CONFIDENCE REPORT: TRACTOR AERODYNAMICS

ABSTRACT This report documents the confidence that North American Class 8 trucking should have in Tractor Aerodynamic Devices for improved fuel efficiency. The study team engaged with the entire industry in generating the findings that are presented here. Thanks to all of those who contributed to this important work.

Trucking Efficiency Trucking Efficiency is a joint effort between NACFE and Carbon War Room to double the freight efficiency of North American goods movement through the elimination of market barriers to information, demand and supply.

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Executive Summary

The fuel costs faced by the tractor-trailer industry have been swiftly and steadily rising over the past decade. In 2014 diesel fuel costs were $0.58 per mile, costing the industry as much per annum as the costs of drivers' wages and benefits combined. Despite recent fuel cost decreases, all indications are that fuel price volatility will continue, forcing the industry to find solutions that increase its fuel efficiency in order to stay profitable.

Fortunately, myriad technologies that can cost-effectively improve the fuel efficiency of Class 8 trucks are readily available on the market today. Unfortunately, multiple barriers have stymied industry adoption of such technologies, including a lack of data about the true performance gains these technologies offer, and a lack of confidence in the performance testing data that does publicly exist today. To overcome those barriers and facilitate the industry's trust in and adoption of the most promising fuel efficiency technologies, the North American Council for Freight Efficiency (NACFE) partnered with Carbon War Room (CWR) to form Trucking Efficiency. The work of Trucking Efficiency has begun by producing a series of Confidence Reports, of which this report on technologies to improve the aerodynamics of tractors is the twelfth.

> "THE STANDARD MODELS OFFERED BY THE TRUCK BUILDERS ARE HIGHLY AERODYNAMIC, AND FLEETS SHOULD ONLY DIVERT FROM THOSE WHEN THEIR DUTY CYCLES PROMPT A SPECIFIC REASON TO, LIKE GROUND CLEARANCE."
> Rick Mihelic,
> NACFE Study Manager

The goals of this Confidence Report are: (a) to give the industry a foundational understanding of tractor aerodynamic devices; (b) to provide an unbiased review of tractor aerodynamic technologies available on the market today; and (c) to increase investment in cost-saving tractor aerodynamic technologies.

Methodology

This report's conclusions were generated through desk research, conversations at a variety of trucking industry events around the country, and a series of structured interviews with fleets, truck OEMs, and aerodynamic research experts active in the North American market today.

FUEL SAVINGS AND TRACTOR AERODYNAMICS

Tractor aerodynamics increase fuel efficiency by lowering air resistance so that less fuel is needed to move down the road as speed increases. The per-vehicle fuel economy benefit of optimizing the aerodynamics of a tractor can be quite high—the few classic sleepers that are operated in over-the-road applications today are a full 30% less fuel efficient than a modern, aerodynamically optimized tractor. Given these potential savings, the optimization of the aerodynamic performance of a tractor is very much worth pursuing as part of spec'ing a new vehicle.

There is, however, a long-standing misperception in the trucking industry that improved aerodynamics will only save fuel at speeds above 55 mph. Due to this, day cabs and other duty cycles have lagged long-haul sleepers in their aerodynamic performance improvements. But in reality, aerodynamic drag is acting against the vehicle at all speeds above 0 mph. Given the many low- or no-cost design elements that can reduce drag, even fleets operating at lower speeds should consider adoption.

However, the heavy-duty tractor is a purpose-built vehicle optimized for specific tasks and environments; customers specifying the features of their truck create thousands of unique permutations of vehicles. As a starting point for optimizing performance for a particular need, OEMs offer a range of tractor models, reflecting broad design elements that are each prioritized by a certain segment of the trucking industry. The importance of tractor aerodynamics is well recognized, and is a major consideration of OEMs in designing their base models.

Each base model will be aerodynamically optimized by the OEM, which will view the entire tractor as a unified system interacting with the air flows. This means that for the majority of the parts that can impact air flow, it is not possible or useful to compare between devices from different manufacturers—each base model will be offered with the best devices for that tractor.

If the aerodynamic features are removed from the OEM's aerodynamic base model, a fleet can expect to lose about 10% in fuel economy. Another 10% can be lost simply by pairing a mid-roof tractor with a dry van or refrigerated trailer. Even at today's fuel prices of about $2 per gallon, 10% of fuel spend represents $3,500 per year per truck.

While aerodynamic improvements are technically possible with all vehicles, and many are actively being researched, the greatest opportunity in terms of miles-driven and resultant fuel use is with the on-highway van trailer segment—both day cabs and long, high roof sleepers.

CHALLENGES OF TRACTOR AERODYNAMICS

The challenges of optimizing the aerodynamic performance of a tractor include:

- **Cost**—Historically, aerodynamic features added on to the tractor incurred a higher initial cost; this is still the case for some features. However, many aerodynamic improvements today are achieved simply by redesigning the shape of an existing aspect of the tractor, and do not entail the addition of a new device or any associated cost.

- **Payback Calculation**—The methods for testing aerodynamic device performance are complicated, and it is difficult to compare between testing results, as there are multiple ways of measuring and evaluating performance (described in a separate "Determining Efficiency" Confidence Report). Moreover, since aerodynamic performance is the net of all of the interactions of the components, each option

"TRACTOR AERODYNAMICS PAY FOR THEMSELVES– DON'T BUY A TRACTOR WITHOUT THEM. IF YOU DO, YOU'LL REGRET IT!"
Mike Roeth, Operation Lead, Trucking Efficiency

may perform differently for each configuration. For this reason, following general rules of thumb or using tabulated data to estimate the performance gains or losses caused by the addition of each aerodynamic option can be misleading, as the gain or loss may only be directly applicable to one overall vehicle configuration. Additionally, fleets will see the greatest benefit from adopting multiple aerodynamic devices, but the net benefits from the package of devices will not simply equal the sum of the benefit of each individual device, making it difficult for fleets to prioritize investment decisions and feel confident about their paybacks.

- **Accessibility, Maintenance, and Repair**—It is important that fleets clearly understand the interplay of any aerodynamic device with their specific duty cycles, particularly when it comes to the accessibility of other tractor features for maintenance and repair.
- **Added Weight**—While the devices currently available on the market do add some weight to the vehicle, weight's impact on fuel economy is just 0.5%–0.6% per 1,000 pounds of weight. There is less than a 2,000-pound weight difference between the most aggressively optimized aerodynamic tractors and the least, so the maximum mile-per-gallon reduction due to the aerodynamics is less than 1.2%, much smaller than the significant MPG gain offered by the improved aerodynamic performance.

TRACTOR AERODYNAMIC TECHNOLOGIES

The Confidence Report explores five key areas or topics of consideration on a tractor where a fleet may choose to seek additional aerodynamic optimization and fuel savings. Multiple technologies are applicable in some of these areas. The areas are:

1. Frame Layout and Tractor/Trailer Gap
- **1.1.** Cab and Roof Extenders
- **1.2.** Chassis Fairings
- **1.3.** Drive Wheel Fairings

2. Cab
- **2.1.** Aero Hoods, Fenders, and Headlamps
- **2.2.** Aero Bumpers
- **2.3.** Aero Mirrors
- **2.4.** Roof Fairings
- **2.5.** Sunshades

3. Fifth Wheel Settings
- **3.1.** Fifth Wheel Locations
- **3.2.** Fifth Wheel Height

4. Part Removal or Relocation
- **4.1.** Exhaust
- **4.2.** Hood Mirrors, Lights, Grab Handles, etc.

5. Other Equipment
- **5.1.** Wheel Covers
- **5.2.** Vented Mud Flaps

The report also discusses these features as to their application on both sleepers and day cabs.

PERSPECTIVES FOR FUTURE SYSTEMS

Tractor aerodynamic technologies and strategies are constantly and rapidly evolving. The options detailed in the report are all currently available on the market today, as part of each OEM's aerodynamic base model—their function as a fuel-saving design modification is well proven. In the near term, new technologies and/or regulatory changes that open the door for platooning, long combination vehicles, and longer trailers could significantly improve aerodynamics and increase fuel economy. Other technologies that are under development but have not yet reached market readiness include:

- Active Flow Control Systems
- Onboard Aerodynamic Sensing
- Aero Adaptive Cruise Control and Routing Systems
- Automation Systems
- Geometry Morphing
- Trailer/Tractor Ratio Reduction
- Dedicated Truck Highways and Lanes
- Hybrid Electric Vehicles
- Advanced Automation (combining technologies)—drones, robots, road trains, etc.

CONCLUSIONS AND RECOMMENDATIONS

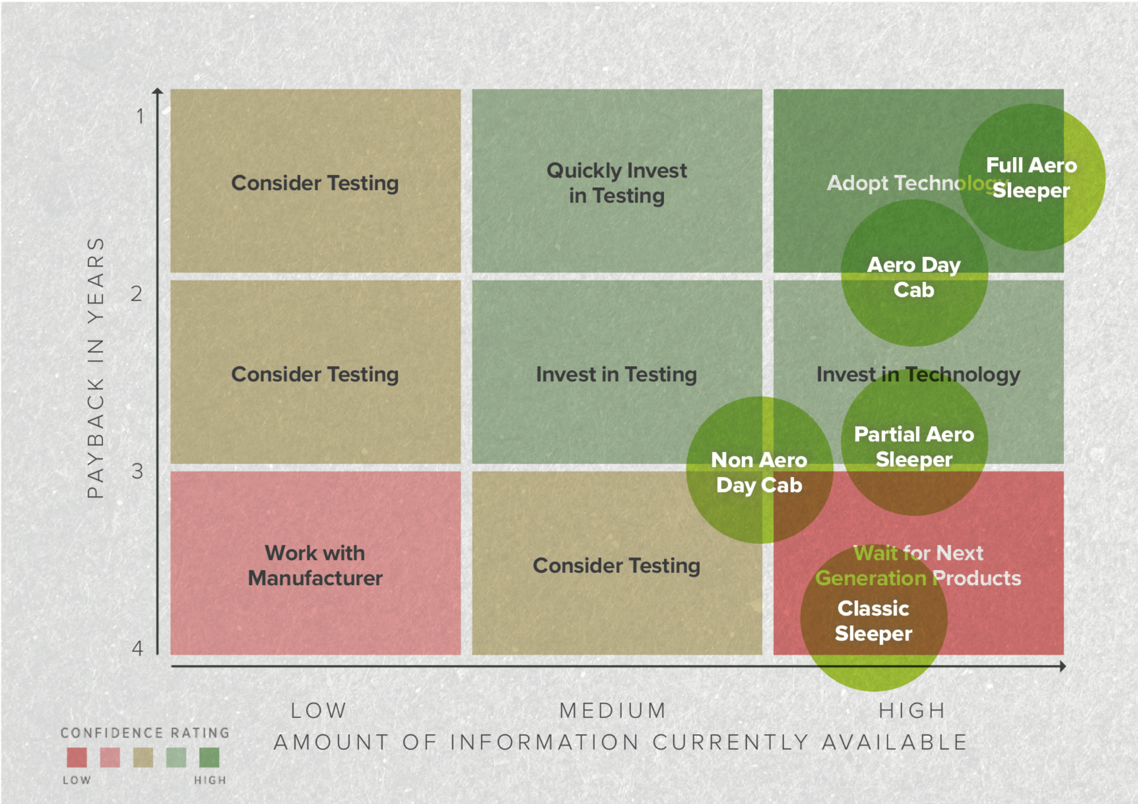
The OEM model is the first option in aerodynamics for on-highway van haulers that a fleet will encounter, and many fleets should look no further in optimizing their aerodynamics, as the aerodynamic OEM models will have already been extensively optimized at the complete vehicle level to provide the best performance for a significant portion of their customer base. However, they will not be optimized for 100% of customers, meaning every customer will not see the same performance gains. Moreover, fleet choices can impact tractor aerodynamics in two ways:

- First, fleets can choose to remove aerodynamic options that were included in a base model. Depending on the features removed, as much as a 10% decrease in fuel efficiency is common from this choice. Thus, it is recommended that fleets consider very carefully before taking this action, and only divert from the manufacturer-recommended sleeper aero configurations when there are clearly identified and justifiable reasons in a specific duty cycle.
- Second, fleets may make other non-aerodynamic changes to the base model tractor that in turn reduce its aerodynamic performance. Because this performance loss may be inadvertent or unexpected, it is recommended that fleets work with their OEMs to review their tractor's aerodynamics once more at the end of the spec'ing process, and check for opportunities for further optimization.

Additional recommendations for obtaining the lowest aerodynamic drag and hence the maximal fuel economy include:

- Tractor and trailer heights should be matched for as many miles driven as possible as the fuel economy reduction from mismatched heights is in excess of 10%.
- Fleets operating day-cab tractors should pursue greater adoption of tractor aerodynamics than is common today, as many day cabs operate at highway speeds during nearly all of their duty cycle, where aerodynamics can increase fuel efficiency by as much as 13%. Even day cabs operating in start-stop city driving will see savings from certain aerodynamic technologies.
- Tractor manufacturers should design and make available aerodynamic features for day-cab tractors, including those on natural gas tractors, as the industry migration to shorter hauls will likely result in more day cabs seeing significant highway and interstate miles. Aerodynamic technologies have not been fully developed for all day-cab configurations, including natural gas, and the tractor manufacturers should develop and release these components.
- Future EPA and NHTSA greenhouse gas regulations will challenge tractor builders to continue to improve

CONFIDENCE MATRIX FOR TRACTOR AERODYNAMICS



the aerodynamic drag of these vehicles in excess of what has been demonstrated in the Department of Energy SuperTruck programs. OEMs should start planning for this today, as the lead time required to design new models is significant and can be costly.

CONFIDENCE RATING

For each of the Confidence Reports completed by Trucking Efficiency, the various technologies assessed are plotted on a matrix in terms of the expected payback in years compared to the confidence that the study team has in the available data on that technology—that is, not only how quickly fleets should enjoy payback on their investment but how certain Trucking Efficiency is in the assessment of that payback time. Technologies in the top right of the matrix have a short payback, usually thanks to their low upfront cost, and moreover are found to have high confidence in those short payback times, usually because the technology is more mature or otherwise has a more substantial track record of results.

Trucking Efficiency is highly confident that all fleets should be considering the aerodynamics of their tractors, and that the optimization of tractor aerodynamics represents a major pathway for saving fuel. The size of the savings will depend on the duty cycle, so while both benefit, sleeper cabs likely will save more fuel than day cabs.

Trucking Efficiency is always seeking to expand the data or case studies that we can provide to the industry. We invite you to share your own experiences with tractor aerodynamic technologies.

TRUCKING EFFICIENCY

Trucking Efficiency is a joint effort between NACFE and Carbon War Room to double the freight efficiency of North American goods movement by eliminating barriers associated with information, demand, and supply.

Worldwide, heavy-duty freight trucks emit 1.6 gigatons of CO_2 emissions annually—5.5% of society's total greenhouse gas emissions—due to the trucking sector's dependence on petroleum-based fuels. With fuel prices still commanding nearly 40% of the cost of trucking, the adoption of efficiency technologies by all classes of trucks and fleets offers significant cost savings to the sector while reducing emissions. These technologies are relatively cheap to implement and widely available on the market today.

Trucking Efficiency provides detailed information on cost-effective efficiency technologies, including data from across a variety of fleets and best practices for adoption. This Confidence Report series from Trucking Efficiency aims to serve as a credible and independent source of information on fuel efficiency technologies and their applications.

In order to generate confidence on the performance claims of efficiency technologies, Trucking Efficiency, via these reports, gathers and centralizes the multitude of existing sources of data about the performance results of different technology options when employed in a variety of vehicle models and duty cycles, and makes all of that data openly accessible and more easily comparable. Furthermore, we assess the credibility of the available data, and provide an industry-standardized ranking of confidence in performance results, including ROI and efficiency gains.

www.truckingefficiency.org

Trucking Efficiency welcomes outside views and new partners in our efforts to help accelerate the uptake of profitable, emission-reducing trucking technologies.

