 kg)**
Net total	**–2,300 (1,111 kg)**

Tractor-trailer combinations are limited to specific heights, widths, and lengths by state and federal Departments of Transportation (DOT) regulations, but their volumetric capacity can still be raised by lowering the floor. Certain trailer floor sections can be thinned by low-profile, high-strength materials and designs. Small-diameter wheels and tires can also slightly lower the vehicle. Finally, a low-profile "fifth wheel" (the industry term for the connecting mechanism) can bring the tractor's connection point with the trailer closer to the tractor's frame. These features can be seen in a demonstration vehicle by Freightliner (Figure 6). All told, experimental evidence from an experienced operator shows that these measures can lower the trailer floor by 6 inches (15 cm), increasing a typical 53-foot trailer's cubic capacity by 5 percent (Table 2)[21]. This allows our Step 1 fleet scenario to haul equivalent freight in the U.S. with 5% fewer vehicles on the road.

Table 2: Six inches of floor lowering can raise a new trailer's volume by 5 percent

	H (in)	W (in)	L (ft)	Volume (ft^3)
Current trailer	110 (2.79 m)	101(2.57 m)	53 (16.15 m)	4,012 (113.61 m^3)
New trailer	116 (2.95 m)	101(2.57 m)	53 (16.15 m)	4,231 (119.81 m^3)

Even more important than these modest initial gains in hauling capacity are the large reductions in tractive load permitted by modern aerodynamic and tire technologies systematically applied.

Figure 6: Freightliner Argosy demonstrates a lowered trailer floor & low profile tires

Aerodynamics

We described earlier how 100hp of the energy needed to move a Class 8 tractor-trailer at 60 mph (96 km/h), more at higher speeds. Thus, in very round numbers, saving a fifth of the aerodynamic drag can save about a tenth of the fuel [23].

Reducing aerodynamic drag is surprisingly easy, yet widely ignored after initial success with cab-roof deflectors (see box: History of Aerodynamic Retrofits). Although tractors' aerodynamics has won more attention, the opportunity is actually about equally shared between tractor and trailer, which respectively cause about 40–50 and 60–50 percent of total aerodynamic drag [23]. Today's market offers two main options:

- sleeker new tractors like the Freightliner Cascadia (Figure 8), whose smoother shape changes the slope of the windshield and recesses lights out of the airstream, and
- retrofittable improvements to trailers.

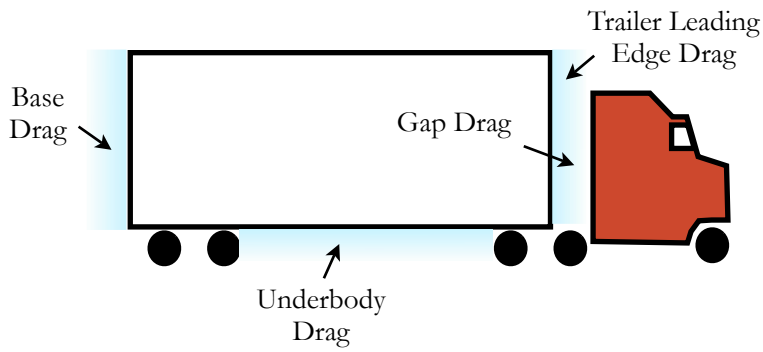
All these opportunities are catalogued by the U.S. Department of Energy's 21st Century Truck Partnership and the Environmental Protection Agency's SmartWay Transport Partnership. Being incremental, they are worthwhile but produce only modest gains, especially since tractor and trailer design are typically dis-integrated, yet the tractor and trailer challenges are closely related (Figure 7): the four most common drag problems for a trailer are the area behind the back of the trailer (the "trailer base"), the area in front of the trailer that is not sheltered by the roof fairing (the "trailer leading edge"), the area beneath the trailer (the "underbody"), and the area between the tractor and the trailer (the "gap"). Thus tractor and trailer aerodynamics cannot be optimized separately.

History of Aerodynamic Retrofits

Origins
The first aerodynamic device was a cab-mounted roof deflector, developed in the 1960s by Airshield [17]. It wasn't until the oil shocks of the 1970s that these technologies were really accepted. They're still not universally used.

Their introduction into the field
In the past, retrofits focused mainly on improving the aerodynamics of the tractor. Modifying the tractor is a comparatively easy first step since an average fleet owns 1 tractor for every 3 trailers. The rising price of diesel fuel is quickly reducing the payback period for trailer add-on aerodynamic devices, making them viable options for saving fuel .

Figure 7: The Four Trailer Aerodynamic Drag Problems



We'll first describe these well-known options, then show how to integrate and extend them by improving trailer aerodynamics at the factory, drastically resculpting the tractor to reduce discontinuities in the airstream, and aerodynamically integrating the tractor and trailer.

Table 3 shows retrofits proven to improve trailer and gap aerodynamics. Together they reduce the typical tractor-trailer's drag coefficient from a nominal 0.6 only to 0.45.

Table 3: Add-on component drag and fuel increments [22, 23, 24]

		Average ΔC_d (100 kph)
Base drag reduction		
Advanced Transit Dynamics TrailerTails		-0.0612
Trailer leading-edge fairings		
Manac prototype trailer leading-edge frame (includes roof fairing)		-0.0335
Underbody drag reduction		
Aggressive	Freight Wing belly fairing (low rider)	-0.0435
	Laydon Composites main and rear skirts	
Gap sealing		
Fifth wheel forward 254 mm (resulting in what gap width?)		-0.0163
Total Drag Reduction:		**-0.1545**

Further drag can be saved in the tractor (Figure 8), as Freightliner did in its Cascadia vs. Columbia model, saving 3% of total fuel use [25].

Figure 8: Freightliner Cascadia (right) delivers a 3 percent fuel economy gain over its predecessor, Freightliner Columbia (left).

Transformational Tractor-Trailer Path

Much larger drag reductions require a transformational tractor-trailer integrating four key features:

1. a nearly sealed tractor-trailer gap, using deployable four-sided gap sealing (Figure 9);
2. full skirting of the tractor and trailer (equivalent to Figure 10);
3. a rear drag device (boat-tail) approximately 3 feet in length (Figure 11); and
4. a different cab shape with minimal aerodynamic discontinuities.

Sealing the tractor-trailer gap (Figure 9) reduces drag and, like the boat-tail (Figure 11), is especially helpful in crosswinds (See box: Yaw Angle). At low speeds, the four-sided “gap seal” would retract against the cab so the vehicle can articulate around corners. A two-sided prototype version of this kind of device was released by Mack in November 2006. Smooth logistics require that the retractable gap-sealing system allow the tractor and trailer to be detached by normal means, and that new and old tractors and trailers are compatible with one another.

Full skirting of the tractor and trailer has been done in the past, and recently several rear-drag devices (Figure 11) have proven effective in prototype tests. We propose that the tractor be far more aerodynamic and fully integrated with the trailer. It might adopt the “cab-over”[2] designs common in the United States during the 1970s, but other configurations could also meet our drag targets.

[2] “Cab-over” describes the relative position of the cab and the engine. In a cab-over design the cab is positioned over the engine.

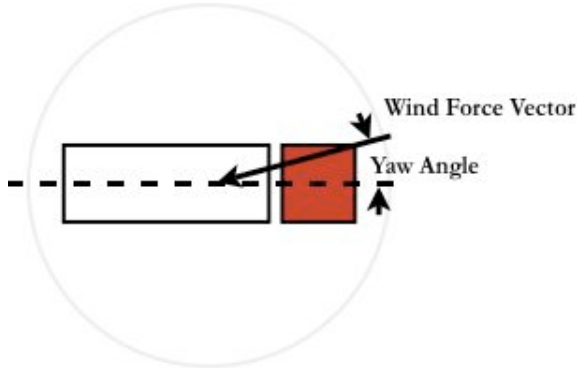
Figure 9: Gap Seal Prototype [26]

Figure 10: Full Skirting Device [27]

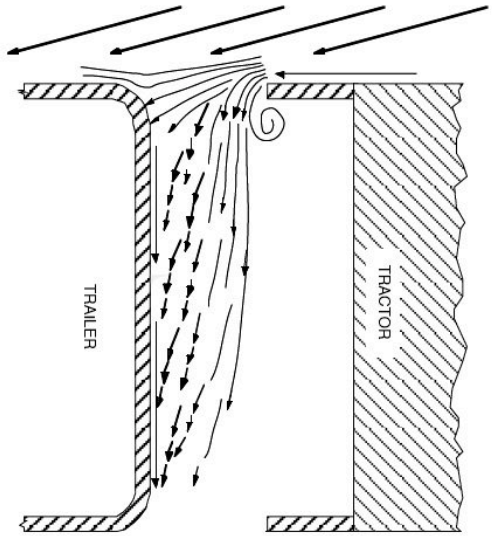
Figure 11: Rear Drag Device [28]

Yaw Angle, Cross-gap flow, and its affect on drag

When a tractor-trailer moves through the air, any cross-wind creates what is known as a “yaw angle” in the oncoming air.



This yaw angle causes air to move from one side of the vehicle to the other through the gap between tractor and trailer, a phenomenon known as cross-gap flow shown below [22]. Depending on the direction and strength of the cross wind, this cross gap flow can significantly increase the aerodynamic drag of a tractor-trailer.



Source: Solus, [22]

Gap sealing systems as shown in Figure 9 can eliminate this type of drag. Rear drag devices shown in Figure 11 also reduce drag in yaw situations by controlling airflow around the base of the trailer.

Figure 12. Likelihood of yaw angle [29].

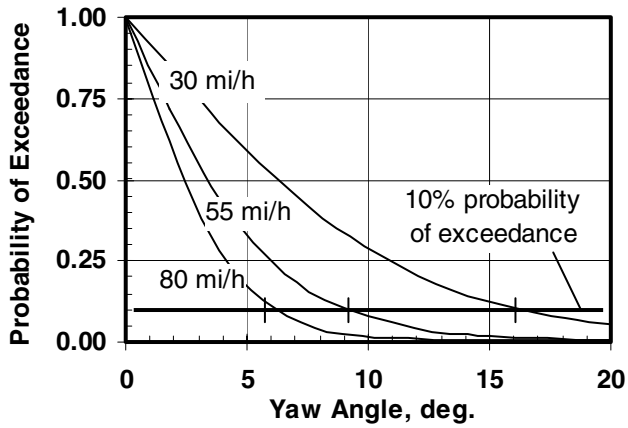
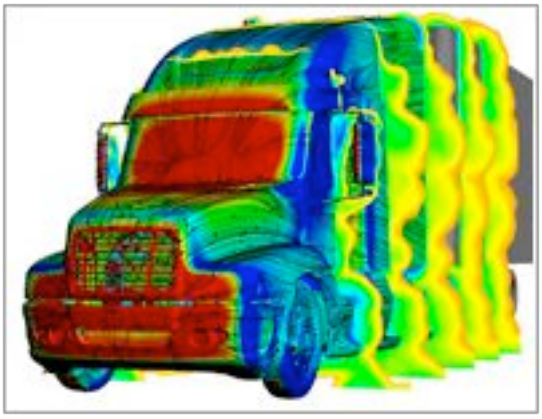


Figure 13: Pressure discontinuities on the tractor's grill, hood, windshield, and roof [30]



The best design will incorporate the features of Figures 9–11 while avoiding the pressure discontinuities of Figure 13, where red areas on the windshield and grill/bumper reveal multiple energy-wasting pressure buildups that should be reduced in both number, size, and severity. Such a design is illustrated by an articulated bus with dimensions similar to those of a heavy truck, as seen in Figure 14. A wind-tunnel test by National Research Council Canada (NRC) on a Prevost articulated bus demonstrated a coefficient of drag of just 0.384. In its stock form, this bus incorporates a gap seal, low sides that emulate tractor and trailer side skirts, and a flat front end that eliminates the multiple aerodynamic discontinuities caused in a tractor by the horizontal separation between hood, windshield, and sleeper roof [17]. When this heavy vehicle was tested with minor aerodynamic modifications, including the addition of a rear drag device and the removal of its mirrors, the modified articulated bus (Figure 14) achieved 0.311 C_d—barely over half that of a typical Class 8 tractor of similar size.

Table 4: Measured average coefficient of drag of a Prevost bus after incremental changes

	Average ΔC_d (60mph)
Single Prevost Bus	0.384
Articulated Prevost H5-60 bus	0.418
Articulated Prevost H5-60 bus, no mirrors	0.344
Advanced articulated bus	0.311

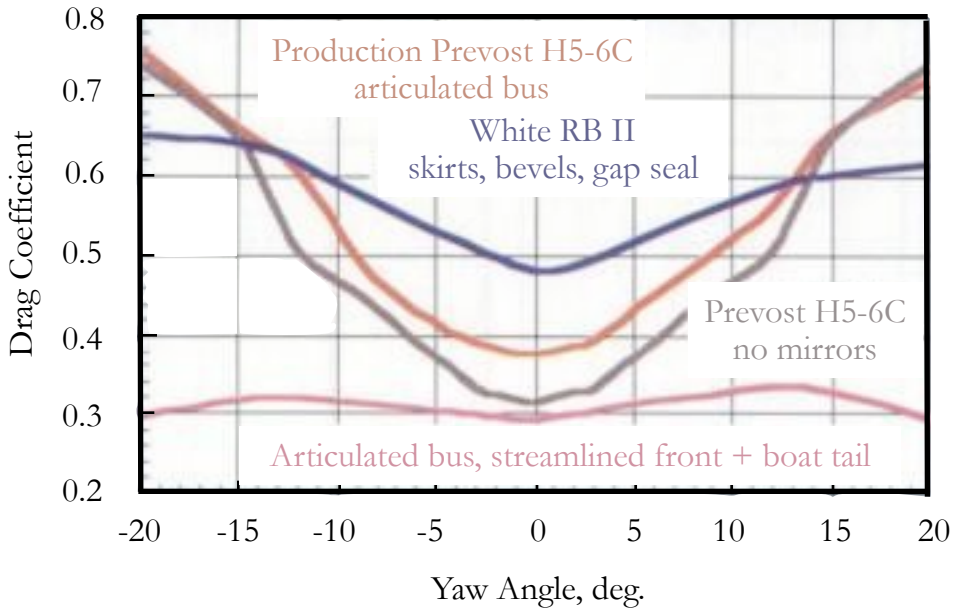
Figure 14: Prevost H5-60 Bus with C_d of 0.384, later reduced to 0.311

This bus's design addresses all four of the aerodynamic trouble areas in a tractor (Figure 7) with integrated solutions that can all apply to a Class 8 tractor-trailer. While we were unable to locate a Class 8 truck test where this exact combination of devices was analyzed, we are confident that a tractor-trailer applying these principles and other aerodynamic innovations would be fully capable of achieving a coefficient of drag of ~0.3, although it might look quite unfamiliar.

To be sure, this bus isn't designed to haul heavy loads up long grades, so it lacks the tractor's big radiator. But the truck's reduced tractive load reduces engine size and cooling needs by one-fourth, as discussed below, from a nominal baseline design; turbocompounding would further reduce the cooling needed per horsepower delivered; and the resulting drag can be made small or negative by aerodynamic ducting of cooling air from positive- to negative-pressure zones. Radiator airflow can also be actively managed with a simple shutter system in the grill to minimize real-time drag by opening to maximize flow on long steep grades where speed is low while closing to minimize flow while cruising at high speed; the vehicle aerodynamics community is considering this option for light- and heavy-duty vehicles.

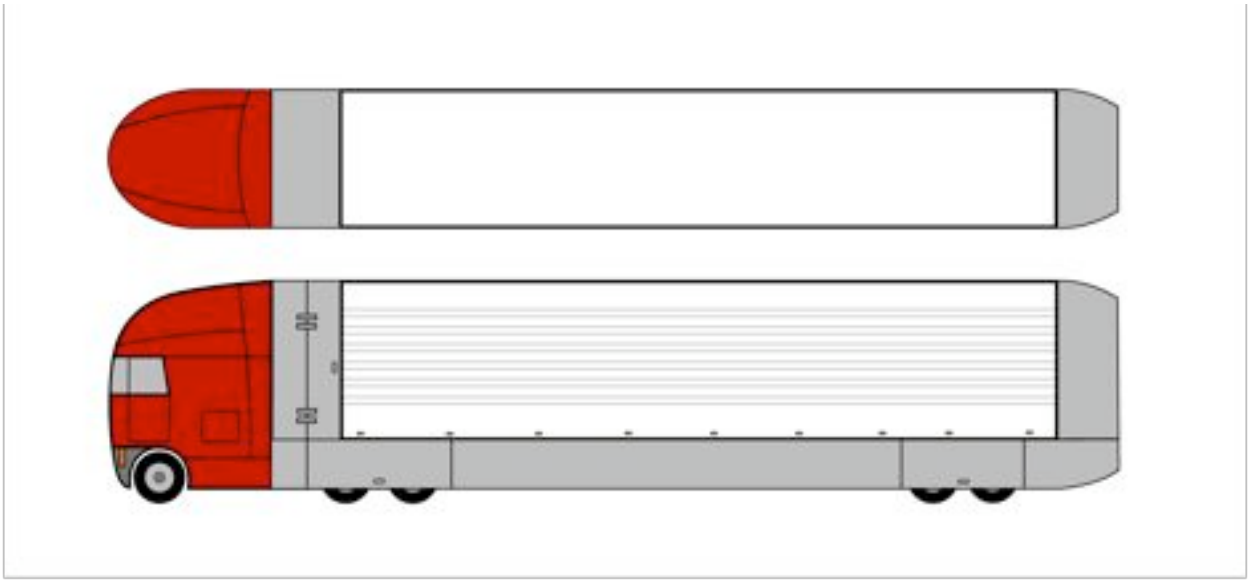
Figure 16's dependence of drag on yaw angle is important. Driving in crosswinds makes air swirl through the tractor-trailer gap, causing more turbulence and drag. Sealing the gap and adding a rear drag device can nearly eliminate this dependence (bottom curve). Figure 12 further demonstrates that a highway truck is <10% likely to experience >10˚ yaw while operating at 55 mph, so higher yaw angles are a rare U.S. design condition. Note that at high yaw angles, total drag increases due to greater effective frontal area, which must be multiplied by C_d.

Figure 16: Drag Coefficient of the Prevost H5-60 *vs.* a Typical Tractor-Trailer Retrofitted with the Aerodynamic Improvements in Table 4 [17]



A tractor trailer designed with all of the above aerodynamic considerations may look like the artist's rendering shown in Figure 15. This sketch incorporates one possible embodiment of the important aerodynamic features we include in our Step 1 analysis while retaining the basic shape and function of an articulated tractor trailer.