CARBON WAR ROOM

Carbon War Room (CWR) was founded in 2009 as a global nonprofit by Sir Richard Branson and a group of likeminded entrepreneurs. It intervenes in markets to accelerate the adoption of business solutions that reduce carbon emissions at gigaton scale and advance the low-carbon economy. CWR merged with Rocky Mountain Institute (RMI) in 2014 and now operates as an RMI business unit. The combined organization engages businesses, communities, institutions, and entrepreneurs to transform global energy use to create a clean, prosperous, and secure low-carbon future. The combined organization has offices in Basalt and Boulder, Colorado; New York City; Washington, D.C.; and Beijing.

www.carbonwarroom.com

NACFE

The North American Council for Freight Efficiency works to drive the development and adoption of efficiency-enhancing, environmentally-beneficial, and cost-effective technologies, services, and methodologies in the North American freight industry by establishing and communicating credible and performance-based benefits. The Council is an effort of fleets, manufacturers, vehicle builders, and other government and non-governmental organizations coming together to improve North American goods movement.

www.nacfe.org

1. Introduction

This Confidence Report forms part of the continued work of Trucking Efficiency, a joint initiative from the North American Council for Freight Efficiency (NACFE) and Carbon War Room (CWR) highlighting the potential of fuel efficiency technologies and practices in over-the-road (OTR) goods movement. Prior Confidence Reports and initial findings on nearly 70 available technologies can be found at www.truckingefficiency.org.

The fuel costs faced by the tractor-trailer industry have been extremely volatile over the past decade, as shown in Figure 1. By 2015, through an unexpected combination of global political and economic forces, fuel prices actually dropped to 50% of their 2008 levels. These significant swings in fuel cost are expected to continue in the future, and make fuel costs the least predictable aspect of freight operations.

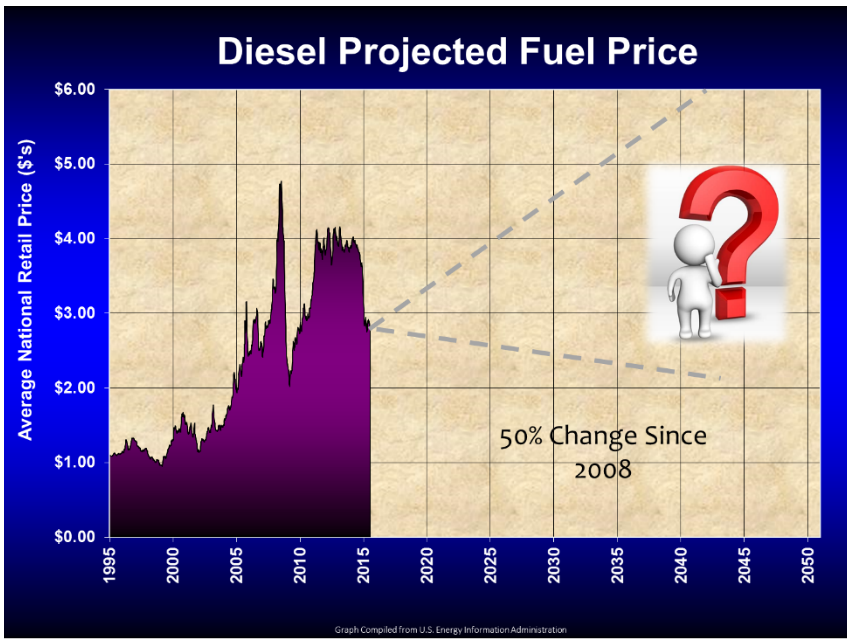


Figure 1 U.S. Diesel Fuel Prices

Truck operating costs have seen steady inflationary increases for labor, but, as Figure 2 shows, in 2013 fuel costs surpassed those for the driver, while in 2014 they began decreasing to $0.58 per mile, on par with the costs for the driver (wages plus benefits). The 2015 data likely will show further fuel cost decreases, but it is expected to again rise as the oil producing countries return to more price conscious business models versus the market share capture approach seen in late 2014 and 2015.

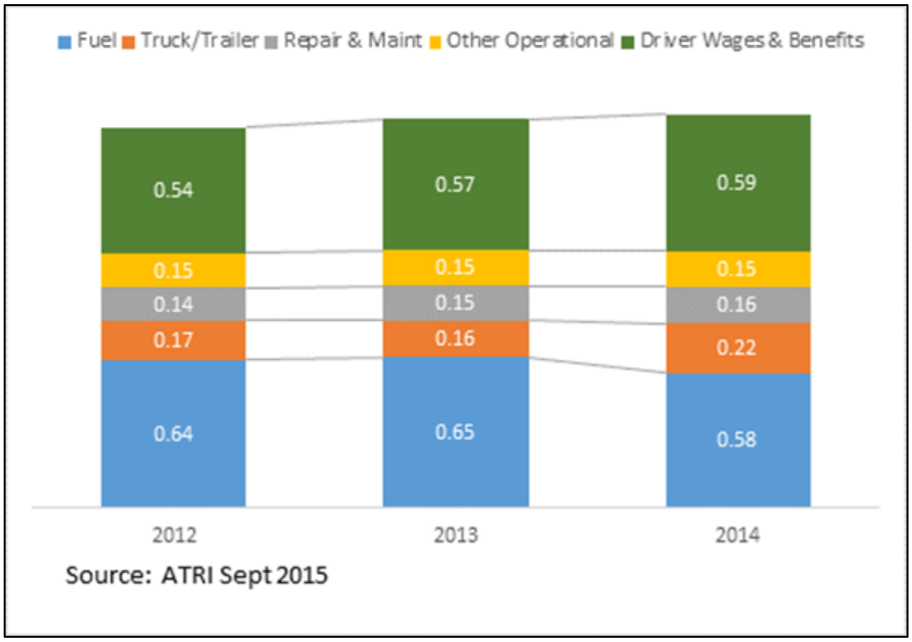


Figure 2 Trucking Operational Costs per Mile

Investment into proven technologies and practices that allow a truck or fleet to increase their fuel efficiency – meaning that they can do the same amount of business while spending less on fuel – is a hugely promising option for the industry in light of this trend of volatility.

To understand, and thereby better facilitate, the uptake of such technologies, NACFE conducts an annual review, the "Fleet Fuel Study," of the industry-wide adoption rates of nearly 70 fuel efficiency technologies currently available for Class 8 tractors and trailers. This work, available on the www.nacfe.org website, has been called "the most comprehensive study of Class 8 fuel efficiency adoption ever conducted." (Truck News, 2012)

Figure 3 Fleet Study Participants

The overriding take-away from the most recent Fleet Fuel Study, completed in 2015, is that fleets are enjoying dramatic improvements in their fuel efficiency by adopting combinations of the various technologies surveyed — savings of about $9,000 per tractor per year compared to a fleet that has not invested in any efficiency technologies. It found that these fleets have fleet-wide fuel economy of just under 7.0 mpg, while the U.S. average, for the approximately 1.7 million tractors in over-the-road goods movement, is 5.9 mpg. This finding was drawn from research into the use of fuel efficiency products and practices by 14 of the largest, most data-driven fleets (Figure 3). Those fleets represent both regional and long-haul tractors and trailers, in both dry goods and refrigerated cargo movement, and boast a combined inventory of 53,000 tractors and 160,000 trailers. The 2015 study reviewed twelve years of adoption decisions by these ten fleets, and describes their specific experience with the nearly 70 technologies. Each fleet shared the percentage of their new purchases of tractors and trailers that included any of the technologies. They also shared twelve years' worth of annual fuel economy data for the trucks in their fleet. With these two pieces of information, which will be updated every year, NACFE is able to generate insights into the following aspects of the industry:

- Adoption curves for each of the technologies, indicating which technologies have the steepest adoption rates, which are being adopted steadily but slowly, and which are not being purchased at all. These curves also show how uniformly (or not) fleets are acting in their adoption patterns.
- Identification among the various fleets of the innovators, early-majority, late-majority, and even laggards, in new technology adoption.
- Comparison of technology adoption rates to overall fuel efficiency.
- Identification of three key insights: that the adoption of automated manual transmissions has reached high levels, that aerodynamics are now available for natural gas tractors, and that the optimization of engine parameters is being pursued more widely as a fuel-saving strategy by large, medium, and small fleets.

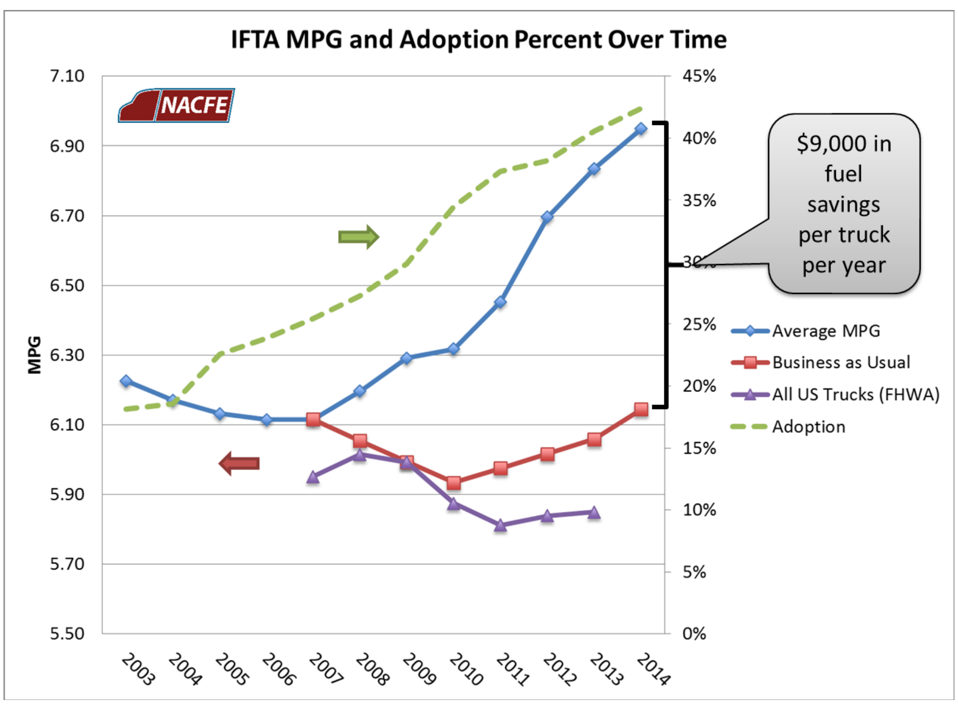


Figure 4: Fuel Savings per Truck – Blue line represents fleets surveyed by the Fleet Fuel Study

1.1. Trucking Efficiency's Confidence Reports

NACFE's Fleet Fuel Studies provide useful insights into adoption trends in the industry, as well as into the specific practices of different major fleets. NACFE hopes that this information could alone spur additional investment, particularly by fleets that may be lagging behind the overall industry when it comes to certain widely-adopted technologies. However, in the course of conducting the studies, it became clear that some technologies are still only being adopted by the most progressive or innovative of fleets in spite of their showing strong potential for achieving cost-effective gains in fuel efficiency. In order to facilitate the wider industry's trust in and adoption of such technologies, NACFE and CWR formed Trucking Efficiency and began this series of reports, called "Confidence Reports," which will take an in-depth look at those most-promising but least-adopted technologies one-by-one.

Confidence Reports provide a concise introduction to a promising category of fuel efficiency technologies, covering key details of their applications, benefits, and variables. The reports are produced via a data mining process that both combs public information and collects otherwise-private information (which is shared with Trucking Efficiency for the purpose of the reports), in order to centralize an unparalleled range of testing data and case studies on a given technology set.

Aerodynamic tractors represent one such technology set. The most recent Fleet Fuel Study found that, since 2003, fleets have been ramping up their investment in aerodynamic tractors. However, adoption rates, even among the most efficiency-conscious fleets, are still around 70% (Figure 5).

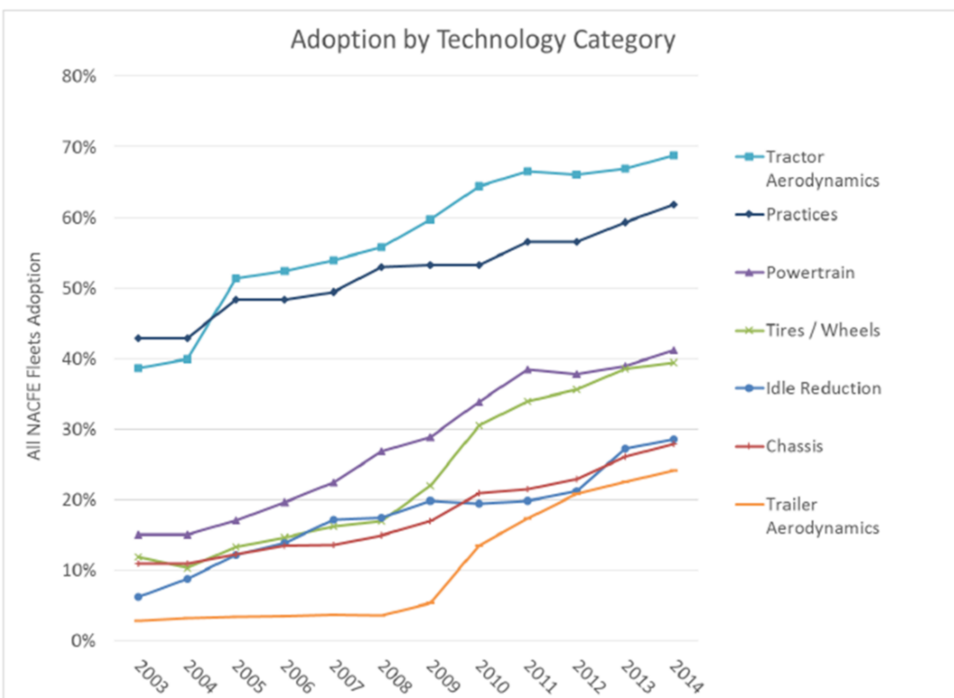


Figure 5 Aerodynamic Technology Adoption by Category (NACFE)

Aerodynamic tractors help to increase fuel efficiency by lowering air resistance, so that it takes less fuel to move down the road as speed increases.

Given the potential savings of 10 to 15%; aerodynamic tractors are an obvious choices of on-highway applications hauling van trailers. Note that this Confidence Report refers to “aerodynamic tractors” as a single concept, instead of discussing “aerodynamic devices for tractors.” This is because, whereas trailers have many competing aerodynamic device choices that can be applied to multiple OEM trailer brands, aerodynamic tractor devices are extensively customized as-a-system by each OEM for their specific models, and the devices are not interchangeable between manufacturers.

The choices for fleet buyers is therefore not a comparison between the device options of two different OEMs or technology manufacturers, but rather one of understanding the impacts of subtracting or adding devices from their OEM’s optimized configuration.

The goals of this Confidence Report are: (a) to give the industry a foundational understanding of tractor aerodynamics; (b) to provide an unbiased review of available tractor aerodynamic technologies on the market today; and (c) to increase investment into cost-saving tractor aerodynamics.

This NACFE Tractor Aerodynamic Confidence Report is one in a series of NACFE-focused reports on configuring vehicles and operations to improve their fuel efficiency. Visit www.truckingefficiency.org to view this and other completed reports on tire pressure systems, 6x2 axles, idle reduction, electronically controlled transmissions, electronic engine parameters, low rolling resistance tires, lightweighting, downspeeding, preventative maintenance, trailer aerodynamic devices and determining efficiency testing methods.

1.2. Report Scope

The scope of this Tractor Aerodynamic Device Confidence Report focuses on aerodynamic options for two types of on-highway tractors pulling single van trailers: the sleeper tractor and the day cab. While aerodynamic improvements are technically possible with all vehicles, and many are actively being researched, the greatest opportunity in terms of miles-driven and resultant fuel use is with the on-highway van trailer segment, both day cabs and high roof sleepers, as illustrated in Figure 6.