Figure 15: Artist's Impression of a Tractor-Trailer Incorporating Integrated Design Methods



Low-Rolling-Resistance Tires

New technologies can reduce the energy required to overcome the rolling resistance of a tire, caused by friction between and within its many structural layers as the shape constantly shifts between round and flat. The energy lost to heating the tire and road can be reduced by changing the rubber compound, other materials, and construction (layering). Changing the types, quantities, and configurations of all the tire's materials offers considerable latitude in such characteristics as longevity, stiffness, rolling resistance, heat tolerance, traction, and handling. The tire is an exception-ally complex structure and must be optimized in concert with the vehicle design as well as driving conditions, but there is still a well-established potential to reduce rolling resistance without compro-mising other qualities, as illustrated by the gap between the best-in-class and average tires on the market. That is the gap our analysis exploits; potential further gains are possible but not assumed.

Tractor-trailer operators can also replace dual tires with a wider-tread single tire, often called a wide-base tire. Wide-base tires do the work of separate dual tires, with the same performance and safety, but they weigh less because they have fewer sidewalls and have other construction changes. An axle equipped with wide-base tires on aluminum rims is typically 200 pounds (91 kg) lighter than typical dual tires with steel rims. Michelin performed tests where they blew out the steer, drive, and trailer tires and found no significant difference in performance when compared to duals [31].

Combining advanced construction and rubber compounds with wide-base tire designs can save 5 percent of a typical Class 8 fleet's fuel [32]. We assume the following coefficients of rolling resistance (C_{rr} in automotive parlance) for average and best-in-class tractor-trailer tires (Table 5):

Table 5: Portfolio Assumptions for Coefficient of Rolling Resistance [20, 33]

Portfolio	Coefficient of Rolling Resistance
Baseline	0.0073
Step 1	0.0052

Powertrain

These aerodynamic and tire improvements can together save two-fifths of tractive load (Table 6) as calculated from vehicle physics (Appendix 1). This lower load then permits a smaller engine with less weight and cost (Table 6).

Table 6: Efficient tractor-trailers need less pulling power

Portfolio	Operating Conditions
Baseline	185 horsepower road load (138 kW) @ 60 mph (97 km/h) steady state
Step 1	110 horsepower (82 kW) road load @ 60 mph (97 km/h) steady state

The average U.S. Class 8 tractor-trailer is powered by a nominal 400-hp (298 kW) engine. The difference between that peak power output and "steady-state" horsepower is called "reserve torque" and is available for acceleration during passing and hill climbing. Because we have lowered the steady-state horsepower requirement by 73 hp (54 kW), the Transformational Truck characterized in Step 1 will be able to use a 300 hp (224 kW) engine to achieve the same normal performance as a conventional truck using a 400-hp engine (298 kW). We assume no efficiency

benefit from the smaller engine, but it does weigh about 1,000 pounds (454 kg) less, and cost about $2,000 less [34, 35].

Matching engine performance to required steady-state horsepower may significantly reduce hill-climbing speed at very steep grades, but need not do so at ordinary grades. RMI's vehicle-physics analysis (Appendix 1) confirms that with Step 1 improvements, a 2 percent grade can be sustained at 60 mph (97 km/h) at full GWVR with a 300-hp engine turbocompounded to 330 effective hp—the same speed on a 2% grade that originally required a 400-hp engine in the baseline tractor-trailer. That is, the decrease from 400 to 300 hp is offset by reduced aerodynamic drag and rolling resistance, plus turbocompounding.

Increasing engine efficiency and reducing engine auxiliary loads, such as fans and pumps, is a key focus of the DOE 21st Century Truck Partnership. Using a baseline of 42 percent engine efficiency, we propose two well-understood improvements to engines to increase their efficiency. Turbo compounding increases nominal thermal efficiency from 42 to 45 percent and peak engine power by 10 percent; it is commercially available in North America, notably in the new Detroit Diesel DD15. (Some turbocompounding innovations are expected to yield further improvements.) An additional increase in thermal efficiency, from 45 to 48 percent, can come from truck engine friction reductions, auxiliary savings, and combustion improvements, all based on 21st Century Truck Partnership predictions. This new peak engine thermal efficiency of 48 percent for Step 1 is below the 2010 target of 50 percent and far below the DOE 2013 stretch target of 55 percent.

Conclusions, Step 1

Our findings align well with those of DOE's 21st Century Truck Partnership. It found that the current 6.8-mpg fleet could be improved to 11.5 mpg. Our analysis shows that an improvement from 6.5 to 12.3 mpg (at 60 mph) is feasible through tractor-trailer integration and whole-system design. Our conclusion is confirmed by recent track tests of a Mercedes-Benz Actros tractor-trailer that demonstrated 12.4 mpg hauling a 25-tonne payload at 50 mph [37]. This saving is worth $30,000 per year per truck,[3] or when spread across a baseline fleet of 500,000 trucks, to $15 billion worth of diesel fuel and 40 million metric tons[4] of CO_2 equivalent saved. Table 7 below summarizes these results. To achieve this savings, RMI considers the aerodynamic goal to be critical, requiring attention from the entire industry. This target is also perhaps the most challenging, though not technically-speaking, of the improvements we recommend as it requires collaboration among the segmented businesses of truck makers and trailer makers, in coordination with the needs of the customer base.

3 Assuming implemented on 500,000 trucks that travel an average of 100,000 miles per year at 60 mph. U.S. average price of diesel is $3.94/gal [36].

4 Using the following CO_2 eq, for CO_2, CH_4, and N_20 respectively, 2.73 kg/L, .00325 kg/L, and .02384 kg/L.

Table 7: Summary of Results of Step 1

	Baseline	Step 1
No. long-haul tractor-trailers	500,000	475,000
Distance traveled (miles/y)	100,000	100,000
Fuel economy (mpg)	6.5	12.3
Freight efficiency (ton-mile/gal)	130	275
Fuel used (gal/y)	7,700,000,000	3,900,000,000
Fuel saved (gal/y)	n/a	3,800,000,000

Step 2: Increased Use of Long Combination Vehicles (LCVs)

Step 1 proposes a vehicle that moves freight more efficiently primarily by reducing the amount of drag it creates. In contrast, Step 2 explores hypothetical changes regulations so that trucks can haul more freight on each trip. To do this we propose that nationwide truck length and weight laws allow trucks to haul two trailers on certain roads. Step 2 includes the productivity benefit from adding a second trailer and increasing the maximum allowable vehicle weight to 120,000 pounds, while including the vehicle efficiency changes described in Step 1.

In fact, the United States has some of the lowest weight limits of western countries. This can create bottlenecks for freight. Canada allows combination vehicles up to 138,000 pounds; Scandinavia[15], up to 130,000 pounds. The U.S. Department of Transportation's 1995 Comprehensive Truck Size and Weight Study found that "Europe specifies a unique GVW limit of 97,000 pounds for a six-axle semitrailer combination handling an international container. Mexican and Canadian general weight limits are high enough to accommodate fully-loaded ISO containers.

Canada's regulations also permit configurations which can handle one-20 foot and one-40 foot fully loaded containers on the same vehicle, or three-20 foot containers nearly fully loaded [sic]."

LCV Use In The U.S.

Adding a second or a third trailer to Class 8 trucks is common in certain states, and is a simple way to deliver more goods per trip. Because many trucks in the United States are loaded to capacity in volume but not in weight, adding a second trailer allows additional goods to be carried. Step 2 of this study proposes double 48-53-foot trailers.

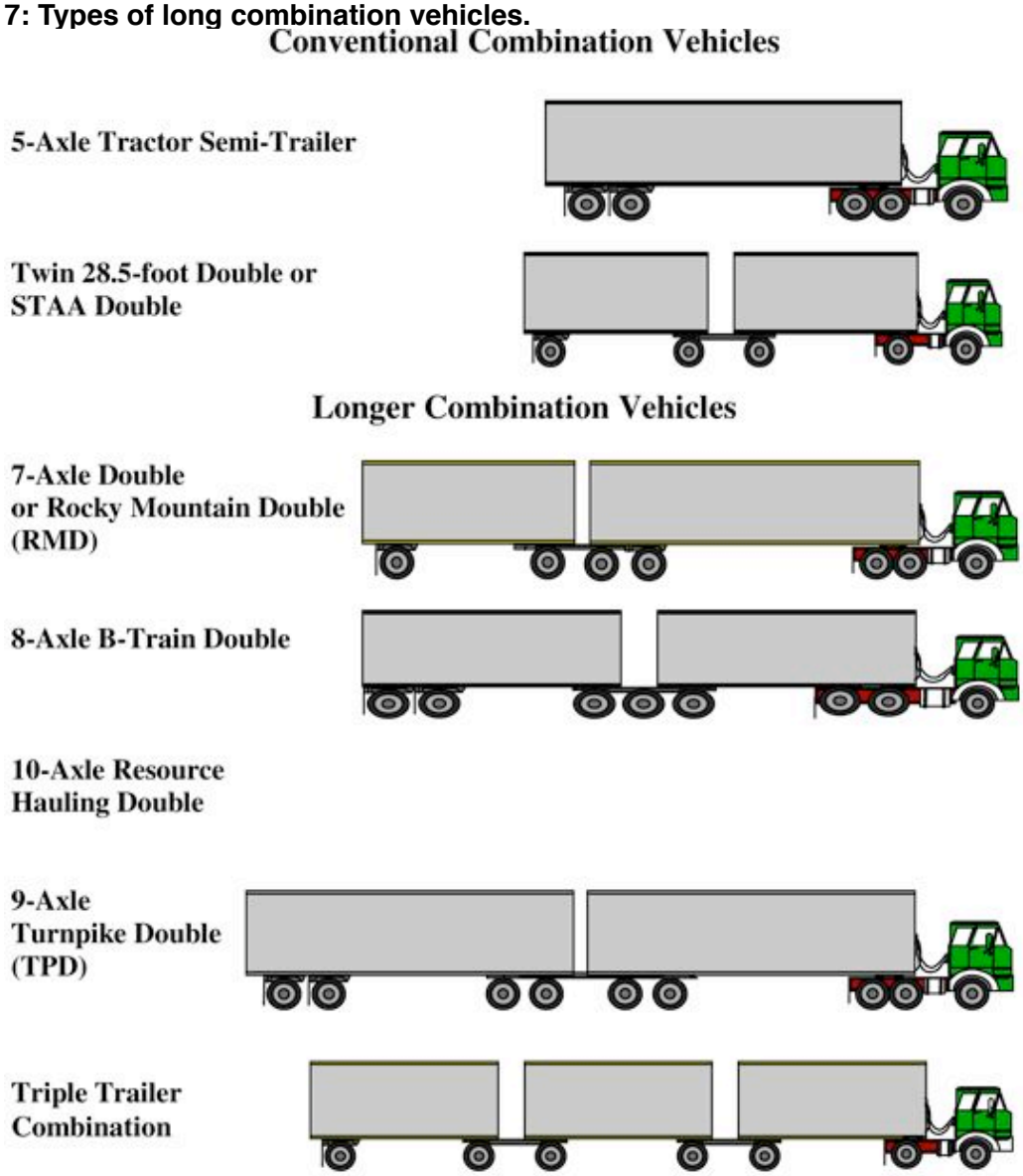
Table 8: Long Combination Vehicles in 13 North American States [38]

States	Truck Tractor and Two Trailing Units		Truck Tractor and Three Trailing Units	
	Length (ft)	Weight (1000 lb)	Length (ft)	Weight (1000 lb)
Colorado	111	110	115.5	110
Idaho	95	105.5	95	105.5
Kansas	109	120	109	120
Montana	93	137.8	100	131.06
Nebraska	95	95	95	n/a
Nevada	95	129	95	129
North Dakota	103	105.5	100	105.5
Oklahoma	110	90	95	90
Oregon	68	105.5	96	105.5
South Dakota	100	129	100	129
Utah	95	129	95	129
Washington	68	105.5	n/a	n/a
Wyoming	81	117	n/a	n/a

Long combination vehicles (LCV) are defined as multi-trailer combination vehicles operating on the U.S. “National Network” and weighing more than 80,000 pounds (36,287 kg) GWVR. Today, all 50 states allow double 28-foot trailers, and 22 states allow trucks to weigh more than 80,000 pounds (36,287 kg) (the U.S. Federal maximum). By harmonizing laws to permit higher weights and longer vehicles, U.S. truck fleets could deliver more freight per trip, using less fuel per ton-mile delivered.

As seen in Figure 17, LCVs in the United States take many forms depending on many circumstances, including regional infrastructure, freight demand, and company logistics. This study, emphasizing long-haul economics, evaluated a combination vehicle whose available data for vehicle productivity, vehicle stability, and vehicle safety overlapped: two 48-ft trailers weighing up to 120,000 pounds, commonly known as a “turnpike double.” That’s more broadly defined by the Department of Transportation as a tractor pulling two 48-ft trailers or, in Canada, two 48–53-ft trailers. We recommend that broader regulations permit both 48-ft and 53-ft trailers in the U.S. because a large portion of freight in North America is currently hauled on 48–53-ft trailers that could be hooked together with little additional equipment.

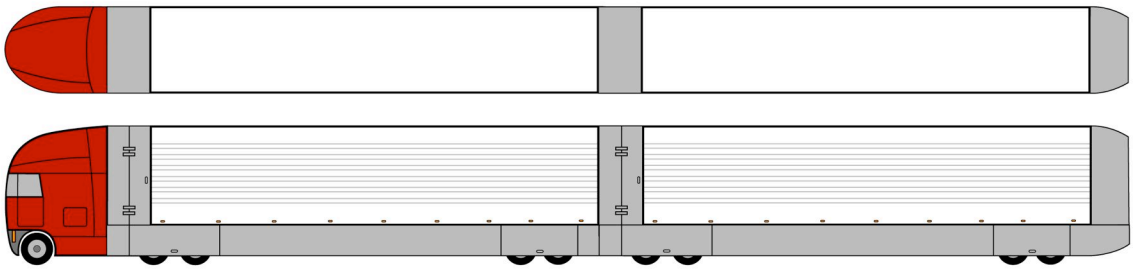
Figure 17: Types of long combination vehicles.



Assumptions, Step 2

Our analysis applies Step 1 efficiencies before Step 2 combinations. A turnpike double has two aerodynamic gaps to seal, not one. To seal the gap between the two trailers, we propose adjusting the aerodynamic surfaces on the first trailer's rear drag device: actively changing the panel angles could continuously optimize the fit while driving around curves. The second trailer's rear drag device will serve as the rear drag device for the entire combination vehicle. Clearly, the tractor's miles per gallon will drop when towing a second trailer whose extra capacity nonetheless delivers more total ton-miles per gallon despite the second trailer's empty weight, cargo weight, aerodynamic drag, and rolling resistance. A recent study by ATRI evaluates this net effect based on the cargo's weight and volume .

Figure 18: Schematic of one possible version of a fuel-efficient turnpike double.



The American Transportation Research Institute (ATRI) recently released an update to its study "Energy and Emissions Impacts of Operating Higher Productivity Vehicles." That study used widely accepted modeling methods—notably Cummins's Vehicle Mission Simulation Tool—to identify the benefits of changing truck size and weight regulations. The study compared today's common five-axle tractor-trailers and a double-trailer configuration with various other combinations of length and weight. Taking into account the drop in miles per gallon (mpg) when towing a second trailer, the study calculated fuel saved per ton-mile of delivered freight. Though the tractor's mpg actually went down, that was offset by the truck's hauling twice as much freight as with a single trailer.

Analysis, Step 2

ATRI found that where 120,000-pound GVWR is permitted, a turnpike double could haul additional freight with 15–39 percent less energy per ton-mile than a standard single (Table 9). In a volume-limited ("cube-out") scenario, adding the weight of a second trailer was assumed to double the amount of cargo delivered without exceeding GVWR. In a weight-limited ("weigh-out") scenario, the cargo was assumed to be dense enough to make the standard single weigh a maximum 80,000 pounds, so little additional cargo of similar density could be added to the second trailer, reducing the fuel saving per ton-mile to only 15 percent. For simplicity, ATRI did not analyze the potential for sophisticated logistics to optimize the capacity increase by mixing high- with low-density cargoes.

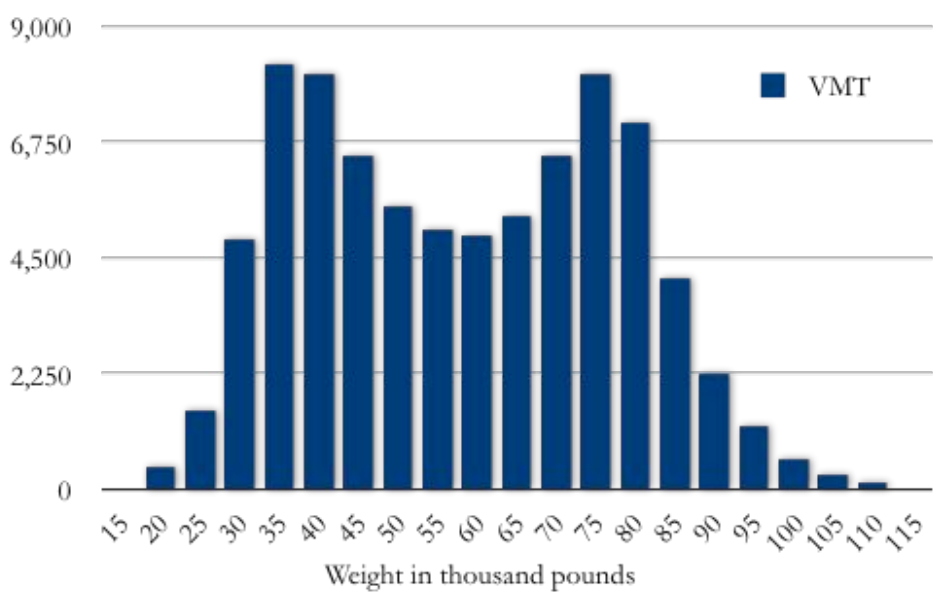
RMI's road load analysis incorporates the increased air drag associated with a longer vehicle [17], its higher weight, and new empty weight to compute the resulting fuel economy. An LCV incorporating our Step 1 design recommendation delivers an estimated 8.7 mpg which is lower, as expected, than a single trailer. However, the increased delivery of goods more than makes up for this, resulting in an increase in freight efficiency of 2.5x over our baseline vehicle.