Figure 6 Day Cabs (left) and High Roof Sleepers (right) (Western Star & Kenworth)

This report begins by discussing the aerodynamics of OEM base model tractors, and then explores many specific "areas" on a tractor where a fleet may choose to seek additional aerodynamic optimization and fuel savings. Those areas are:

1. Frame Layout & Tractor/Trailer Gap
   1.1. Cab and Roof Extenders
   1.2. Chassis Fairings
   1.3. Drive Wheel Fairings
2. Cab
   2.1. Aero Hoods, Fenders and Headlamps
   2.2. Aero Bumpers
   2.3. Aero Mirrors
   2.4. Roof Fairings
   2.5. Sunshades
3. Fifth Wheel Settings
   3.1. Fifth Wheel Locations
   3.2. Fifth Wheel Height
4. Part Removal or Relocation
   4.1. Exhaust
   4.2. Hood Mirrors, Lights, Grab Handles, etc.
5. Other Equipment
   5.1. Wheel Covers
   5.2. Vented Mud Flaps

The report also discusses two more options related to aerodynamics today: 1) Electronic Systems Related to Improving Tractor Aerodynamics and 2) Hybrid and Alternative Fuel Vehicle Aerodynamics.

2. Tractor Design

The heavy-duty tractor is a purpose-built vehicle optimized for specific tasks and environments; the broad range of these tasks and environments has resulted in a wide spectrum of vehicle types and options, and there is no "one-size-fits-all" tractor. Customers specifying the features of their truck create thousands of unique permutations of vehicles. OEMs work diligently to provide choices for customers that can be optimized for their needs, and to balance the multitude of demands with the harsh economics of vehicle design. As a starting point for optimizing performance for a particular need, OEMs offer a range of tractor "models," reflecting broad design elements that are prioritized by each of a certain segment of the trucking industry.

For example, a vehicle intended for both on-highway and off-road use, such as a vocational tractor intended to pull gravel trailers, may have need for high horsepower and high ground clearance, and will be operating at lower average speeds than a highway flyer pulling a van trailer which will spend nearly its entire life traveling at highway speeds on paved routes (Figure 7). OEMs will have a base model for each of these duty cycles, and they will consider aerodynamics in designing that model.

Aerodynamic optimization will mean different things to these two vehicles. The vocational vehicle will want high cooling air flow, implying a large radiator grille. It also may not want aerodynamic skirts because of ground clearance and damage issues. Finally, due to its lower average speeds, it will see a minimal fuel savings from aerodynamic devices, while it might see maintenance costs from its rough environment, and so easy access to external air cleaners may be more warranted for minimizing overall operating costs.. The highway flyer, on the other hand, should see significant fuel savings from reducing its aerodynamic drag, without the associated concerns of the vocational vehicle.

Figure 7 Different Duty Cycles Result in Different Tractor Design (Caterpillar & Freightliner)

2.1.OEM Base Models

The OEM model is the first option in aerodynamics for on-highway van haulers that a fleet will encounter, and many fleets look no further in optimizing their aerodynamics, as the aerodynamic OEM models will have already been extensively optimized at the complete vehicle level to provide the best performance for a significant portion of their customer base. However, they will not be optimized for 100% of customers, meaning every customer will not see the same performance gains. Moreover, as a fleet's other option choices begin to vary from the OEM's optimized configurations, some degradation of aerodynamic performance may occur from what the base model originally offered, and fleets may need to revisit aerodynamics at a later point in the spec'ing process.

OEMs are constantly working on improving the performance of their base models. Some of these changes are introduced as stand-alone during the course of a year, others come out as part of complete new packages or new model introductions.

Figure 8 highlights many of the interacting aerodynamic elements of a modern tractor. These features are typically optimized as a complete system by OEMs to get the best overall performance.

1. Bumper with Air Dam and Rounded Ends
2. Rounded Hood Leading Edges
3. Sloping Hood
4. Rounded A-Pillars and Curved Windshields
5. Aerodynamic Mirrors and Mounting Arms
6. Low Profile or Integrated Flush Marker Lamps
7. Aerodynamic Roof
8. Aerodynamic Roof Rear Extensions
9. Aerodynamic Extenders
10. Wheel Covers
11. Gaps Filled
12. Chassis Fairings
13. Flexible Fairing Ground Effects Strips
14. Close Fitting Fenders
15. Conformal Headlamps

Figure 8 Elements of a Modern Aerodynamic Tractor (Peterbilt)

The cab's overall aerodynamic shape, which is primarily determined by the windshield angle, A-Pillar shape, and cab mirrors, must perform well across a variety of configurations. Moreover, the cab may be optimized around a particular hood length, sleeper length and height, trailer gap, trailer type and aero configuration and other option content. OEMs make decisions on which configurations take precedence in their optimization process based on projected sales volumes, margins, and other factors including the trailer configuration.

An example of the many factors which go into tractor design is that optimizing a tractor cab for SmartWay designation requires not only specific tractor features like skirts and aero bumpers, but also the use of a SmartWay-equipped trailer. Since aerodynamic performance is the net of all the interactions of the components, each option may perform differently for each configuration, for example tractor skirts may perform differently with a non-skirted trailer, and day cab skirts may perform differently than skirts for sleeper tractors. For this reason, following general "rules of thumb" or using tabulated data to estimate the performance gains or losses caused by the addition of each aerodynamic option can be misleading, as the gain or loss may only be directly applicable to one overall vehicle configuration.

The characteristic shapes of aerodynamic sleeper models generally have rounded leading edges, especially at the crown and grille edges, cab A-pillars, and sleeper roof edges. They also generally have conformal headlamps integrated into fenders, curved outer ends to bumpers, bumper air dams, hoods that slope downward at the front, aerodynamic cab access steps, chassis fairings with ground effects skirting, and sleeper extenders. These features are mandatory for vehicles to be classified by the U.S. Environmental Protection Agency (EPA) as "SmartWay tractors." The full list of models which qualify as SmartWay tractors by virtue of their aerodynamic performance is available at EPA's website http://www3.epa.gov/smartway/forpartners/technology.htm and reproduced in Table 1, as it appeared in February 2016.

Manufacturer	Tractor Model	Model Year
Navistar	Prostar	2007, or newer
Navistar	9200i	2007, 2008 & 2009
Navistar	LoneStar	2008, or newer
Mack	Pinnacle	2008, or newer
Daimler	Columbia	2008, or newer
Daimler	Century Class S/T	2008, or newer
Daimler	Cascadia	2008, or newer
Volvo	VN 630	2007, or newer
Volvo	VN 670	2007, or newer
Volvo	VN 780	2007, or newer
Kenworth	T2000	2008, 2009, 2010 & 2011
Kenworth	T660	2008, or newer
Kenworth	T680	2012, or newer
Kenworth	T700	2011, or newer
Peterbilt	387	2008, 2009, 2010 & 2011
Peterbilt	386	2008, or newer
Peterbilt	384	2010, or newer
Peterbilt	587	2011, or newer
Peterbilt	579	2012, or newer

Table 1 EPA Designated SmartWay Tractor Models

Note that merely possessing these descriptive attributes are no guarantee of actual performance. The actual performance of each tractor is subject to many variables, not least of which are the trailer configurations hauled by the tractor, and moreover even data about performance for identical trucks will vary depending on the testing and performance evaluation method that was used to obtain. For greater insights on these factors, refer to the both the Determining Efficiency Confidence Report and the Trailer Aerodynamic Devices Confidence Report, available at the http://www.truckingefficiency.org website.

The more recently released SmartWay aerodynamic high roof sleeper cab models are shown in Figure 9.

Figure 9 OEM Aerodynamic High Roof Sleeper Models - Peterbilt 386 (2005), Navistar ProStar (2006), Mack Pinnacle (2006), Kenworth T660 (2007), Freighliner Cascadia (2007), Navistar LoneStar (2009), Peterbilt 587 (2010), Kenworth T680 (2012), Peterbilt 579 (2012), Western Star 5700XE (2014), Volvo Optimized VNL (2013), Freightliner Cascadia Evolution (2014), Kenworth T680 Advantage (2014), Navistar ProStar ES (2014), and Peterbilt 579 EPIQ (2015)

The OEMs' model design of day cab tractors generally use the same basic cab as used for their sleeper models; Figure 10 demonstrates this with the Freightliner Cascadia Evolution family, which employs the same basic cab for different configurations.

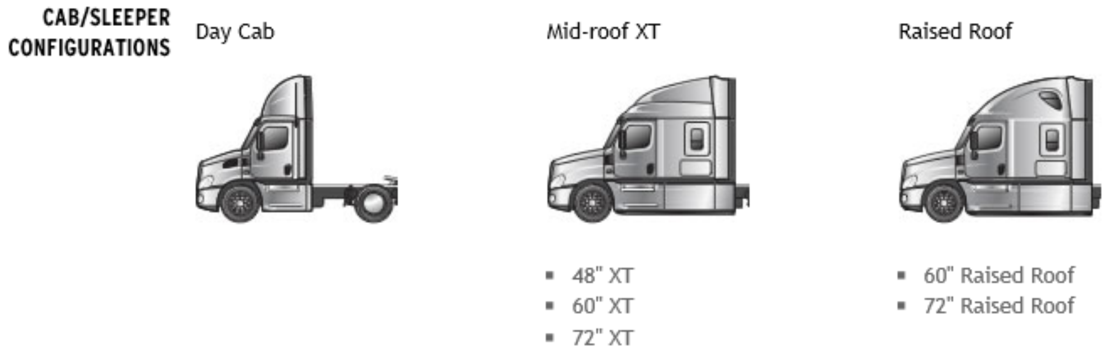


Figure 10 Day Cabs & Sleepers Are Related (Freightliner)

Aerodynamic day cab models from the various OEMs are shown in Figure 11. The day cab tractors commonly have pronounced sloping hoods, and both the roof fairings and the extenders are uniquely designed for the day cab models, but other features like mirrors, bumpers, chassis fairings, etc. may be common with their high-roof sleeper variants.

Figure 11 Examples of Aerodynamic OEM Day Cab Models – Freightliner Cascadia, Volvo VNL, Western Star 5700, Mack Pinnacle, Kenworth T680, Peterbilt 579 EPIQ, Navistar ProStar

2.1.1. Day Cabs and Aerodynamics

Just like sleeper tractors, day cabs will also experience aerodynamic drag in the area of the tractor/trailer gap. However, the day cab is a more complex vehicle to optimize because any given model might be used in a much broader range of potential duty cycles than sleeper cabs; some day cabs will never see highway speeds as they will operate in cities with frequent stops, while others will spend most of their time at highway speeds going between ports and train yards and warehouses, and many variations in between. Figure 12 created from data provided by ACT Research shows that about 40% of Class 8 tractors built are day cabs.

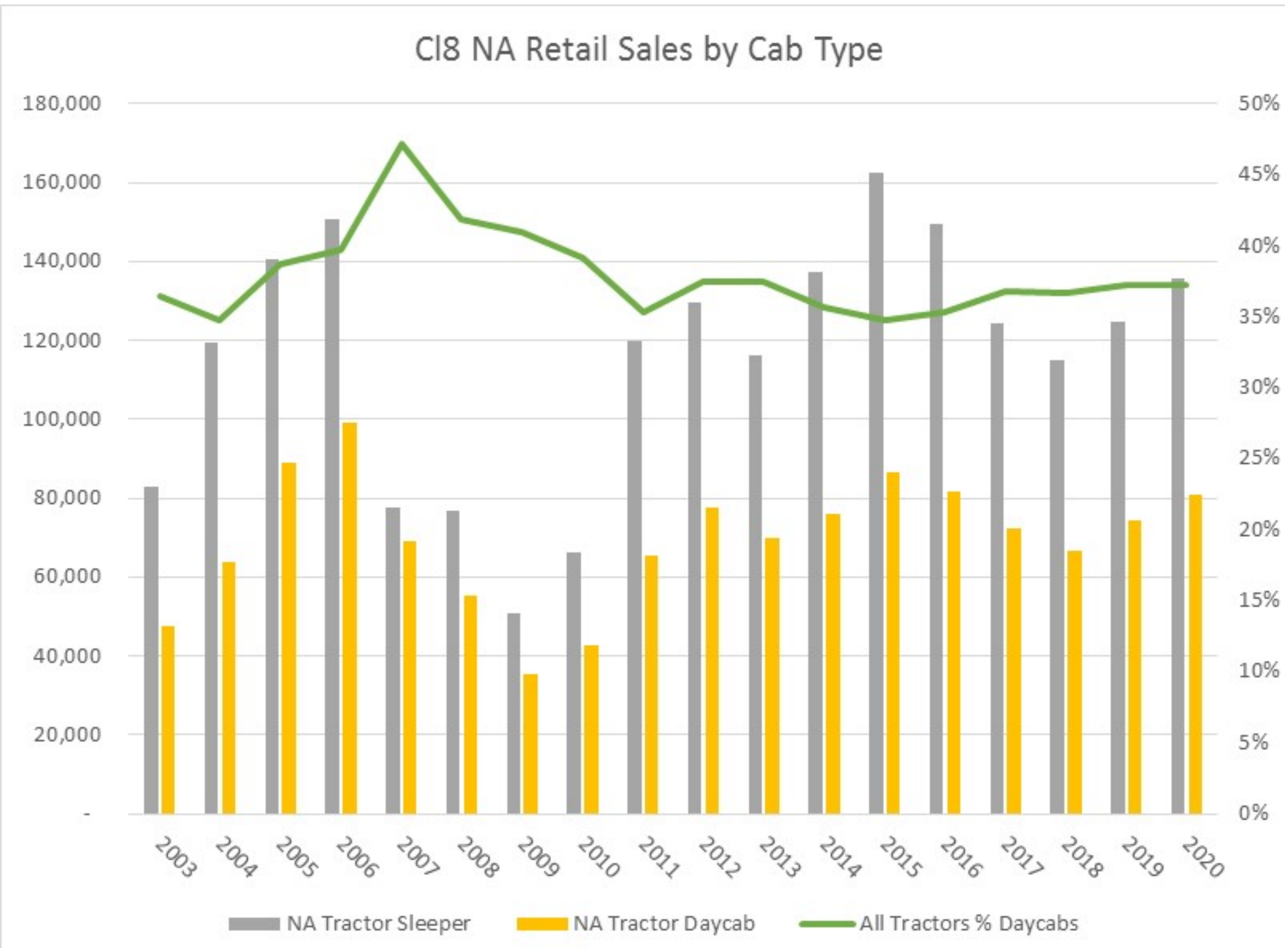


Figure12: Day Cab to Sleeper Production Mix

The figure below gives examples of the drive cycles that day cabs might see, including even line-haul operations. The benefit offered from aerodynamic treatments will vary considerably with each cycle – this is true not only for the side, roof, and chassis devices that can reduce drag at the tractor/trailer gap, but also for the other aerodynamic devices discussed in the following pages of this report.

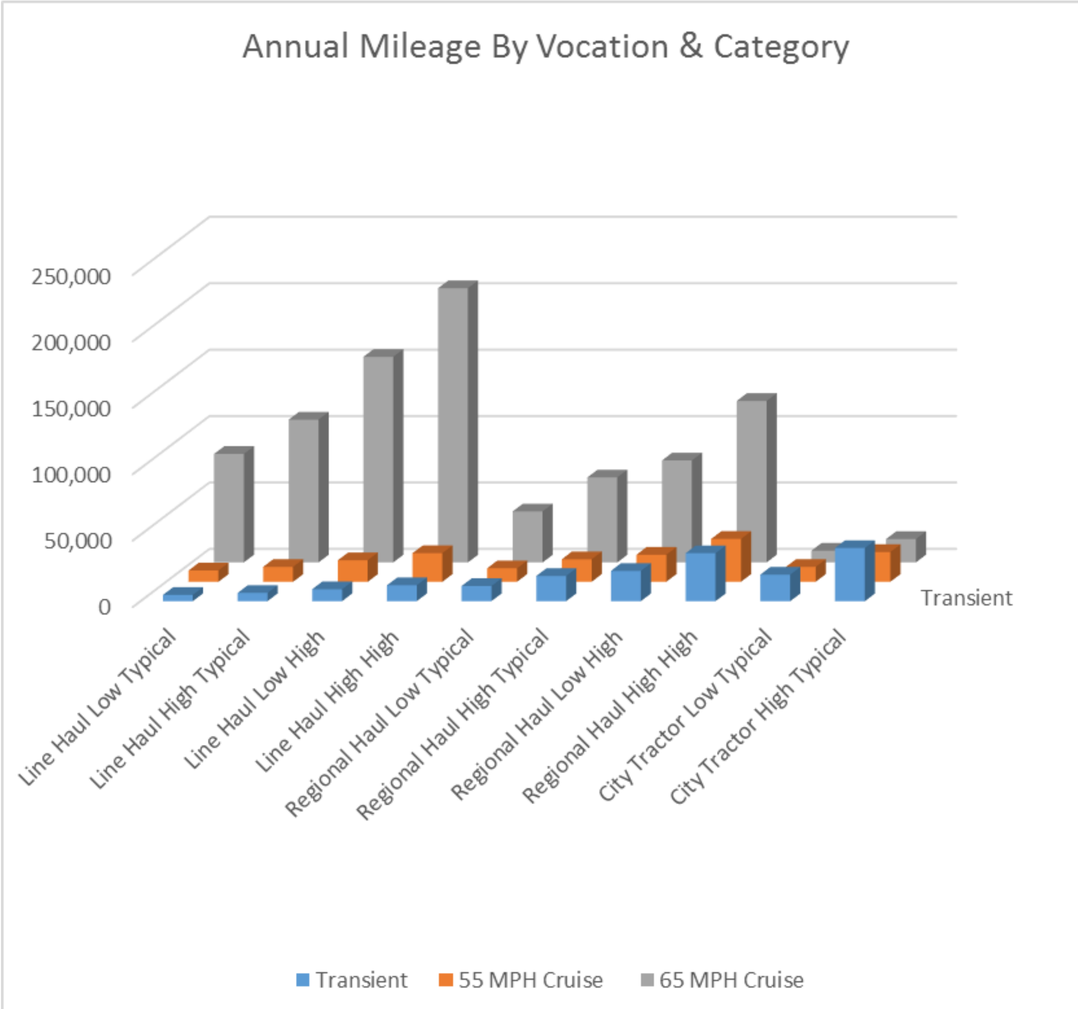


Figure 13 Examples of Day Cab Drive Cycles (Schaller)

The "starting point" for a day cab is the untrimmed cab, as illustrated in Figure 14. This type of tractor primarily does city driving, making frequent stops to unload at various retail outlets, and therefore it has low net mileage, moves at non-highway speeds, and is stationary for a significant amount of its time. Selection of an OEM aerodynamic model will still make sense for such fleets, but although additional aerodynamic treatments to the tractors will still improve fuel economy to some degrees, the payback could take many years.

Figure 14 Example No-Aero Device Day Cab

2.2.OEM Aerodynamic Model Variation

Comparing the aerodynamic performance of different OEM model tractors can be difficult, as detailed in the "Determining Efficiency" Confidence Report available at www.truckingefficiency.org, especially because many aerodynamically-optimized OEM models perform within a few percentage points of each other when comparably spec'd.

Improvement in aerodynamic performance can be illustrated simply with an S-curve, as shown in Figure 15. The older the tractor model, the lower they are on the curve, with the greatest opportunity for significant improvement. Thus an OEM Platform, or group of models utilizing common parts, designed ten or five years ago will have more to gain from aerodynamic refinements than a new one.

Meanwhile, the newest OEM aerodynamic tractor models are struggling nearer the peak of the S-curve, and significant time and money is required to achieve modest gains; an entirely new cab and hood tractor product line can require more than $1 billion in new OEM investment and can take four to ten years to reach production.

Given this, competition between OEMs (on their newest, most aerodynamic high roof sleeper tractor configurations) is measured in differences of just a few percentage points, with each new model pushing the performance envelope. The high percentage aerodynamic improvements for the near term are more likely to come from installing trailer aerodynamic devices and from improved multi-vehicle aerodynamics such as platooning, and incorporation of various electronic devices to optimize operational use of vehicles.

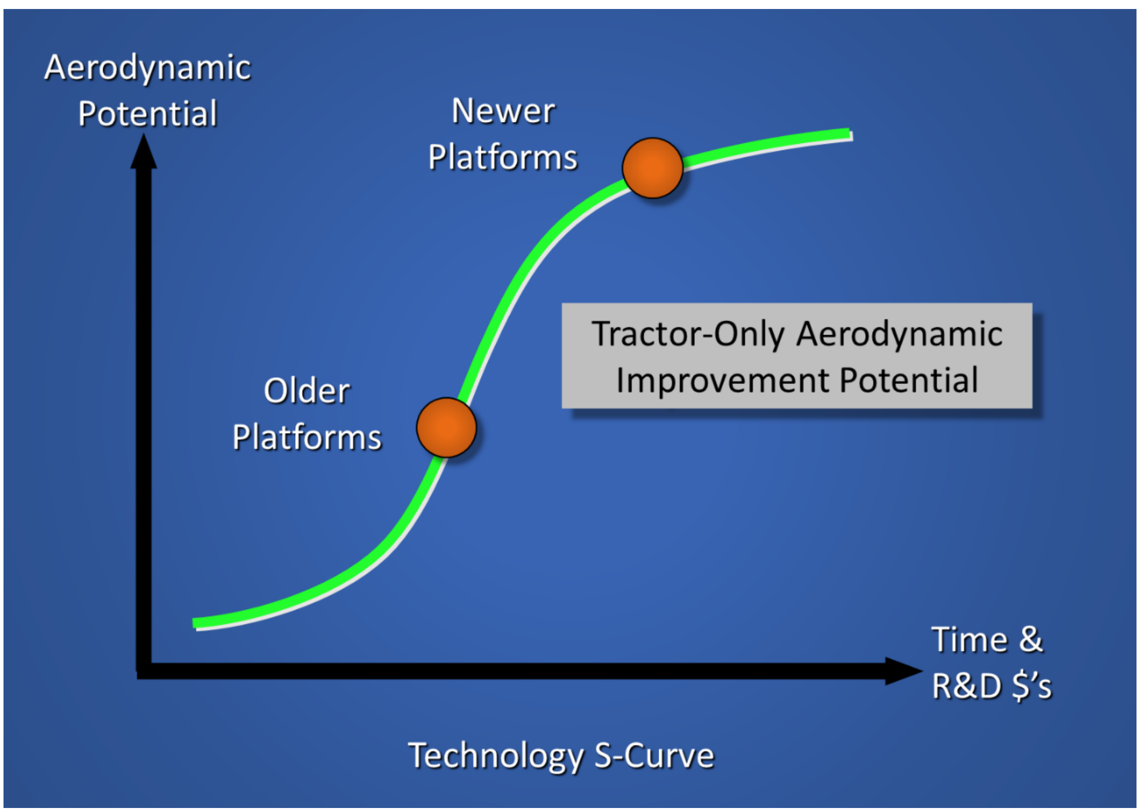


Figure 8 Aerodynamic Technology S-Curve

The EPA/NHTSA Green House Gas Phase I rules and Phase II proposed rules, which encompass the tractor OEM's annual production, can be used to put numbers behind these small degrees of difference. The Phase I rules divided the entire spectrum of high roof sleeper tractor aerodynamic performance into five bins, or ranges, as defined by their "drag coefficient area" (CdA), while the Phase II rules expand these five bins to seven, as shown in Table 2. The higher the drag coefficient the worse the fuel economy.

Table 2 Proposed EPA/NHTSA Phase II Aerodynamic Bins (EPA)

Table 3 of § 1037.520—Bin determinations for Phase 2 High-Roof Tractors Based on Aerodynamic Test Results (C_DA in m^2)

Tractor Type	Bin I	Bin II	Bin III	Bin IV	Bin V	Bin VI	Bin VII
Day Cabs	≥7.5	6.8-7.4	6.2-6.7	5.6-6.1	5.1-5.5	4.7-5.0	≤4.6
Sleeper Cabs	≥7.3	6.6-7.2	6.0-6.5	5.4-5.9	4.9-5.3	4.5-4.8	≤4.4

OEM representatives told the study team that current market penetration estimates from the EPA suggest that nearly 70% of 2015 high-roof sleeper tractor production would fall into the proposed Bin 2, with a CdA between 7.2 and 6.6 (Sproul). This range from maximum to minimum equates to a change of 8.3%, meaning that over 2/3rds of new high-roof sleeper tractors are separated by at most 8% in their aerodynamic performance – or about 4% in fuel economy. By 2018, the EPA's Regulatory Impact Analysis for the Phase II rules estimates that 70% of high roof sleeper production would have improved their aerodynamics enough to fall into Bin 3, which has a slightly smaller range of a 7.7% difference from the best to the worst performance in the bin. That same EPA estimate projects that a full 20% of the production in 2018 would be in Bin IV with the lowest CdA figures, representing the most aerodynamic high-roof sleepers.

While specific OEM data about CdA measurements is not publically available, it is likely that the distribution of vehicle CdAs even within the ranges of these bins is not uniform, and that the most optimized OEM models are likely grouped in even smaller ranges, with equally configured tractors paired with the identical trailers separated by only a couple of percent in their aerodynamic performances.

Although the nomenclature is in common use, it is a misleading choice of words to divide the tractor segment into "aerodynamic" and "classic" (less aerodynamic) OEM models, as both are subjected to the physics of aerodynamics at all times they are in motion, and moreover, particularly for sleeper tractors, the most common, "flagship," models of the OEMs, which in a sense serve as the traditional product offering, do also represent highly aerodynamic designs. The study team for this Confidence Report has found that there may actually three segments of high-roof sleeper tractors today:

- Aerodynamic
- Transitional
- Classic

The “transitional” term that NACFE suggests represents a mid-point in aerodynamic performance and design between the aerodynamic models and the more classic ones. NACFE proposes that currently available models may be sorted between these categories as follows:

Aerodynamic	Transitional	Classic
Navistar ProStar	Mack Pinnacle CXU series	Peterbilt 388
Freightliner Cascadia	Navistar LoneStar	Peterbilt 389
Kenworth T680	Western Star 5700	Kenworth T800
Kenworth T700	Freightliner Coronado	Kenworth W900 & Icon 900
Kenworth T660		Mack Pinnacle CHU series
Peterbilt 587		Western Star 4900
Peterbilt 579		Navistar 9900i
Peterbilt 386		
Volvo VNL 670		
Volvo VNL 780		

Table 3 Proposed EPA/NHTSA Phase II Aerodynamic Bins (EPA)

There are many reasons why the classic tractors exist as a viable commercial platform. For one thing, residual value is another key factor in tractor choice, and in the free-market world of today’s trucking, there are customers that place a premium on other factors than aerodynamics for their operations. In addition, whether spec’ed new or for resale, a tractor hauling a combine, drill site tank, cattle trailer, bridge girders, or parts of wind turbines, is not going to see significant benefits from investing in greater aerodynamic performance, because the trailer load of these duty cycles is so un-aerodynamic it will offset any advantages provided by the tractor shape (Figure 16).

Figure 9 Odd Size Loads and Non Aero Trailers May Cancel Any Aero Benefits of Tractor

3. Benefits of Aerodynamic Tractors

The benefits and challenges of utilizing any specific aerodynamic tractor feature will vary depending on the specific area of the tractor to which the feature pertains. However, certain benefits are available from being conscious of aerodynamics overall in tractor design, and seeking to optimize aerodynamic performance.

3.1. Fuel Savings

Fuel savings from aerodynamic improvements are real, and can be substantial, as documented in NACFE's annual Fleet Fuel Study (Figure 4) and countless other sources. Knight Transportation, for example, states in their 2016 SEC Form 10-K (Knight), "We continue to update our fleet with more fuel-efficient post-2014 U.S. Environmental Protection Agency ("EPA") emission compliant engines, install aerodynamic devices on our tractors, and equip our trailers with trailer blades (skirts), which lead to meaningful improvements in fuel efficiency." Even with the reduced fuel prices seen as of 2015, the multiplying small fuel savings over an entire fleet can create large savings to the bottom line. Typical on-highway single driver tractors can see between 120,000 and 140,000 miles per year, dual drivers can see over 220,000 per year. One representative of Mesilla Valley Transport, an aggressive adopter of aerodynamic technologies, stated at the March 2016 TMC meeting that every 0.1 mpg improvement in fuel economy translates to over a million dollars in savings.

Moreover, fuel price volatility is a reality, and although fleets can lessen their sensitivity to it via fuel surcharges, this is not a surety, as Werner stated in their 2016 SEC Form 10-K (Werner): "We cannot predict whether fuel prices will increase or decrease in the future or the extent to which fuel surcharges will be collected from customers." And even with surcharges, fuel remains one of any fleets largest expenses. As the Celadon Group states, "Fuel is one of our largest operating expenses. Diesel fuel prices fluctuate greatly due to economic, political, climatic, and other factors beyond our control. Fuel is also subject to regional pricing differences and often costs more on the West Coast, where we have significant operations." Fuel efficiency, especially in the world of surcharges and fuel contracts, plays a key role in how fleets stay profitable.

While aerodynamic improvements are technically possible with all vehicles, and many are actively being researched, the greatest opportunity in terms of miles-driven and resultant fuel use is with the on highway van trailer segment—both day cabs and long, high roof sleepers.

However, while the fuel benefits of better aerodynamics on high-roof sleeper tractors are well-recognized in the industry, some remove these features from the OEM offerings. If the aerodynamic features are removed from the OEM's aerodynamic base model, a fleet can expect to lose about 10% in fuel economy. Another 10% can be lost simply by pairing a mid-roof tractor with a dry van or refrigerated trailer. Even at today's fuel prices of about $2 per gallon, 10% of fuel spend represents $3,500 per year per truck.

There is, however, a long-standing misperception in the trucking industry that improved aerodynamics will only save fuel at speeds above 55 mph. Due to this, day cabs and other duty cycles have lagged long-haul sleepers in their aerodynamic performance improvements. But in reality, aerodynamic drag is acting against the vehicle at all speeds above 0 mph. Given the many low- or no-cost design elements that can reduce drag, even fleets operating at lower speeds should consider adoption.

Many still believe that the lower annual miles and slower average operating speeds of daycab tractors limit or even eliminate the value of tractor aerodynamics. It is true that aerodynamic devices save greater amounts of fuel at higher speeds, they are still valuable in many daycab applications. The study team for this Confidence Report worked with a truck manufacturer to run a comparison between a daycab tractor with fully optimized aerodynamics and one with no aerodynamics, and found that at 65 mph, the aerodynamic tractor enjoyed a 13% gain in its fuel economy. Multiple fleets verified this estimate in tests they've conducted with aero and non-aero day cabs in their operations.

3.2. Driver Visibility

Aerodynamic tractors with sloped hoods and fenders offer a clear forward visibility improvement. This allows drivers to see objects directly in front of the vehicle and to the forward right and left sides of the tractor. Improved visibility is important to all on highway tractor applications, but is very important for day cabs which experience more city driving where automobiles, pedestrians, infrastructure, etc. are commonly in the path of one of these vehicles and where drivers must maneuver around. Improving the sloop of the hood that lowers drag and subsequently improves fuel economy, also makes for a more visible driver experience.

4. Challenges of Aerodynamic Tractors

The most appropriate title of this section is in fact "challenges of *maximizing* the aerodynamics of tractors," as there are no challenges inherent to the entire class of aerodynamic devices, particularly given that all of the OEMs offer highly aerodynamic tractors as their base models. However, fleets may still be able to save additional fuel by maximizing the aerodynamics of the unique tractor they ultimately spec, both by adding aerodynamic devices above and beyond those include in the OEM model, and by optimizing their final tractor design with aerodynamics in mind.

4.1. Cost and Payback Calculation

There are a multitude of proposed duty cycles defined for industry and government use. A good summary of many of these is found in the Draft EPA GHG Phase II Regulatory Impact Analysis (RIA) issued in 2015 (http://www3.epa.gov/otaq/climate/documents/420d15900.pdf starting on page 3-58), and reprinted in Table 4. The main takeaway here is that there are significant differences between typical Day Cab and Sleeper Cab duty cycles, so it is important to understand a fleets specific actual duty cycles. For example, the EPA Composite Duty Cycle states that Sleeper Cabs operate at 86% of its time at 65mph cruise, which may be accurate on average for the entire United States, but will not be accurate for fleets operating exclusively in California where the maximum speed limit is 55 mph.