Table 9: Configurations and fuel savings

Configuration	Description	Percent improvement in ton-mile/gal
Baseline configuration (Traditional tractor-trailer)	Single trailer, 5-axle combination vehicle, 80,000 lbs max. GVWR	N/A
Turnpike double adopted by a volume-limited fleet	Two trailer, 9-axle combination vehicle, 120,000 lbs max. GVWR, operating at approx. 100,000 lb	39%
Turnpike double adopted by a weight-limited fleet	Two trailer, 9-axle combination vehicle, 120,000 lb max. GVWR, operating at 120,000 lb	15%

To estimate the impact of these Step 2 improvements in the fleet, we must assume how many U.S. freight ton-miles could reasonably be shipped in turnpike doubles. About 63 percent of ton-miles are traveled on highways, the rest in urban areas [38]. Since congestion and infrastructure constraints might make turnpike doubles problematic in cities, we conservatively assumed that LCVs could carry 63 percent of all U.S. ton-miles, with the remainder carried by our Step 1 tractor-trailer. We also assumed that 80 percent of ton-miles are volume- and 20 percent weight-limited, consistent with Figure 19, which shows that 21 percent of vehicle-miles traveled by 5-axle tractor-trailers weighing up to 80,000 pounds were in fact laden to 75–80,000 lb [39].

Figure 19: U.S. tractor-trailer VMT, in millions of miles, allocated by total vehicle weight for 5-axle tractor-semitrailer combinations [39]



Operational Considerations

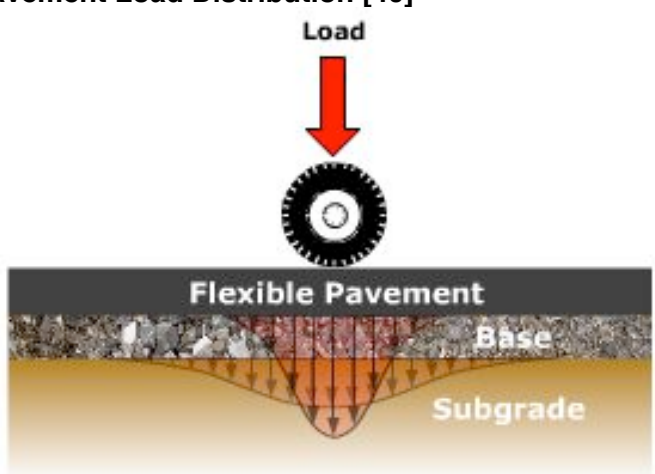
Long combination vehicles require bigger turning radii, wider turning lanes at intersections, a different ratio of trailers to trucks, and probably a different logistical dispersion of drivers and equipment to meet shippers' demands. We also recognize a need to understand the infrastructure needed for parking trailers before entry into cities as a single combination vehicle; to explore the impact on bridges; and to consider changes in wear on road surfaces. Lastly, LCVs will affect road safety, both because they interact differently with traffic and because they will reduce the total number of tractor-trailer trips.

Infrastructure Impacts: Pavement subhead to "LCV considerations"? & same below
Pavement wear depends less on gross vehicle weight than on its distribution: on the configuration of the axles and how they distribute the load on the pavement. The farther these axles are spaced, the more they behave like a separate "loading" for pavement impact analysis or highway design. "Equivalent single-axle loads" (ESALs) are used to describe this distribution.[5] An ESAL expresses the amount of stress on the pavement caused by an 18,000-pound loading on an axle. Table 10 (page 27) shows payload tons per ESAL for three configurations at various nominal weights, indexed to a five-axle semi-trailer weighing 80,000 pounds (shown as 100 weight units).

Pavement Types

Flexible pavements are surfaced with bituminous materials. Their surface and base deflect under load, then a base layer distributes and transmits the load to the subgrade.

Figure 20: Flexible Pavement Load Distribution [40]



Rigid pavements are surfaced with concrete whose stiffness spreads the load over a bigger area.

[5] It should be noted that although ESAL is the unit most often used, it does not differentiate between fatigue and rutting and cracking like the load equivalency factor (LEF) does.

Figure 21: Rigid Pavement Load Distribution [40]

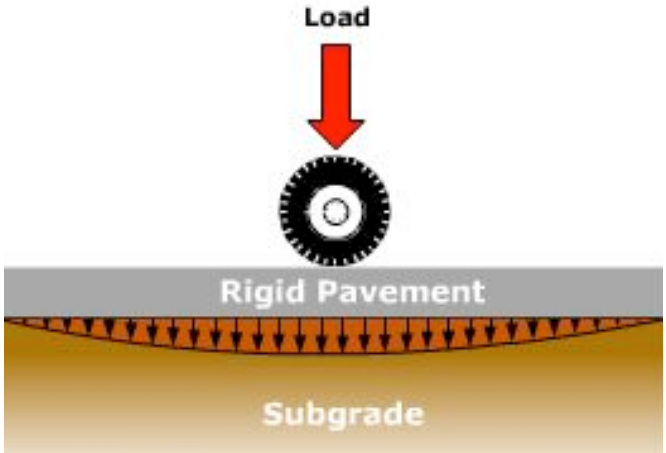


Table 10: Evaluating Axle Configurations Based on Payload Tons Per ESAL[6] [41]

Axle Configuration	GVW	Payload Tons Per ESAL (indexed: 80,000 pound CS-5=100 units)	
		Rigid Pavement (10-inch thickness)	**Flexible Pavement** (structural number 5, terminal PSI 2.5)
5-axle Tractor Semitrailer	80,000	100	100
	85,000	81	83
6-axle Double-Trailer Combination (STAA Double)	80,000	221	148
	97,000	120	86
9-axle Double-Trailer Combination (Turnpike Double)	95,000	380	333
	129,000	139	139

The nine-axle turnpike double tractor-trailer configuration we propose can carry more payload per unit of pavement damage than can the baseline single-trailer combination: 3.8 times as much on rigid or 3.33 times as much on flexible pavements. Thus at least this LCV configuration should markedly reduce highway wear, because its number and spread of axles increases faster than its load.

[6] The structural number determines the total number of ESALs that a particular pavement can support. Present Serviceability Index correlates ridability to pavement measures such as slope variance and cracking. Terminal PSI is the end-of-life Present Serviceability Index.

Infrastructure Impacts: Bridges

Adding turnpike doubles to the U.S. fleet will make the fleet smaller but heavier, requiring evaluation. Bridges' load ratings are typically either 55 percent or 75 percent of the "yield stress" at which they start to bend irreversibly. Changing a truck's weight changes the moment, shear, and fatigue stresses it exerts on a bridge, proportionally to its weight, its axle loading, or closer axle spacing that concentrates the load into a shorter span. Classically, only steel bridges are susceptible to fatigue, but some studies suggest that commonly used prestressed concrete spans, if overloaded, are also susceptible. Experimental data and fracture mechanics principles have shown that for steel, fatigue damage is proportional to the cube of the stress range amplitude—the maximum range of stresses created as the vehicle passes [42]. Moment (bending) forces are predominant in bridge design and are often used as a proxy for shear and fatigue stresses. Worst-case moment forces are used to ensure that turnpike doubles can cross safely.

To determine LCV fleets' potential impact on bridges, most studies use states' 55–75-percent-of-yield-stress ratings, or an intermediate value like the 68.8 percent used by the Federal Highway Administration (FHWA). This range of assumptions can drastically change the number of bridges needing repair or reinforcement to accommodate LCVs, so there is a consensus that infrastructure would need improvement but not on how much. In 1991, the Transportation Research Board published a study showing $9.2 billion (2007 $) in bridge improvements to make rural U.S. bridges safe for turnpike doubles[7], but using a higher percent than their 55 percent of yield stress could greatly reduce this [43]. This uncertainty doesn't seem important, since our assumed Step 2 adoption of LCVs, assuming efficient turnpike doubles to be representative, would save the U.S. an additional (beyond Step 1) $2 billion worth of $3.94/gallon diesel fuel per year. However, the issue merits further study, because Appendix A of the DOT Comprehensive Truck Size and Weight Study says that both simple GVWR rating and the Federal Bridge Formula B covering LCVs may be insufficient. That DOT study found that turnpike doubles at 128,000 lb GVWR (more than our assumed 120,000 lb) would cause up to 22% more stress on a bridge than today's common single-trailer tractor-trailers [44]. Since many existing bridges need repair just to carry today's loads reliably, $9.2 billion, the marginal cost of upgrading them for LCVs should be assessed against LCVs' marginal benefits.

Road Geometry

An LCV must fit on the road, through intersections, and around curves. The American Association of State Highway and Transportation Officials (AASHTO), which recommends road geometry standards, notes that these may not always suffice for turnpike doubles [45]. One area of concern is "offtracking." Depending on the wheelbase between the tractor and trailer, and the number of articulation points, offtracking may occur when the swept path width exceeds the lane width, and differs at low speed (Figure 22) and high speed (Figure 23).

[7] Assuming 129,200 lbs per turnpike double.