Table 3-24 Phase 1 Vehicle Duty Cycle Composite Weightings

VEHICLE CATEGORY	PHASE 1 COMPOSITE WEIGHTINGS OF DUTY CYCLE MODE		
	Transient	55 mph Cruise	65 mph Cruise
Vocational	42%	21%	37%
Vocational Hybrid Vehicles	75%	9%	16%
Day Cabs	19%	17%	64%
Sleeper Cabs	5%	9%	86%

Table 4 EPA Phase I GHG Composite Duty Cycles

The draft EPA GHG Phase II rules issued in 2015 contains an updated table of duty cycles proposed for future use (Table 5). The EPA RIA describes how duty cycles are documented by various groups, involving using data loggers on a number of vehicles over a sufficient period of time to get statistically meaningful picture of the actual operation. NACFE recommends that fleets perform this valuable self-assessment to understand their own operations so that better decision making can occur on technology investments.

Table 1 of § 1037.510—Weighting Factors for Duty Cycles

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

Table 5 EPA GHG Phase II Composite Duty Cycles

While ideally day cabs and SmartWay high roof sleeper tractors never idle, thanks to the no-idle automatic shutdown systems or other no-idle systems many of them must be equipped with (see the Idle Reduction Confidence Report at www.truckingefficiency.org), their net mileage is related to the driver's allowable driving time, which is affected by how long vehicles are spend stopped while the driver is working. Vehicles not moving have zero freight efficiency, even if their engines are shut off, causing zero loss in fuel. One of the benefits of a fleet analyzing its own drive cycles is that it can highlight lost time-in-motion due to warehouse dock loading and unloading and other delays such as maintenance and repair down time that ultimately impact the net miles driven per year, which should be a critical part of investment decisions and ROI calculations on aerodynamic technologies.

Dead-heading time, travelling with an empty trailer, creates another complication on using averaged data about technology performance, as not all fleets have the same percentage of dead-heading. Typical fleets see 11% to 13% of their miles as deadhead miles. If their dead-heading percentages differ, mpg will be a misleading metric to compare two different operations, as the one with lower dead-heading will have worse fuel efficiency than the one with greater dead-heading, even though they may in fact have great freight efficiency. Amalgamated data such as shown in Table 4 assume that all fleets have the same amount of deadheading, as well as the same average freight loads. Fleets must use better figures specific to their own operations in order to interpret and use the averaged data reported in testing and regulations.

Historically, aerodynamic features that were added on to the tractor incurred a higher initial cost; this is still the case for some of the optional devices such as sloped hoods, aerodynamic mirrors and bumpers, chassis fairings, etc. detailed in section 5 of this report.

However, many aerodynamic improvements are achieved simply by redesigning the shape of an existing aspect of the tractor, and do not entail the addition of a new device. These options include slopped hoods, and aerodynamic mirrors and bumpers. The engineering of these redesigned parts have matured over the last decade, and their associated costs have lowered with scale. For both add-on and redesigned aerodynamic improvements, increased adoption and larger production volumes has allowed manufacturers to move to more highly tooled manufacturing to even further reduce costs. Due to the design of these parts being so specific to each OEM, end users will consult directly with them for costs comparisons of aero to non-aero tractors and for individual aerodynamic features. The study team found that as volumes increase the difference in costs between these total configurations are merging to being equal, meaning aerodynamics are becoming more common and standard each year.

Even though many aerodynamic improvements can be had with little to no cost, there is a misconception in the trucking industry that there is a magic speed of 50 mph above which aerodynamics work to improve fuel efficiency, and below which, they do not. This belief causes many fleets, particularly those spec'ing day cabs, to overlook the process of aerodynamic optimization when designing their vehicles. The study team finds that this misconception stems from the way aerodynamics have been simplified and "marketed" within the industry – the graph in Figure 27 is exemplary of this. It illustrates how the engine must burn fuel to overcome both mechanical drag (rolling resistance and accessories, etc.) and aerodynamic drag and move the truck forward. The graph indicates that, for late-1990s-vintage aerodynamic tractors, aerodynamic drag takes an increasing share of horsepower compared to mechanical drag only at speeds of 50 mph or higher. Thus aerodynamic drag has commonly been understood as a concept *relative to* mechanical drag, when in fact the engine is overcoming both drag types at all speeds above zero, and a reduction in aerodynamic drag will improve to fuel economy at all speeds. Moreover, care must be taken when using such dated curves as the one shown in Figure 13, because newer, more aerodynamic tractor models will have cross-over points at much higher speeds; this does not mean that further improvements in their aerodynamics will not be cost-effective at lower average speeds.

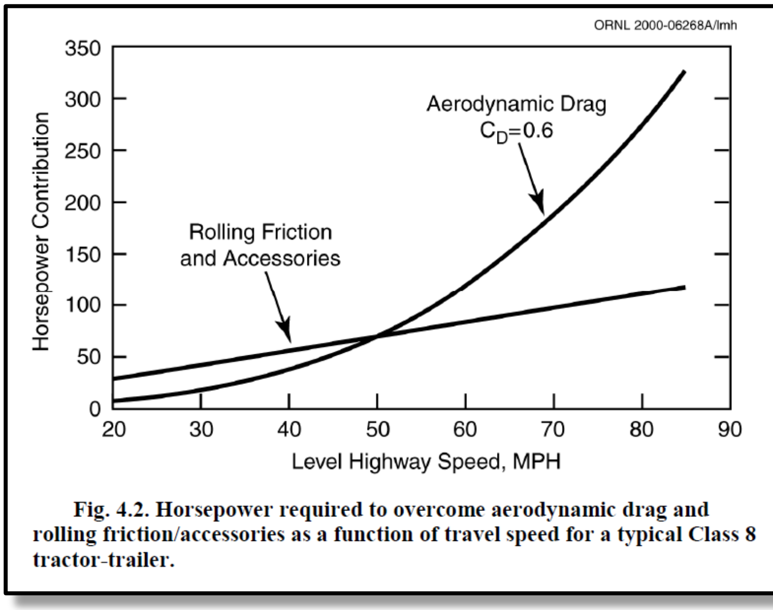


Fig. 4.2. Horsepower required to overcome aerodynamic drag and rolling friction/accessories as a function of travel speed for a typical Class 8 tractor-trailer.

Figure 10 Horsepower vs. Speed (DOE circa 1998)

Another common "marketing" simplification has been that a 2% improvement in aerodynamic drag equates to a 1% improvement in fuel economy. This 2:1 ratio can be misleading as it applies only at a specific speed that is unique for each vehicle. Using it to compare between different vintages of aerodynamic tractors can lead to significant errors.

Misunderstandings like these make it difficult for fleets to accurately calculate the paybacks available from the adoption of aerodynamic devices, and may have caused many fleets to miss out on savings.

4.2. Accessibility, Maintenance, and Repair

It is important that fleets clearly understand the interplay of any aerodynamic device with their specific duty cycles. For instance, large aerodynamic chassis skirts that nearly completely close the gap between the side of the tractor and the ground may work fine on routes with good roads, but for those which contain pot holes, may have frozen snow and ice, or the delivery locations have otherwise uneven surfaces, such low skirts could cause maintenance and repair issues. Similarly, side of cab extenders can be damaged hitting the trailer in hard turn maneuvers in loading and unloading situations.

A few of aerodynamic devices actually cover up other vehicle features that need periodic maintenance, for example, wheel covers and chassis side skirts limit access to wheels and chassis components.

Different manufacturers offer more or least aggressive parts, so a fleet can limit damage by specifying a different aerodynamic device design, and still gain some benefit, rather eliminating the feature from their specs.

4.3. Weight

Add-on aerodynamic devices (as compared to those features which are redesigned for improved aerodynamic performance) can add weight to the vehicle, and this should be considered in calculating their expected effect on fuel economy, particularly if the added weight may impact the ability to haul payload.

However, fleets whose payload is not weight sensitive should consider that the impact of vehicle weight on fuel economy is just 0.5% - 0.6% per 1,000 pounds of weight. Even the most aggressively optimized aerodynamic tractors require less than 2,000 lbs. of aerodynamic devices to be installed, so the maximum mile-per-gallon reduction due to the weight of add-on aerodynamic fairings would be less than 1.2% - this is much smaller than the significant mpg gain offered by the improved aerodynamic performance.

5. Aerodynamic Device Options

There are many specific “areas” on a tractor where aerodynamic performance may be optimized. Some of these areas are routinely optimized as part of an OEM’s base model; others may be optimized by fleets in spec’ing their vehicle for additional fuel savings.

5.1. Frame Layout & Tractor/Trailer Gap

The space between the steer wheels and the drive wheels is premium real estate for a variety of chassis components (Figure 18), as OEMs must generally fit cab-access steps, air tanks, battery boxes, fuel and DEF tanks, deck plate access steps, APUs, fenders, and other equipment between steer and drive axles. These chassis option content choices can also affect fifth wheel placement, which in turn can impact axle loading choices.

Figure 18: Sleeper cab with chassis options

The accumulation of these chassis options can cause the final tractor to deviate from the optimal aerodynamic configuration that was designed in the OEM’s base model, particularly by causing longer tractor-to-trailer gaps than what the OEM used in optimizing the vehicle surfaces. Multiple studies and tests have shown that as trailer gaps get longer, overall aerodynamic drag increases. A more recent wind tunnel scale model evaluation from the National Research Council of Canada concluded that “wind averaged C_D (drag coefficient) increases with gap width by approximately 2.7% C_D per foot. They reported that this trend was consistent for both sleeper-cab and day-cab configurations as tested in the NRC wind tunnel against a non-aero trailer (NRC). Other values have been reported from actual on-road vehicle tests, CFD analyses, and other wind tunnel studies, but while all differ somewhat in magnitude, they generally all show increased aerodynamic drag as gap increases.

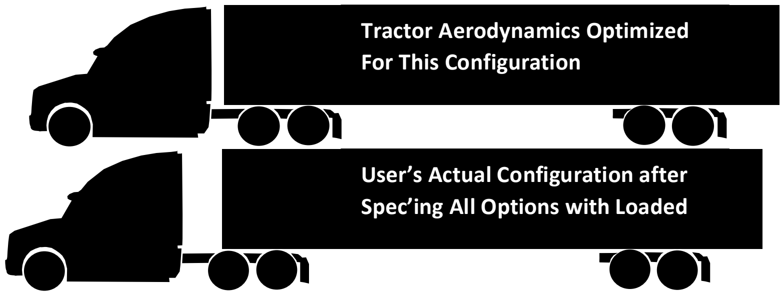


Figure 19 Frame Options Drive Tractor/Trailer Gap

These chassis packaging challenges occur for day cabs as well. Figure 20 shows a day cab configuration equipped with deck access steps and long fuel tanks.

Figure 20 Chassis Option Choices May Affect Optimum Aerodynamics (Navistar)

Aerodynamic devices, including extenders and fairings for the side, roof, and chassis of the tractor are all available to help compensate for the wider gap between tractor and trailer caused by the addition of other features. The design of the fairings for any of the three locations will be dependent on other parts of the vehicle. Figure 21 depicts that the tractor/trailer gap space in blue, and the arrows show all the different direction from which air can leak; some air leaks in and some leaks out of every direction. Moreover, if the flow of air into one direction increases, the flows out of the others must also change to compensate.

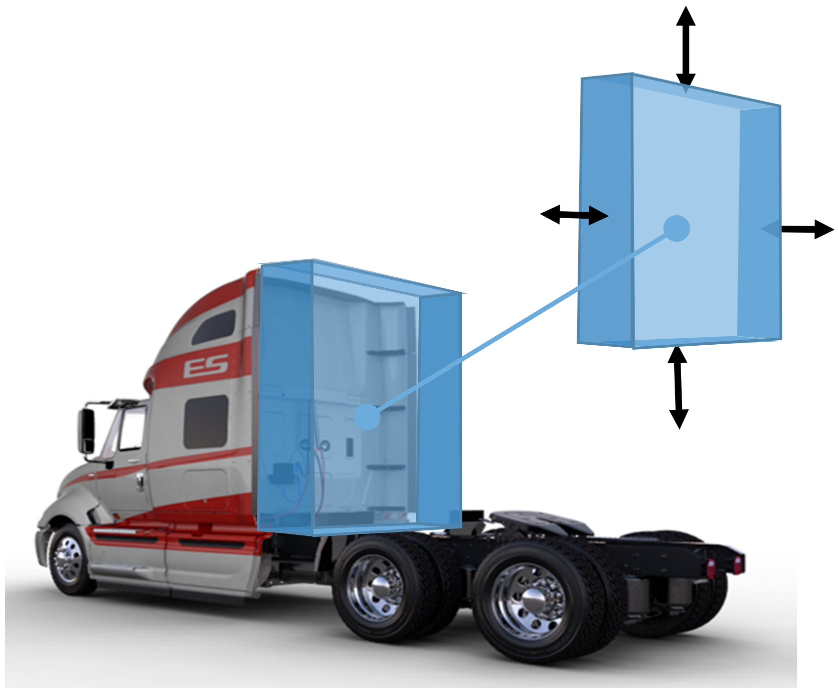


Figure 21 Tractor/Trailer Gap

Aerodynamic devices that change the flow in any of these directions will therefore affect the performances of devices on other surfaces. For example, a deck plate added to the bottom of the gap space will restrict flow from the chassis area up into the gap. That reduction in flow may mean increased flow at the roof and from the sides. Adding longer side extenders will decrease flow into the gap along the sides, causing flow to try to increase from the roof and from the chassis, top and bottom of the gap space respectively.

This complex interrelation between devices makes it difficult for designers to choose one or two extender designs that perform equally well for multiple configurations. Instead, devices are generally optimized around a few higher sales option configurations, and fleets should understand that performance will likely degrades somewhat as vehicles stray from those configurations.

Fleets should work with their OEM to determine which vehicle configurations offer the best starting point of an aerodynamic tractor/trailer gap configuration for the intended duty cycle, and then can compare that ideal against the fleet's final configuration to identify any features that may reduce actual performance, and provide some qualitative guidance on how significant these changes will be.

Because the area of the tractor/trailer gap can encounter aerodynamic drag at a variety of points, there are three sets of devices which improve aerodynamics in this area – cab and roof extenders, and chassis fairings.

5.1.1. Cab Extenders

Extenders help close the tractor/trailer gap area (Figure 22) by extending the vehicle side surfaces into the gap, ideally without interfering with trailer swing and dip motion that frequently occurs at loading dock apron areas. The majority of extender designs are static fairings, that is, they are fixed aerodynamic surfaces. Their primary purpose is to restrict air flow from entering into the trailer gap by shortening the effective tractor/trailer gap width and attempting to route air over the gap to the trailer side. Without extenders, air leaving the rear edge of the tractor would hit the front edge and face of the trailer, increasing drag; cross wind conditions, sometimes referred to as yaw, would likewise increase drag without extenders.

Figure 22 Extender

There are a variety of designs in production, as OEMs may offer configurations in various widths, materials, with or without a flexible edge, and with or without grab handles or other options. The extender may be in multiple sections vertically to deal with cab/sleeper roof height variants and/or to facilitate repairs. Some extenders also have attachments to roof fairings. The shape of the extender may have an outward slant as the majority of trailers are slightly wider than the tractors. Additionally, day cabs and sleepers will likely have unique extenders designed for each, illustrated in Figure 23.

Figure 23 Sleeper Extenders - Kenworth T680 Advantage, Navistar ProStar ES, Freightliner Cascadia Evolution, Peterbilt 579 EPIQ, Mack Pinnacle, Volvo VN780, Western Star 5700 XE

In sum, each OEM model is different, so comparison between specific cab-side extender devices is not meaningful, as the optimum choice will be the one offered by the OEM that was designed for their specific vehicle. Instead, the decision fleets must make involves assessing how far their specific tractor configuration diverges from that of the OEMs optimized model, and whether the resulting performance loss, if any will be significant to the fleet's operation or paybacks. Cab and roof extenders improve fuel economy by about 1-2%, depending on their shape.

5.1.2. Roof Extenders

OEMs have developed rear extenders for tractor roofs which improve air flow from the tractor to the trailer roof, as shown in Figure 24 and the next few illustrations.

The need for this device stems from the difference in height between the top of the sleeper or sleeper roof fairing and the front top edge of the trailer. OEMs typically only offer one design of roof extension for their model, which will be designed to share space with vertical exhausts, avoid contacting the trailer during swing and dip maneuvering, and fit in with styling while still improving aerodynamics.

As with side extenders, the wide variety of OEM designs highlights that each vehicle has been uniquely optimized for that specific vehicle's performance, and comparison between devices is not meaningful. The fact that all the major models of sleepers have some variant of a device that improves the passage of air from the tractor to trailer indicates that it is a critical element of aerodynamic performance. Cab and roof extenders improve fuel economy by about 1-2%, depending on their shape.

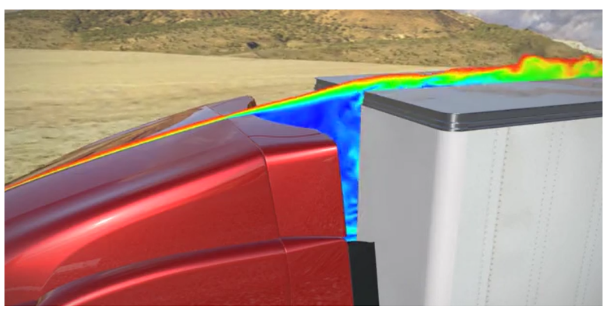


Figure 24 Analysis shows Roof Extension Helps Air to Jump Gap (Peterbilt) Navistar

Figure 25 Freightliner Cascadia Roof Extension (Freightliner)

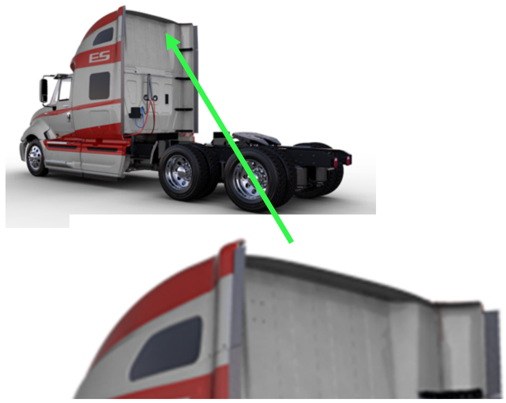


Figure 26 Navistar ProStar Roof Extension (Navistar)

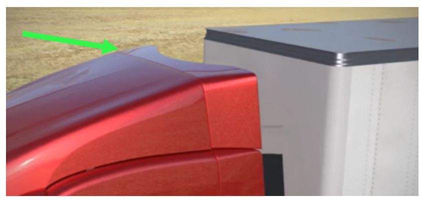


Figure 27 Peterbilt 579 EPIQ Bridge Fairing (Peterbilt)

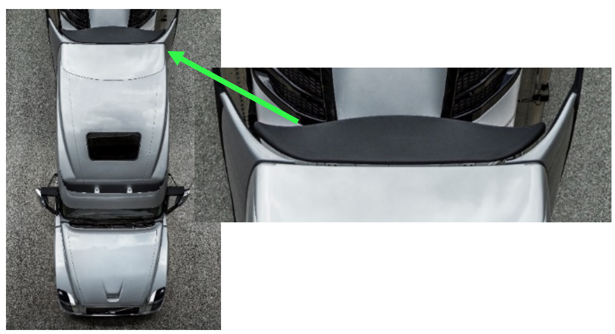


Figure 28 Volvo VNL680 Roof Extension (Volvo)

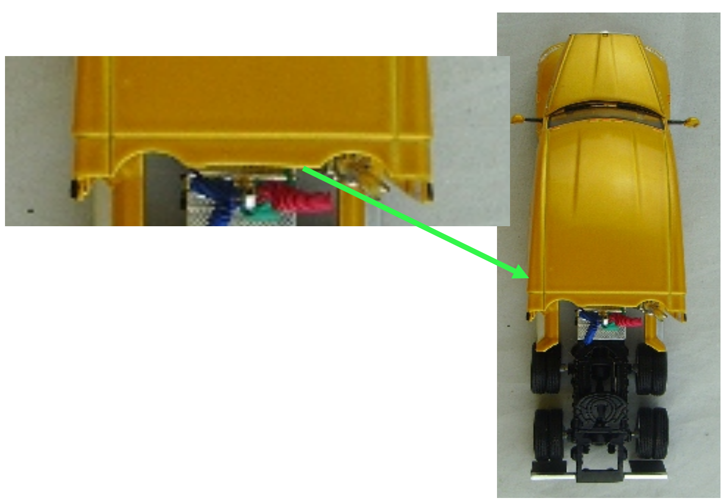


Figure 29 Kenworth T680 Roof Extension w/Cut Outs Removed (DieCast Collecting)

Figure 30 Western Star 5700XE Roof Fairing Rear Edge (Western Star)

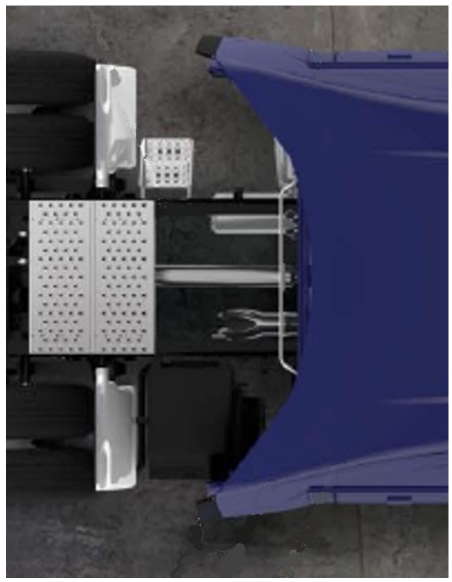


Figure 31 Mack Pinnacle Roof (Mack)

5.1.3. Chassis Fairings

The purpose of the chassis fairing, sometimes called chassis skirts, or even fuel tank skirts, is to provide a clean aerodynamic surface on that side of the tractor, and eliminate the multiple forward facing steps and ridges apparent in exposed chassis components. The devices are also designed to kick air slightly outboard of the tractor drive wheels, so that it does not directly impact the face of the tread of the tires. How the air interacts with the vehicle after that depends a great deal on the configuration of the trailer, i.e. whether or not it has skirts and if so which skirt design is in use. Chassis fairings can offer in the range of 2% to 4% improvements in fuel economy for aerodynamic tractors pulling 53’ van trailers.

Chassis fairings are generally required for SmartWay-designated sleeper tractors. That said, within the category of chassis fairing devices there are options for various lengths and end treatments, all of which are viewed equivalently by SmartWay, but that may differ in their actual performance. Most tractor chassis fairings generally run the length from the cab steps to the end of the sleeper; it can end there, or it can have various extensions that carry it over the first drive wheel. The fairing may require steps or it may be smooth, depending on whether deck access is required, and they may be in various lengths, to match with the tractor wheel bases. The four examples in Figure 32 are exemplary of the range of choices that most OEMs offer.

Figure 32 Sleeper Chassis Fairings – Peterbilt 579 full length with skirt, Mack Pinnacle with sleeper length skirt, Volvo VNL780 full length with steps, Western Star Sleeper length with extension.

Figure 33 shows prototypes of tractors which offer the best aerodynamic performance around the chassis area to date, thanks to chassis fairings that run all the way to the first rear axle and then typically add additional treatments around both rear axles. These prototypes include the recent DOE SuperTrucks and other future concept vehicles such as the Walmart WAVE. All show the importance of sealing as much of the lower side of the tractor as possible.

Figure 33 Optimizing Skirt Aerodynamics - Recurring Themes in Highly Optimized Prototypes

There are more trade-offs in adopting chassis fairings than for cab and roof extenders, as the skirts add a measureable amount of weight, as well as extra steps in maintenance when accessing chassis components. They are also another body surface, generally called an “A” surface, that must be manufactured and maintained for image. Some fleets have considered aerodynamics and chosen not to include chassis skirts, as their experience is that for their operations the aerodynamic performance gains are not offset by the additional maintenance costs and weight (Figure 34). While NACFE recommends tractor chassis skirt fairings for pulling 53’ on-highway van trailers, there are other configurations with shorter trailers, flatbeds, containers, etc. where the net mpg performance gain from the skirts may be insignificant compared to other challenges.

Figure 34 Examples of Otherwise Aerodynamic Tractors but w/o Chassis Fairings

5.1.4. Drive Wheel Fairings

The aerodynamics associated with rotating tires and wheels are complicated by many factors. Drive wheel fairings mounted between and behind the drive wheels of the tractor streamline the airflow around the rotating tires and direct airflow as it leaves the tractor. They provide a net benefit to the fuel economy of the vehicle, and are often used in combination with wheel covers on the tractor for a higher net benefit. Typical improvement in fleet fuel economy range from 1.5 to 2%.

The cost, weight, and installation time of drive wheel fairings is relatively small. One set of four drive wheel fairings for a tractor complete with mounting bracketry may add 45 to 60 pounds to the tractor. In combination with wheel covers the total added weight may be 60 to 75 pounds. Fleets have reported installation times as low as 30-45 minutes each for multiple installations, and 45-60 minutes each when installing one set at a time.

Currently only one drive wheel fairing product is available. The primary design challenge has been ensuring that the tractor is accessible for inspection, maintenance, and repair.

Figure 11 FlowBelow Drive Wheel Aero Kit and Wheel Covers

5.1.5. Unique Day Cab Implications

Day cabs with higher mileage and higher average speeds will gain more benefit from tractor aerodynamic treatments, with the most significant gains offered by the addition of roof extension fairings. The fuel efficiency gains achieved by installing a roof fairing on a day cab pulling a van trailer are large – 10% to 15% mpg for a high mileage day cab tractor that sees mostly highway miles – and also well-proven, having been studied for over 60 years, since Trailmobile did testing at the University of Maryland in 1953 (Figure 36).

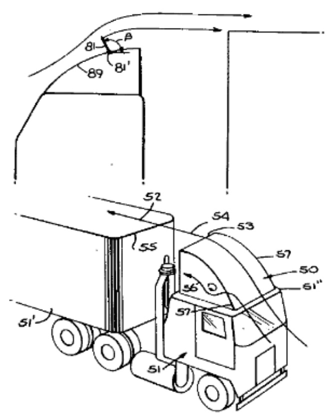


Figure 36 Roof Fairing Patent Image (Trailmobile)

The savings offered to other drive cycles will be less, but can still be substantial. For example, a day cab vehicle that has a 50% low speed and 50% highway speed cycle might still see 5% to 7% mpg gains. Even vehicles that operate mostly at low speeds will still see some improvement in fuel economy.

Adjustable roof fairings are an option for day cabs that might haul a variety of trailer types, to ensure the heights of the tractor and trailer always match. However, anecdotal feedback from fleets is that any aerodynamic device that requires driver interaction will not be properly deployed 100% of the time, so fleets want adjustable devices to operate without driver involvement. The study team found cases where the adjustable features on roof fairings had never once been adjusted after installation.

The next most promising option for improving the aerodynamics of the tractor/trailer gap on day cabs is offered by the side extenders, as for sleeper cabs. Most tractors are not as wide as the trailers they pull, in the case of day cabs more so, with tractor widths commonly in the range of 72 to 89 inches, and trailers commonly measuring 102” wide (Figure 37). This difference in widths exposes the front edges of the trailer directly to airflow, creating significant drag. Side extenders expand the width of the tractor to match that of the trailer, thus moving the air flow outboard so it jumps over the tractor/trailer gap. Figure 38 shows an example of optimized aerodynamic day cab extenders and matching roof fairing which completely shield the exposed trailer.

Figure 37: Unfaired Day Cab Exposes Blunt Trailer Top Front and Sides to Airflow

Figure 38: Similar Tractor with Cab Extenders and Roof Fairing

The extensive shaping of day cab roof fairings and extenders done by OEMs, as shown in Figure 38, highlights what the OEMs have found to be necessary to optimize these parts as a system, versus lesser add-on options and aftermarket choices, as shown in Figure 39. This add-on system would improve drag and save fuel for highway speed, and can be a very good option for day cabs that have multiple uses where lowering the roof fairing would save fuel, such as deadheading or when hauling a flatbed.

Figure 39 Day Cab Aerodynamic System vs. Add-On Approach to OEM Roof Fairing and Extender Design

Finally, chassis fairings similar to those for sleeper tractors are available for day cabs. The OEMs offer small versions which cover only the cab step package, as well as longer versions which run the first drive axle. Additional drive wheel fairings such as FlowBelow fairings, wheel covers, and vented mudflaps can run the overall aerodynamic treatment to the rear end of the day cab tractor. Many fleets choose to minimize their use of day cab chassis fairings because their duty cycles, including their trailers and vehicle operations, show insufficient payback periods from their own testing and field experience. This may not indicate that there is zero benefit, but rather that the net benefit of the chassis fairing package may be smaller than the precision of the fuel economy measurement systems are able to register. Other day cab fleets have seen measurable improvements from chassis fairings.

Overall, the OEMs deal with a wide range of customers and while they cannot quote specific customer information, they are likely the best single source of industry fleet experience in spec'ing options for their models of day cabs for specific duty cycles and operations. NACFE recommends that fleets work with their tractor OEMs to make the key tradeoffs for their day cabs, and where possible, conduct A-vs.-B testing of similar configurations where only the aerodynamic content differs. For more background on performance testing, see the Determining Efficiency Confidence Report at www.truckingefficiency.org.

If the fleet economics must choose between chassis fairings or adding a roof fairing and extenders, the most fuel economy gains will come from the roof fairing and extenders. If only one aerodynamic device is to be chosen, it should be the roof fairing versus the extenders for day cab tractors.

5.2. Cab Mirrors

All of the OEM's aerodynamic base models have optimized their cab mirror systems for use with their specific cabs. Non-aerodynamic OEM models may still offer a range of cab mirror styles, but fleets are typically limited to aesthetic items like appearance (painted, black, or chrome) and internal options like anti-icing or temperature readouts, when specifying the mirrors of the aerodynamic models; the shape itself is generally not an option, except perhaps the addition of antennas.

SAE Paper 920204, Aerodynamic Drag Implications of Exterior Truck Mirrors, contains a detailed description of full-scale wind tunnel testing of mirrors; Figure 40, taken from that report, shows the progression from non-aerodynamic mirrors to today's teardrop shapes. Mirror head and mounting arms will operate in a mix of air flows coming from the cab windshield, the hood top and sides, and in some cases, recirculation flow from the chassis areas. Combined with varying wind yaw angles, the mirror is an extremely challenging tractor area for engineers to optimize a single shape that aerodynamically works reasonably well in all conditions.

A 2007 TMA/DOE study by Freightliner titled Test, Evaluation, and Demonstration of Practical Devices/Systems to Reduce Aerodynamic Drag of Tractor/Semitrailer Combination Unit Trucks, highlighted a range of drag percentages for mirrors based on both wind tunnel and CFD analyses, concluding that the mirrors for one cab varied between 2% and 6% depending on wind angle. A key take-away in that study is "…the mirrors and cab should be designed as one integrated system. With well-designed mirrors, aerodynamic drag can be reduced 2 to 3 percent." They also estimated that "Eliminating mirrors altogether would yield a 6 percent improvement;" current highway safety regulations preclude this option, although it is being investigated by many groups.

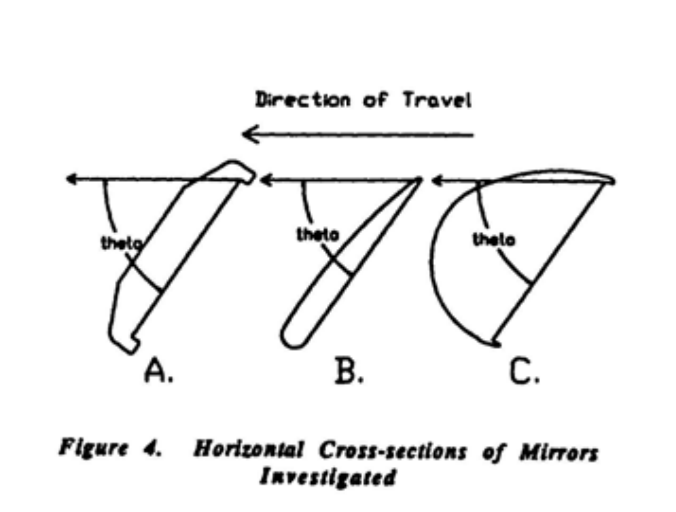


Figure 12 Mirror Progression to Aerodynamic Shape

Suffice to that that the final production mirror head shapes and mounting systems have been arrived at through considerable OEM and supplier tradeoff studies, field evaluations and analysis for their specific cab. Comparing different OEM mirror heads and arms is not relevant since they are not interchangeable between OEMs (Figure 41).