Figure 22: Low speed offtracking. [46]

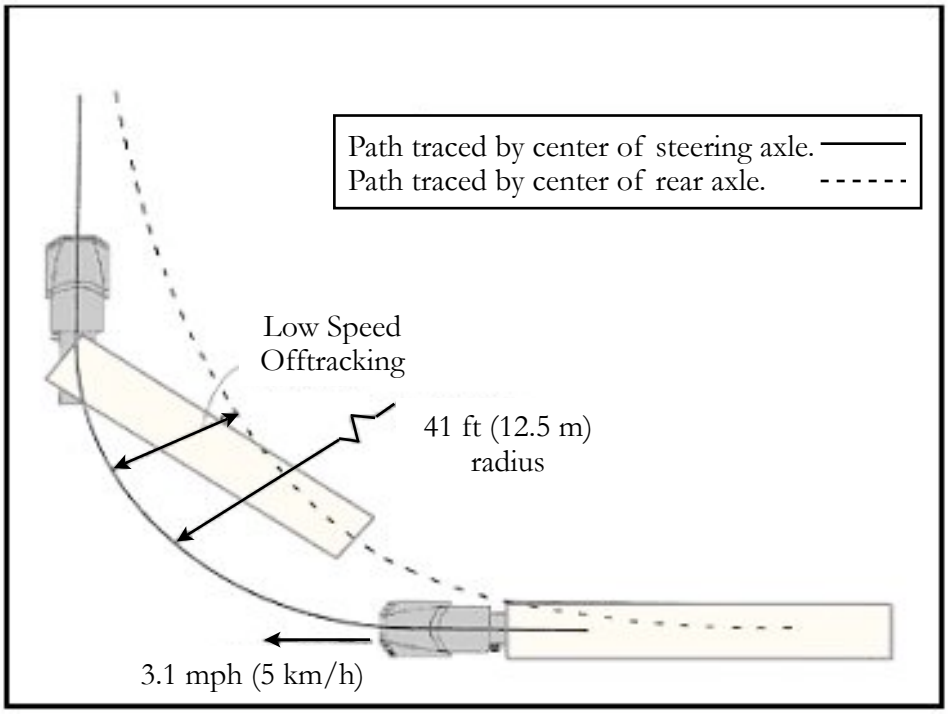


Figure 23: High speed offtracking. [46]

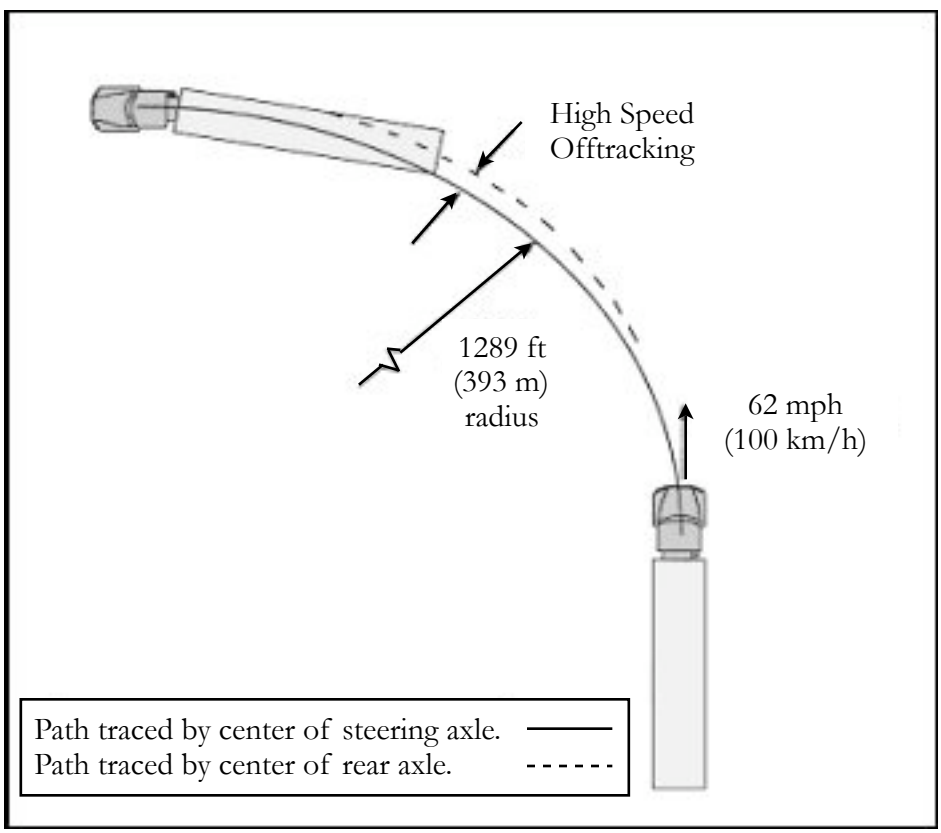


Table 11 shows how the truck making the tightest turn at the lowest speed will experience the most offtracking, and how a turnpike double may require more turning space than a single.

Table 11: Comparison of maximum swept path width of the semi-trailer and turnpike double for three different scenarios and two different speeds.[8,9] [46]

	Maximum Swept Path Width (Feet) at Design and Very Slow Speeds on the Sharpest Horizontal Curve Allowed by AASHTO Design Policy		
Design Speed (mph)	30 mph	40 mph	60 mph
Curve Radius (feet)	273 ft	509 ft	1348 ft
5-Axle Tractor Semitrailer	11.88 ft/13.65 ft	9.43 ft/11.12 ft	8.5 ft/9.3 ft
9-Axle Turnpike Double	14.29 ft/16.69 ft	10.5 ft/12.83 ft	8.5 ft/10.05 ft

In a Department of Transportation study, turnpike doubles at certain interchange ramps offtracked 20 percent more than five-axle 48-foot semi-trailer combinations. AASHTO therefore recommended in 1997 that when LCVs are driven on "moderate to severe curves," pavement widths should be "increased to prevent encroachments." Table 11 shows that for the worst-case scenario, the turnpike double required a lane 2.5 feet wider lane than the current norm to prevent offtracking at design speeds. At low speeds, such as those that would occur in normal urban traffic, the offtracking is worse. On routes used by turnpike doubles lane width needs to be increased to accommodate these offtracking requirements. The marginal cost of this improvement has not been assessed, but again would need to be compared with marginal benefits.

Vehicle Safety and Equipment Performance

A common concern with LCVs is vehicle stability and control. However, certain characteristics of a turnpike double actually make it safer and more stable in certain respects than the commonly used A-train doubles (Figure 24 below).

Stability depends on many attributes, including the load's center of gravity, the vehicle's track width, how the second trailer is connected, and suspension and tire properties. "Static roll stability" (SRS) measures a vehicle's tendency to roll over while turning at constant speed. The harder it is to lift a wheel off the ground, the less susceptible the vehicle is to rollover, so higher SRS values are good. A turnpike double has an SRS comparable to a typical 80,000-pound tractor-trailer's—about 0.3 g (~11 ft s–2) of acceleration, vs. ~0.8 g (~25 ft/s^2) or higher for a typical car, so the common perception that tractor-trailers are prone to rollover is correct, at least relative to cars, much as many SUVs are less stable than sedans.

8 The speed that an interchange is designed for is the design speed.

9 The last two rows indicate maximum swept path at design and very slow speeds. (maximum swept path at design speed/maximum swept path at very slow speeds)

Table 12: Evaluation Criteria for Safety Measures.[10] [47]

	Evaluation Criteria
SRS	SRS<0.3: very poor 0.3–0.35: poor 0.35–0.4: good SRS>0.4: excellent
Rearward Amplification	Values of 2 or less indicate acceptable performance.
Load Transfer Ratio	Should not exceed 0.6

Table 13: Evaluation of LCVs based on SRS, rearward amplification, and load transfer ratio, highlighting safety differences between STAA doubles and turnpike doubles [47].

VEHICLE STABILITY (SHADED BOXES EXCEED RECOMMENDED LIMITS)		Static Roll Stability (higher is better)	Rearward Amplification (dynamic; lower is better)	Load Transfer Ratio (dynamic; lower is better)
Legal Nationwide	Tractor and Single-Trailer, van, 80,000 lbs	0.36	1.244	0.5447
	STAA double: van, 28x28, 80,000 lbs	0.377	2.15	0.919
Legal in Certain States	Turnpike double: van, 45x45, 129,000 lbs	0.376	1.37	0.5599
	Turnpike double: van, 48x48, 129,000 lbs	0.376	1.28	0.524

"Rearward amplification factor" and "load transfer ratio" measure a vehicle's susceptibility to rollover during evasive maneuvers; lower values of both are better.

- The rearward amplification factor is the ratio of the lateral (sideways) acceleration of the rearmost trailer to the lateral acceleration of the tractor when making a sharp turn. Values below 2 are normally considered acceptable. Single-trailer combination vehicles typically

[10] All evaluation criteria are taken from the "Western Uniformity Scenario Analysis." References are provided below.
Static Roll Stability: Mueller, T.H., De Pont, J.J., Baas, P.H. "Heavy Vehicle Stability versus Crash Rates." Transportation Engineering Research New Zealand Limited. Accessed June 2008 at www.landtransport.govt.nz/publications/docs/stability.pdf. Page 1. 1999.
Rearward Amplification: National Road Transport Commission. "Performance Based Standards for Heavy Vehicles in Australia." Accessed June 2008 at www.ntc.gov.au/DocView.aspx?page=A02302402400380020. 1999.
Load Transfer Ratio: Vehicle Weights and Dimensions Study Implementation Planning Subcommittee. "Recommended Regulatory Principles for Interprovincial Heavy Vehicle Weights and Dimensions." Accessed June 2008 at www.comt.ca/english/programs/trucking/Regulatory%20Principles.pdf. September, 1987.

have a rearward amplification factor of 1.24, turnpike doubles 1.28, and STAA doubles[11] 2.15. By this measure, the turnpike double configuration is safer than the widely accepted STAA double currently in use nationwide.