Figure 13 Examples of Aerodynamic Cab Mirrors and Mounting Arms

5.3.Sunshades

Some OEM tractor models offer external sunshades, others have internal ones, and some offer both options. The external sunshade on an OEM model is not an afterthought; like mirrors, it will have been designed as part of the whole tractor system that includes the cab, hood, sleeper and other primary aerodynamic elements. Those OEMs that have chosen the external sunshade as a standard feature on their aerodynamic base models (Figure 42) have optimized the design of that visor for a range of aerodynamic configurations and conditions. Like the mirror heads and arms, this area of a tractor is very challenging to aerodynamically optimize, and the designs have evolved through computer analyses, lab, and field testing. The final designs incorporate many requirements beyond aerodynamics (including providing meaningful shade from the sun) as the OEM balances the various functional demands.

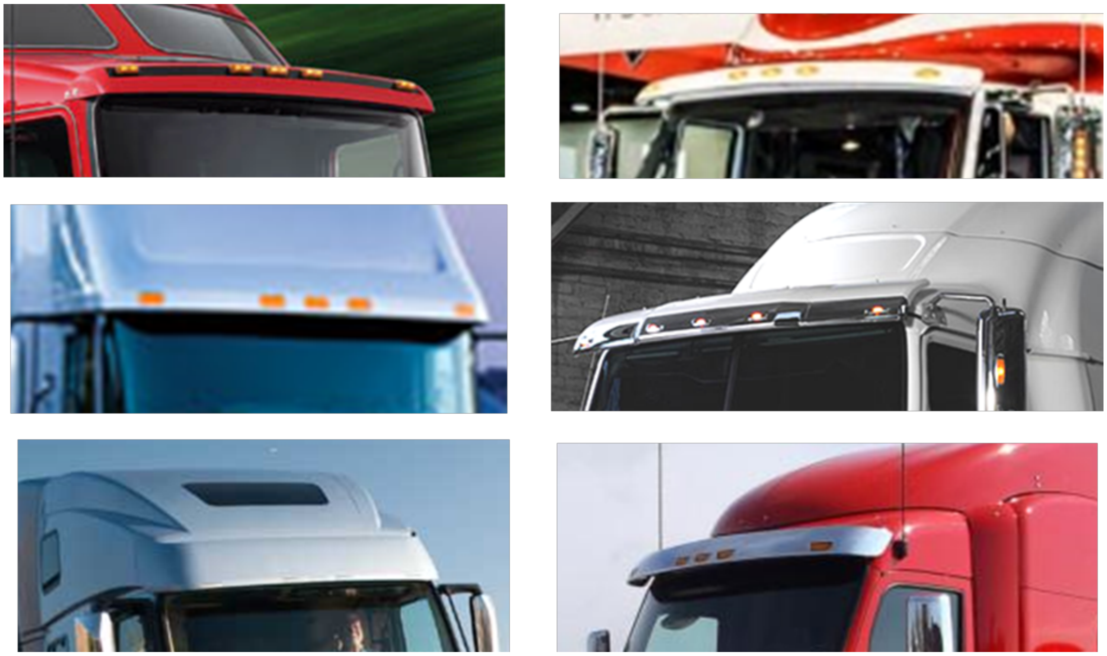


Figure 42 Sunshades Are Designed for Aerodynamics - Volvo VNL670, Peterbilt 579 EPIQ, Western Star 5700 XE, Mack Pinnacle, Kenworth T660, Navistar ProStar ES

Comparison of sunshades between OEMs is not relevant as they are not interchangeable and each is optimized for their specific cab systems. Comparison of one OEM's model that has a sunshade and a different OEM's model that has no sunshade is likewise problematic. As stated earlier, the flagship aerodynamic models from all vendors are not separated by large differences in performance. The goal of a properly designed sunshade should be to complement the vehicle aerodynamics, or at worst be neutral. As the sunshade performs other functions besides aerodynamics, if it is removed, other parts of the vehicle must try to compensate for the change, for example, dash gauge sun glare may increase requiring revision of the dash design, or driver visibility to street signals may be reduced. NACFE recommends that fleet buyers purchasing OEM models choose the most typical OEM configuration, whether that is with an external sunshade or without, as it is likely the best optimized aerodynamic configuration.

5.4. Headlamps

Headlamps on aerodynamic tractors are designed as integral parts of the hood shape. Figure 43 shows examples of how the designers at all the OEMs have contoured the headlamps to conform to the body shape. Other OEM models may offer headlamp alternatives, but the aerodynamic flagship models have been aerodynamically optimized around single shapes. As with the other devices, comparison between OEMs is not useful.

Figure 43 Aerodynamic Headlamps and Bumpers Conform to Hood Shape – Volvo VNL780, Western Star 5700, Navistar ProStar, Freightliner Cascadia, Peterbilt 579, Kenworth T680, Mack Pinnacle

5.5. Bumpers

Bumpers on the aerodynamic tractors are similarly shaped to conform to the body lines of the vehicle rather than stand out. As evident in Figure 44, the bumper ends are all well rounded. Where the OEMs diverge on aerodynamic bumper design is in their approaches to air dams under the bumper. A variety of schemes have been investigated to optimize this critical area. Functionally, the air dam tends to decrease the front clearance to the ground. This reduction in ground clearance causes the aerodynamic "stagnation point" to shift location on the truck. The stagnation point may be simply understood as the location where the on-coming air has to split to go around the vehicle. The location of the stagnation point affects the share of the air that is routed under the vehicle, to the sides of the vehicle, into the grille, or over the top of the vehicle, which ultimately impact the aerodynamic performance of all the downstream vehicle elements.

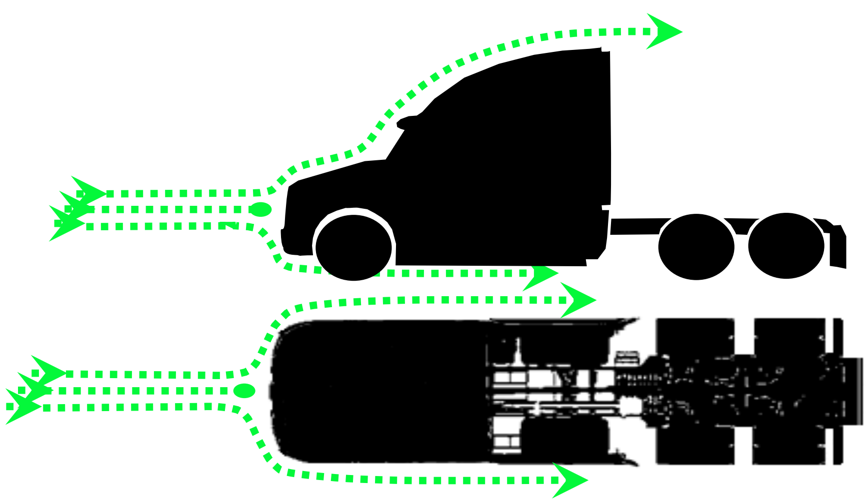


Figure 4414 Stagnation Point (Green dot at front of truck)

Along with changing the stagnation point for better aerodynamics, the air dam also attempts to redirect air from directly impacting the tread face of the tires and to shield low chassis components like axles and oil pans from the air flow. OEMs have arrived at quite sophisticated air dam designs, in order to ensure they accomplish all of these functions while still working well with all the downstream elements. Like many of the other tractor main components, the bumpers have been optimized as a part of a total system, rather than an add-on piece, to attain the best performance. Fleets may need to work with their OEMs to achieve want more ground clearance than that offered by the model tractor, due to operations or unique environments, but in general, NACFE recommends going with the OEM's recommended air dam for best fuel economy.

5.6. Fifth Wheel Locations and Height

The location or adjustable design of a fifth wheel is a tool for controlling the tractor-to-trailer gap. While adjustable fifth wheels can be used to close the gap for aerodynamic gain that translates into improved fuel economy, the reverse is also very true. Some drivers feel that setting the fifth wheel back further from the cab improves ride quality. Two manufacturers of fifth wheels were interviewed for this report and both reported the same trend. Many fleets are converting from 24 inches of adjustment range in the fifth wheel structure, down to 12 inches of adjustment. The dual benefit is less weight and less opportunity for loss in aerodynamics. While it is possible to go one step further and switch to a stationary fifth wheel, fleets feel that will hurt resale value, so they utilize the sliding fifth wheel option. One test engineer reported to us that a rough rule of thumb is eliminating 8 inches of gap to the trailer is worth about 1% improvement in fuel economy.

A number of options exist for reducing trailer drive height, which can reduce overall drag through the reduction in the profile of the vehicle. Combinations of tire choices and reduced fifth wheels can drop the overall trailer front roof height. The caution here is twofold. Firstly, the tractor aerodynamics has likely been optimized around the highest volume fifth wheel height, so the aerodynamics with different configurations may not necessarily be better. Secondly, if the front of the trailer is dipped down but the rear of the trailer is at its standard height, the trailer actually appears as a long wedge shape with increasing height at its rear and whatever benefit may have been achieved at the tractor/trailer gap may be lost by increased drag on the roof and the trailer wake area.

5.7. Wheel Covers

The aerodynamics associated with rotating tires and wheels are complicated by many factors including the type of ground surface, the wheel deformation as it rotates, variations in tread patterns, interactions with other tires, the presence or absence of fenders, the presence of mud/rain flaps, the presence or absence of chassis and trailer skirt fairings, and more. A variety of manufacturers produce aerodynamic wheel covers for use on both the tractor and trailer wheels. Steer axle wheels can also have covers. These are more rarely seen in the field than tractor drive axle and trailer bogie wheel covers.

Wheel covers may be OEM factory options or aftermarket dealer or fleet installations. Small benefits from these devices can be found in very controlled wind tunnel tests and CFD analyses, but are much more difficult to reliably measure in road and track testing. The consensus opinion is that these devices should offer a net benefit to the fuel economy of the vehicle, but the improvement is small enough that it falls into the statistical "noise" of most individual test methodologies. Fleet experience over longer periods of time tends to reinforce that these devices are a net performance benefit, but, again, finding proof of that can be challenging. The National Research Council of Canada Test Report from 2012 titled Review of Aerodynamic Drag Reduction Devices for Heavy Trucks and Buses, NRC report CSTT-HVC-TR-205, concluded "modest aerodynamic improvements may be achieved with the use of wheel covers and slotted mudflaps."

However, wheel cover devices are generally described in advertising and media as offering 1% or better fuel economy savings. These values may be true in a specific controlled test condition and methodology, and the real world improvement may be less.

A 2012 SAE Paper, EPA SmartWay Verification of Trailer Undercarriage Advanced Aerodynamic Drag Reduction Technology, SAE 2012-01-2043, documents well the evaluation of a Solus Wheel Cavity Cover, shown in Figure 45. The device attained a SmartWay rating of 1% or better in concert with various short trailer skirts. The manufacturers then found that drivers and inspectors to be able to view and access the wheels, and improved their device by providing an access hole.

Figure 45 Solus Wheel Cavity Cover

Driver, shop and inspector access to wheel hubs requires that wheel covers be easily removable but must be robust enough to survive on-highway environments. The FlowBelow company also produces an aerodynamic wheel cover; instead of an access hole their model can be easily removed by pushing the center release button as shown in Figure 46.

Figure 46 FlowBelow Wheel Cover Access

One challenge, however, with making wheel covers devices easily removable is that it also can facilitate theft or malicious activity when the vehicle is parked. RealWheels has introduced a locking key option on some of their models. Some of their wheel cover products also involve a closed wheel cover version with clear panels to be able to view inside the wheel space as seen in Figure 47.

Figure 47 RealWheels with Viewing Panes

Wheel covers are made from a variety of materials, including aluminum, polycarbonate and even cloth. An innovative lightweight fabric wheel cover in use by a number of fleets including Schneider is produced by Deflektor (Figure 48).

Figure 48 Deflektor Cloth Wheel Cover

The cost, weight and installation time of wheel covers is small compared to other investments aerodynamics. One set of four covers for a trailer, complete with mounting bracketry may add 20 to 50 pounds to the trailer. Long-term durability and maintenance of wheel covers, as with all heavy truck equipment, is still a factor to consider. Devices offered as listed options from trailer and tractor manufacturers may have undergone additional durability testing beyond supplier's testing and field data. The robustness of any system is fair game to discuss with the supplier, and NACFE recommends asking vendors to provide mean time-to-failure or similar information to help assess durability and predict total cost of ownership.

5.8. Vented Mud Flaps

A variety of mud flap alternatives have been on the market for some years offering improved aerodynamic performance and fuel economy savings. Like wheel covers, these may be OEM factory or aftermarket dealer or fleet installations. As with the wheel covers, it can be challenging to prove significant savings with current testing methods. Again, the general consensus is that these devices should be beneficial but the savings are hard to statistically prove in individual controlled tests, and harder still to prove in fleet evaluations that will include many other factors which will prevent isolation of the benefits to just the mud flaps. The NRC comment again applies: "modest aerodynamic improvements may be achieved."

One critical aspect of mud flap aerodynamics is specifying the correct width of mud flap for the wheels. Differences exist between wide-base singles and duals, meaning one-size mud flap does not fit all vehicles. A mud flap that is too exposed to the air flow, as shown in Figure 56, will create significant drag and downstream issues.

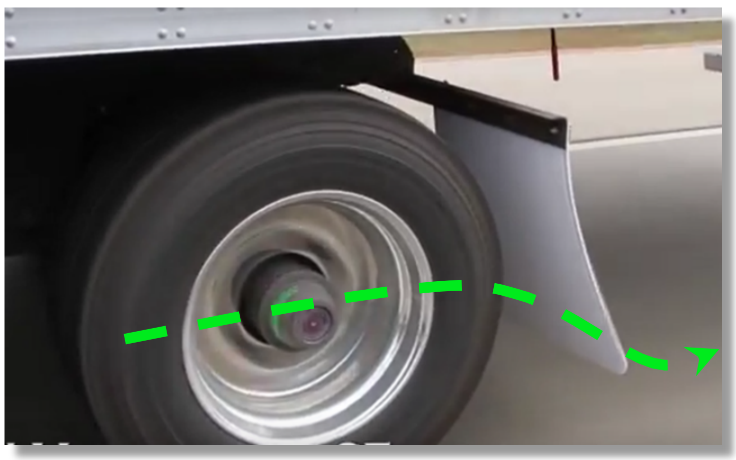


Figure 49: Exposed Wide Mud Flap (Badger)

The aerodynamic effectiveness of mud flaps can be seen during wet weather. Figure 50 shows significant splash and spray from a trailer equipped with standard solid mud flaps in wet weather, compared to the much smaller spray from one equipped with vented mud flaps.