- The load transfer ratio measures a truck's stability while turning. This ratio is the portion of a vehicle's axle load that is carried on one side of the truck relative to the other during a dynamic event, such as an evasive maneuver. An ideal vehicle would have a load transfer ratio of 0.5 while a vehicle with all the weight on one side would have a load transfer ratio of 1. It is commonly held that the load transfer ratio should not exceed 0.6. A turnpike double using 48-foot trailers has a load transfer ratio of 0.52—mathematically more stable than one with two 45-foot trailers, and a standard single as seen in Table 13.

Table 13 uses the evaluation criteria from Table 12 to compare the stability of a single-trailer combination vehicle, an STAA double, and a turnpike double. The turnpike double has an SRS comparable to a single trailer's, and its rearward amplification factor is better than that of the STAA double now in wide use. The load transfer ratio of the turnpike double is the smallest of all combinations analyzed in this study. These numbers are taken from the Western Uniformity Scenario Analysis and therefore use weight limits of 129,000 pounds; that's also used by the Western Governors' Association, and slightly exceeds our Step 2 assumption of 120,000 pounds.

Electronic Safety Equipment

Anti-lock braking systems (ABS) electronic stability control (ESC) are widely known in passenger car markets and are available for tractor-trailers as well [56]. Electronic safety technology for tractor trailers is now well-proven and available but it is rarely required by law in the U.S. Today, advanced systems that look beyond the vehicle itself are also available, such as radar collision avoidance systems that alert drivers to the presence of traffic on all sides or to obstacles in the road [57]. Furthermore, tractor trailers in Europe can be purchased with lane departure warning systems or a very impressive active brake assist system which integrates disc brakes with radar collision avoidance, capable of stopping the truck automatically to avoid head-on collision [58] [62]. The National Highway Traffic Safety Administration (NHTSA) conducts research in these areas and RMI strongly encourages the increased adoption of these technologies in U.S. freight transportation markets [60]. Creating incentives or requirements to encourage installation of similar devices on new trucks would measurably improve safety [60] [61].

Driver Safety and Performance

Driver performance also affects safety. An easily controlled truck means less work, less fatigue, and safer driving for longer. A driver fatigue study sponsored by the Federal Motor Carrier Safety Administration compared drivers' performances in single- and triple-trailer combination trucks [48]. Under normal conditions, each driver operated one of three combinations: a single 48-foot trailer, a triple-trailer combination with three 28-foot trailers and standard A-dollies, and a triple-trailer combination with three 28-foot trailers and double-drawbar, self-steering C-dollies. C-dollies, as seen in Figure 24, use a two-arm hitch system with fewer pivot points, hence less rearward amplification. Under normal operating conditions, driver workload and fatigue increased in the sequence: single-trailer, C-dolly, A-dolly. C-dollies used on a turnpike double make the vehicles easier to control, and thus are safer than the more common A-dolly.

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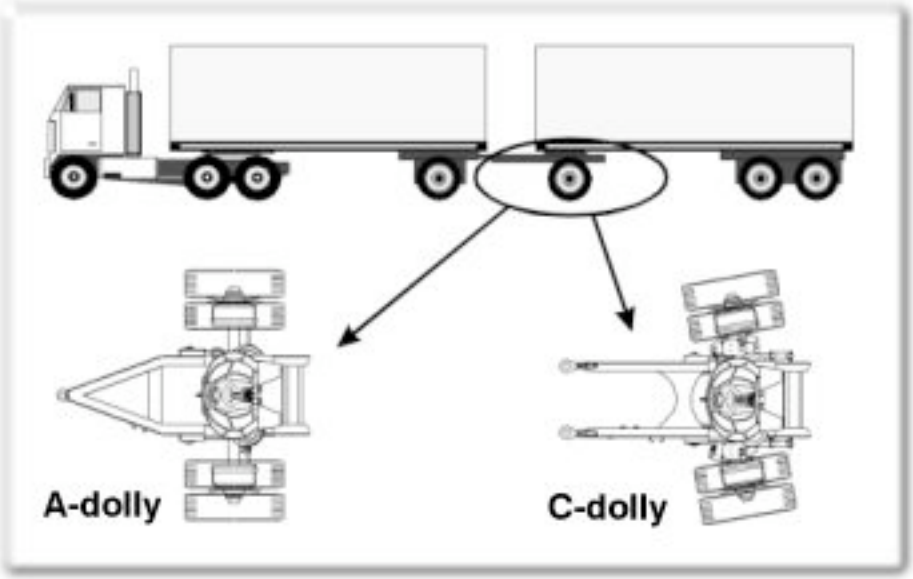
[11] The Surface Transportation Assistance Act (STAA) of 1982 regulates truck size and weight. It required states to allow semitrailers up to 48' long and twin trailer combinations with trailing units up to 28' long (STAA doubles) on federally funded highways designated by the Secretary of Transportation.

Figure 24: Top view of A-Dolly and C-Dolly configurations, respectively. (DOT 2000)



The Engineering Research Division of the University of Michigan Transport Research Institute (UMTRI) recently completed a three-year field study of long combination vehicles using anti-lock brakes (ABS) and double-drawbar dollies [49,50], which explains:

> Two types of converter dollies, which are distinguished by the number of tow bars, are illustrated in Figure 24 [50].
>
> Depending on design style, dollies may have a single- or double-tow-drawbar arrangement for coupling to the towing trailer. In either case, the tow bars terminate in a simple, rugged towing eye. The towing trailer is equipped with one or two pintle hitches consisting of a hook and locking mechanism, which engages and secures the eye(s), thereby supporting and towing the dolly [50].
>
> A-dolly. The defining quality of the A-dolly is its single-point tow bar. The A-dolly is the most common type of converter dolly; over 99 percent of the dollies in use in the U.S. are of this type. The single hitching point allows the dolly to articulate in yaw (steering), pitch (fore/aft rotation), and roll (side-to-side rotation) with respect to the towing trailer [50].
>
> C-dolly. The defining quality of the C-dolly is its double-tow-bar configuration. The C-dolly originated in Canada. Its attractive quality is its ability to improve the stability of multiple-trailer combination vehicles. This is accomplished because the double-tow-bar hitching arrangement eliminates yaw and roll articulation with respect to the lead trailer. Eliminating yaw, in particular, can degrade low-speed maneuverability and produce excessive hitch forces and tire scrubbing during tight turns at low speeds. To mitigate these low-speed problems, the wheels of the C-dolly are allowed to steer by a caster mechanism. However, a centering mechanism provides mechanical resistance to this self-steering action as required for dynamic stability at highway speeds [50].

That study made two key safety findings about dollies: the C-dolly on LCVs reduces rearward amplification in normal use, and it increases an LCV's total maintenance costs by 3–5 percent, due mostly to increased tire wear.

Operating Environment

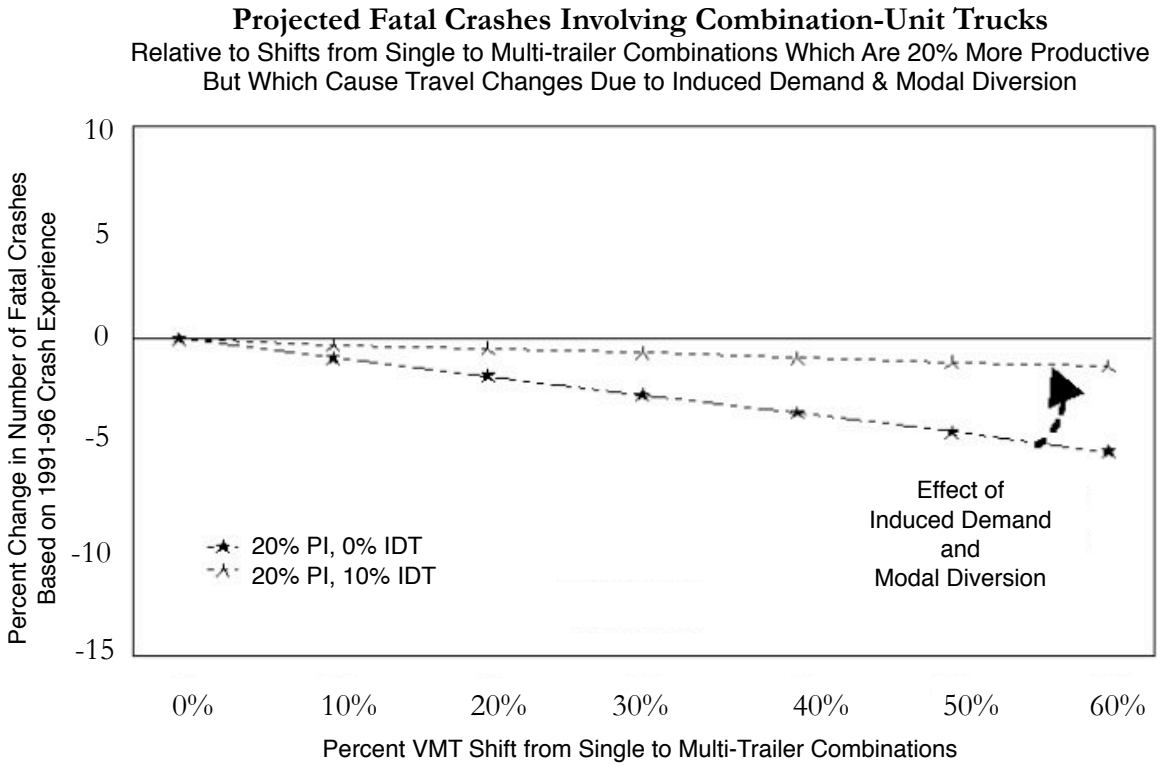
LCVs are longer than singles, so cars take longer to pass them or vice versa. This is especially important to safety on two-lane, two-way roads where passing is in the oncoming-traffic lane. Marked passing and no-passing zones are established based on sight distance criteria only for passenger cars—not trucks (of any length). DOT found that cars on two-lane roads need 8 percent more sight distance to pass LCVs than to pass single trucks (DOT 2000). This is much less than one would expect from LCVs' roughly 50 percent greater length. On the other hand, more LCVs means fewer trucks on the road, hence fewer total passing maneuvers.

Crash Rates

Many studies have compared crash fatality rates associated with tractor-trailers having one vs. more trailers. It's hard to predict the effects of more LCVs, and results are mixed. Deaths per million vehicle-miles travelled for single vs. multiple trailers were estimated at 2.44 vs. 2.08 by a 1993 FHWA study, but at 2.75 vs. 3.02—the opposite relationship—by a 1995–1999 study done for the Western Uniformity Scenario Analysis [47]. Accident reports typically show a tractor-trailer's number of trailers but not its configuration, load, or other vital details. One Canadian study that did classify crash rates by configuration found that traditional single tractor-trailers and turnpike doubles have respective crash rates of 128.1 and 27.06 per 100 million miles—a nearly fivefold safety advantage per tractor (even more per trailer) for turnpike doubles under the conditions of that analysis [51]. Alberta does require enhanced driver qualification requirements and operating restrictions for adverse road and weather conditions.

It's hard to estimate how wider adoption of LCVs would affect overall road safety. Studies of current fleet statistics don't help much because LCVs are far outnumbered by singles,. More LCVs would mean disproportionately fewer singles to haul the same freight—reducing the number of crashes, the amount of congestion, and perhaps the amount of risky passing behavior. On the other hand, each individual vehicle may be at a slightly higher risk for crashing. The net effect, however, probably favors LCVs, because even if LCVs did (as the WUSA study found) have 10 percent higher fatalities than singles per vehicle-mile, they'd still have fewer fatalities per ton-mile, because each LCV hauls more freight. That is, fewer trucks would outweigh the possibility of more danger per truck, as confirmed in Figure 25 [52]. We recommend that future studies count both effects of LCVs—fewer tractor-trailer trips and LCV safety changes at the vehicle level—to assess safety effects on all road users.

Figure 25: LCV's are predicted to result in fewer fatal crashes due to a reduction in overall tractor-trailer VMT, even after including induced demand and modal diversions from rail to truck [52].



Productivity Improvement (PI) is the percent reduction in single trailer VMT attributable to carrying more cargo per truck per trip in muli-trailer.
Induced/diverted travel (IDT) would be attributable to both new commodity movements over greater distances and movements diverted from other modes because of lower trucking costs.

A prior RMI analysis recommended harmonizing to higher GWVR limits, but offsetting any potential risk increase by having uniform and slightly lower speed limits and shorter stopping distances, readily achieved by using disc instead of drum brakes. That study found that safety would improve even as trucks got heavier. We didn't repeat that analysis here because many jurisdictions already permit those or higher weights, and because this study recognizes that four-fifths of loads cube out, and only one-fifth weigh out.

Conclusions, Step 2

In summary, adopting LCVs reduces semi-trailer trips and makes roads safer, partly through greater stability. Such LCVs should be allowed on certain routes but not all. Safe routes would include:

- More than two lanes;
- Climbing lanes, if applicable;
- Roadway geometry designed to prevent LCV off-tracking; and
- Adequate bridge ratings.

Thorough training and safety checks by industry are vital too. More weight means more brake maintenance. In addition, appropriate speed limits should be enforced.

Strict adherence to safe operating procedures will bring multiple benefits. Higher cargo capacity cuts fuel per ton-mile, raises income per trip, and saves trips. This will in turn affect congestion and total travel.

Infrastructure constraints, such as road geometries and bridge ratings, make only some major-highway freight ton-miles—we suggested at least 63 percent—suitable for LCVs. However, over time, infrastructure improvements could advantageously ease these constraints. In our results, 63% of trips are made with Step 2 LCVs, while the remainder are Step 1 vehicles.

It is important to note that increased use of rail to carry goods also offers an opportunity to move goods more efficiently. Intermodal shipping offers the opportunity to transfer truck freight onto rail cars for a portion of the trip. Adding this logistical step can improve overall freight delivery efficiency and also helps remove traffic from US highways. According to CSX, a major U.S. rail company, trains can deliver goods at 432 ton miles per gallon [55].

Table 14: Fuel Results and Assumptions for Step 2

	Baseline	**Step 2**	
		Step 1 tractor-trailers	Step 2 turnpike doubles
No. long-haul tractor-trailers	500,000	176,000	171,000
Distance traveled (miles/y)	100,000	100,000	100,000
Fuel economy (mpg)	6.50	12.30	8.70
Freight efficiency (ton-mile/gal)	130	275	335
Fuel used (gal/y)	7,700,000,000	1,400,000,000	2,000,000,000
Fuel saved (gal/y)	n/a	4,300,000,000	

Conclusion

Costly oil and changing climate demand efficient trucks. Available techniques can improve fuel economy by more than 90 percent, from 6.5 mpg (36.2 l/100 km) to 12.3 mpg (19.1 l/100 km). Combined with the slight incidental increase in hauling capacity, these Step 1 improvements would raise “fuel productivity” by 110 percent, from 130 to 275 ton-miles per gallon. These benefits can be realized without regulatory change and are comparably easy to achieve by an industry motivated by high fuel costs. Our more challenging Step 2 suggestions require new regulations for longer, heavier, but safer and less road-wearing Long Combination Vehicles that could raise individual-vehicle ton-miles per gallon to 335, while reducing the number of trucks on the road by roughly 30% versus our baseline in a fleet scenario. We strongly recommend rapid industry-wide implementation of Step 1, and a cautious investigation of the benefits of Step 2 by industry and government. The resulting savings in U.S. fuel use, money, and carbon dioxide emissions are summarized in Table 14.

Table 14: Result summary of two-step methodology

	Baseline	Step 1	Step 2	
			Step 1 tractor-trailers	Step 2 turnpike doubles
No. long-haul tractor-trailers	500,000	475,000	176,000	171,000
Distance traveled (miles/y)	100,000	100,000	100,000	100,000
Fuel economy (mpg)	6.50	12.3	12.30	8.70
Freight efficiency (ton-mile/gal)	130	275	275	335
Fuel used (gal/y)	7,700,000,000	3,900,000,000	1,400,000,000	2,000,000,000
Fuel saved (gal/y)	n/a	3,800,000,000	4,300,000,000	
Value of fuel saved ($/y)	n/a	$15 billion	$17 billion	
CO_2 eq reductions		40 million tonnes	45 million tonnes	

Other valuable benefits would include higher trucker profits, lower hauling costs, less congestion, less pollution, and fewer deaths. A systematic, comprehensive approach to efficient trucks and freight-hauling systems—including important options not assessed here, such as hybrid drives, idle-preventing auxiliary power units, more-advanced engines, alternative fuels, fewer empty backhauls, fuller road/rail integration, and smarter logistics—is clearly a key to a richer, cooler, and safer world.

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Appendix 1

Analytic Methods
We use the road load equation to calculate the energy required to overcome those forces resisting the motion of a vehicle. We apply only the steady-state portion of the road load equation, which includes three main components—aerodynamic drag, rolling resistance, and grade losses. We also included major energy losses due to the inefficiency of the engine. We did not count driving-cycle effects such as hill-climbing, stop-start operation, idling, or auxiliary loads.

Equation 1: Road load equation and three basic loads (rolling resistance, aerodynamic drag, and grade).

$$F = M_v g C_{rr} + \frac{1}{2}\rho A_f C_d \left(V + V_w\right)^2 + M_v g \sin\left(\alpha\right)$$

Where:
P = normal load
C_{rr} = rolling-resistance coefficient
ρ = air density
A_f = vehicle frontal area
C_d = coefficient of drag
V = vehicle speed
V_w = component of wind speed on the vehicle's moving direction
M_v = mass of vehicle
g = acceleration due to gravity
α = road angle

We modeled this equation using a spreadsheet to determine the fuel economy at 60 mph given the following assumptions.

Table 15: Assumptions for Baseline and Transformational Truck.

	Baseline	Step 1: Transformational Truck
M_v, kg	32,000	32,000
C_{rr}	0.0073	0.0052
A_f, m^2	11	11
C_d	0.6	0.31
E_{engine}, engine efficiency	42%	48%
E_{trans}, transmission efficiency	98%	98%
E_{axle}, axle efficiency	98%	98%

Table 16: Verification of Excel spreadsheet road load model results using PSAT.

Output (Excel/PSAT)	Baseline	Step 1: Transformational Truck
Fuel Economy (mpg)	6.51/6.26	12.31/11.28

Notes on the model output verification using PSAT: The baseline truck engine operates at 131 rad/s and 1,176 Nm of torque at 60mph. The efficiencies of the axles and transmission within the model matched our road load model. The actual engine efficiency reported by PSAT was 43% instead of the scaled (desired) 42%. The Step 1 engine operates at 131 rad/s and 687 Nm of torque at 60 mph within PSAT. The efficiencies of the Step 1 axle and transmission within the model matched our road load model. The engine efficiency, however, was 45% in PSAT instead of the scaled (desired) 48%. This brought about a slightly lower fuel economy output in PSAT when compared to our road load model.