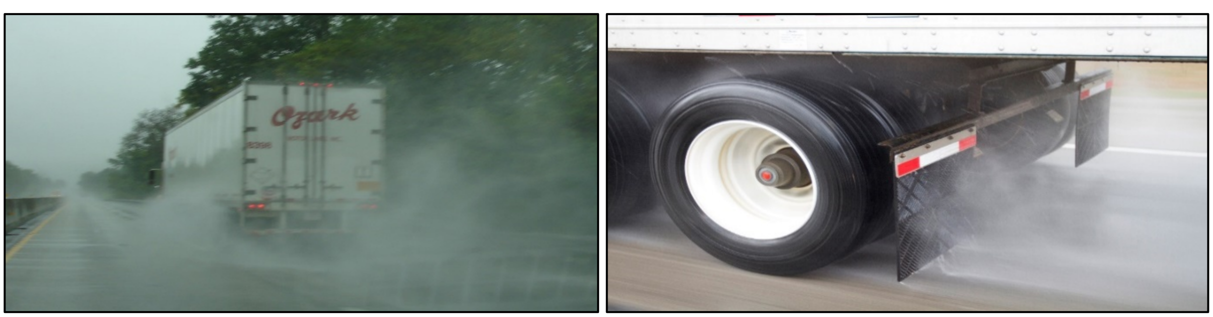


Figure 50 Mudflap Aerodynamic Effectiveness Can Be Seen in Wet Weather (photos courtesy of Cindy Kerr and Amy Hancock)

Aerodynamic mud flap concepts range from simply venting the flap as shown in Figure 51 to actually introducing louvers and progressively more sophisticated aerodynamic surfaces, for example Vortex

Splash Guards' Mud Flap with actual louvered surfaces in Figure 52. Others include AeroFlap by Fleet Engineers and VFLAP by Mudguard.

Figure 51 Simple Vented Flap

Figure 52 Louvered (vented) Mudflap (Vortex Splash Guards)

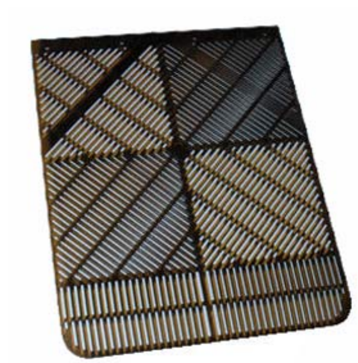


Figure 53 AeroFlap by Fleet Engineers

Figure 54 VFLAP by Mudgaurd

5.9. Part Removal or Relocation

Any part located on the outside of a tractor trailer combination vehicle increases drag lower fuel efficiency. Many fleets reported removing or relocating items such as external air cleaners, cab mounted exhaust, work lights, redundant mirrors, grab handles, etc.

5.9.1. Exhaust

Exhaust location has evolved significantly in modern aerodynamic tractors, and today's optimal designs use horizontal exhausts (Figure 55). The benefit of a horizontal chassis exhaust is to reduce the aerodynamic drag from exhaust piping while also reducing overall weight, but in some configurations, it may force longer wheelbases which can worsen aerodynamic drag by increasing the tractor/trailer gap and adding chassis rail weight. On the other hand, back-of-sleeper exhaust routing requires a portion of the exhaust piping to protrude into the airstream, and this usually increases drag slightly versus a corresponding tractor with horizontal exhaust. OEMs will have considered this in designing their model tractors; fleets who are considering altering the exhaust position from that of the model should likewise assess the impact on vehicle aerodynamics that will result from this alteration.

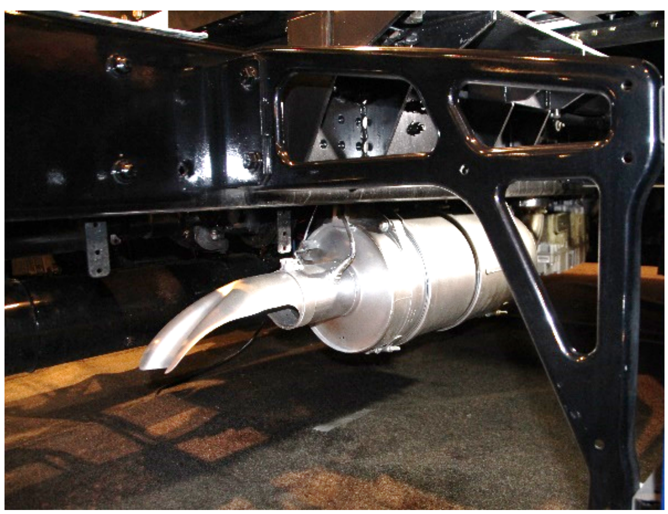


Figure 55 Horizontal Exhaust (Schaller)

5.9.2. Other Parts

Actual tractors in operation will diverge from the OEM's aerodynamically optimized models due to a fleet's decision to add or alter externally mounted options like various hood mounted mirrors, grab handles, lighting systems, license plate locations or bumpers. Figure 56 shows examples of some optional equipment. The OEM, again, should be able to advise what configurations are optimal for aerodynamics, allowing qualitative comparison with a fleet's actual configuration.

Figure 56 Options May Alter Aerodynamic Drag versus OEM Optimized Configuration

Likewise, customers can and do alter their vehicles in the aftermarket and at the dealerships. Examples of such aftermarket changes are hood-top bug shields, cooling module bug screens, and winterfronts, mudflaps, bogie fenders, deck plates, hood mirrors, lights, APUs, roof fairings, and more. The variety of these aftermarket devices means that their effect on each vehicle is likely not well understood and not all the permutations will have been evaluated as complete systems, adding risk that they significantly impact aerodynamic performance.

5.10. Other Optional Equipment

Some other aftermarket devices are marketed specifically as aerodynamic improvement devices, such as the wheel covers or mud flaps discussed previously. Other examples are the VorBlade and Air Tabs shown in Figure 57, as well as new system entering the market, a deployable gap filler by XStreamTrucking, shown in Figure 58. The VorBlade, Air Tab and XStream all address the air flow over the trailer gap. For tractor/trailers with short gaps and wheelbases, the aerodynamics of the gap have likely been well addressed by the OEM's extender and roof fairing designs. For longer gaps though, these devices may be beneficial, but the effectiveness of these devices when tractor-mounted has not been definitively proven in operational tests. Manufacturer data supports that they may improve overall fuel economy, but neither device is currently offered by OEMs as a factory installed device, and independent testing and operational use has seen variable results. The marketplace will ultimately determine the potential of these systems.

Figure 57 VorBlade and Air Tab Aftermarket Aero Devices

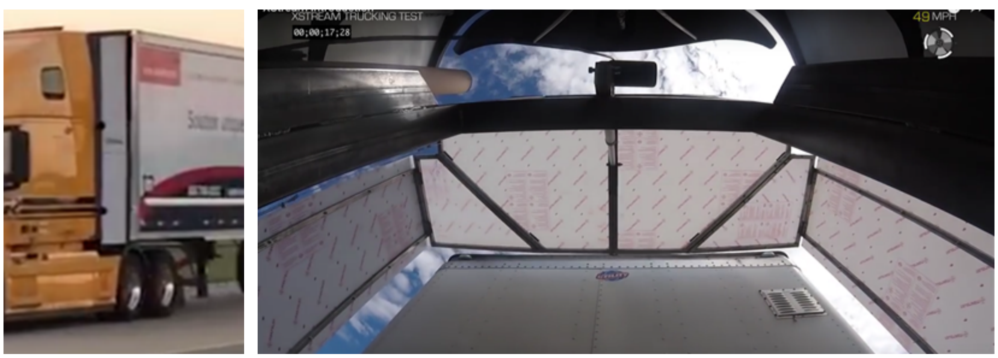


Figure 58 Deployable Gap Filler (XStreamTrucking)

5.11. Electronic Systems Related to Improving Tractor Aerodynamics

Aerodynamic vehicle performance is directly tied to vehicle speeds, freight density, and equipment utilization. Several electronic technologies are available today that can improve average vehicle speeds, minimize the time that tractors are not moving, reduce the use of brakes, avoid traffic delays, improve driver utilization, and make routes more efficient, all of which can result in better overall aerodynamic performance and improved fuel efficiency.

For individual trucks, route management software can prioritize higher speed lanes, predictive cruise control systems can adjust vehicle speeds based on terrain and known route characteristics, electronic vision and collision avoidance systems can assist in maintaining higher vehicle speeds by avoiding energy losses from braking situations, and speed limiters can control speeds to improve fuel economy by reducing excessive fuel used in accelerations and decelerations. Moreover, adaptive cruise control systems can adjust speeds to traffic improving better multi-vehicle aerodynamics such as platooning. Finally, hours of service logging combined with other vehicle data can highlight opportunities to improve vehicle on-road time. These technologies are available both as OEM factory and as aftermarket installations, and include both in cab and back-office opportunities.

In their SEC Form 10-K, Marten Transport discusses on-board and back-office systems that improve aerodynamic efficiency by improving a vehicle's on-highway time, increasing vehicle average speeds, improving freight density which increases freight efficiency per trip, and reducing deadheading. They state: "we employ technology in our operations when we believe that it will allow us to operate more efficiently and the investment is cost-justified. Examples of the technologies we employ include:

- Terrestrial- and satellite-based tracking and messaging that allows us to communicate with our drivers, obtain load position updates, provide our customers with freight visibility, and download operating information such as fuel mileage and idling time for the tractor engines and temperature setting and run time for the temperature-control units on our trailers.
- Freight optimization software that assists us in selecting loads that match our overall criteria, including profitability, repositioning, identifying capacity for expedited loads, driver availability and home time, and other factors.
- Electronic logging devices in our tractors to monitor drivers' hours of service.
- Fuel-routing software that optimizes the fuel stops for each trip to take advantage of volume discounts available in our fuel network."

5.12. Alternative Fuel Vehicle Aerodynamics

Given that a Class 8 tractor is an integration of roughly 13,000 parts, if one significant area undergoes rapid and significant change, other areas may lag behind and take a while to catch up. Natural gas powertrains and aerodynamics are a perfect example of this challenge. When diesel prices rose and natural gas infrastructure became more widely available, the industry saw an increase in fleet's converting to natural gas-powered tractors. Natural gas vehicles have an additional the integration challenge for aerodynamic features, in that the location of and where how to mount the storage tanks for either the compressed natural gas (CNG) or liquefied natural gas (LNG) must be taken into account.

Both CNG and LNG installations can be done with frame rail mounted tanks below the cab. Unfortunately, this virtually always interferes with the use of aerodynamic chassis skirts that were designed to go over and around diesel fuel tanks. For CNG it is also quite common to add tanks behind the back of the cab in a tall vertical stack or cabinet. This new storage system was not compatible with existing tractor aerodynamic options, so in many cases the first few model years saw tractors with the flat surfaces of these tank packages directly hitting the oncoming air in the least aerodynamic configuration possible. This added significantly to the aerodynamic drag of the tractor, negatively affecting fuel economy.

This situation was illuminated in the 2015 NACFE Annual Fleet Fuel Study, available for download at www.nacfe.org/projects. In 2011, Frito Lay decided to pursue Compressed Natural Gas (CNG) powered trucks, beginning procurement in 2012 and ramping to about 80% of their purchases by 2013. But they found that, for a number of reasons, these CNG-trucks were not available with cab extenders and chassis skirts. In spite of Frito Lay's requests, the tractor OEMs remained focused on improving the aerodynamics of sleeper tractors, and struggled to justify the product development of these aerodynamic devices on the smaller purchase volume of CNG day cabs.

The great news is that through collaboration between the tractor builders and the aerodynamics and fuel tank manufacturers, along with Frito Lay's assistance, the fleet's 2015 purchase of CNG tractors included the aerodynamics desired. This is important as the fleet-wide fuel efficiency of the Frito Lay fleet had dropped a bit in the last few years due to this issue (Figure 58). "We have been aggressively pursuing fuel savings and freight efficiency for many years", says Steve Hanson, Frito Lay Director of Fleet Engineering. "Through collaboration with tractor builders and aerodynamic device and fuel system suppliers, we are now able to get the aerodynamics we desire on our CNG powered tractors. This will help us continue to increase our overall fleet-wide fuel efficiency."

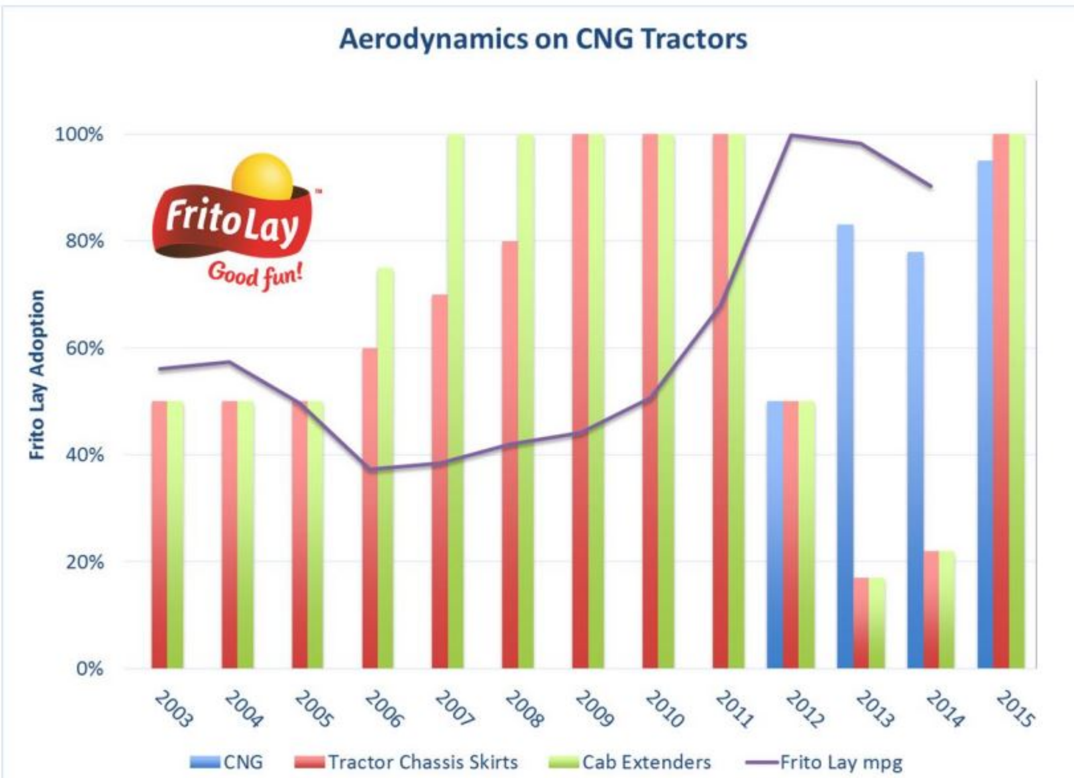


Figure 59: CNG Tractor Aerodynamics Adoption at Frito lay

The total aerodynamic optimization of natural gas powered tractors is not yet complete. Cab roof fairings and cab side extenders are now available on many of the models. However, not all of the cab extenders are serving the same function as they do on a diesel powered tractor, where they serve to bridge the aerodynamic gap between the tractor and the trailer; instead there are many truck models where the current cab extender design for CNG serves only to get the air cleanly around the CNG storage behind the cab. In the pictures below, a progression of improvements can be seen with the final tractor on the upper right having a full aerodynamics package. However, the tractor still does not have extenders that sufficiently close the tractor to trailer gap.

FIGURE 60: CNG Tractor Aero Evolution

In a similar fashion, there are now CNG & LNG tank packages for under-cab chassis mounting that are shaped to roughly serve the same aerodynamic function as chassis skirts (Figure 61). The industry has made tremendous progress, but there are still some steps required for natural gas vehicles to see equal levels of aerodynamic optimization as those of diesel powered models. Other alternative fuel vehicles will likely see a similar progression.

Figure 61: Recent Tank Developments

6. Secondary Market Considerations & Tractor Aerodynamics

The first owner of a truck will spec the vehicle for their specific needs. Buyers of used vehicles must select from among those already-configured units, making it more difficult for them to be selective of option content and to customize that content to their duty cycles and planned operations. Though the majority of used tractors go on to continue pulling van trailers, it is not uncommon, for a used SmartWay high roof sleeper in its second or third life to be pulling gravel trailers, flatbed units, or drayage containers. However, EPA GHG rules discourage modification of the original vehicle configurations during the defined life of the vehicle.

Another aspect of regulation which may impact overall fleet aerodynamics is found in the rules governing trailer length and combination vehicles. NADA used tractor sales data in September 2014 indicated that, on average, used sleepers had 503,844 miles and were 74 months old. The October 2015 data showed an average age of 73.4 months, and that average miles had decreased by 4.3% (Figure 62). The NADA data indicates that the significant drop in fuel prices in 2015 did not result in any significant increases in per vehicle mileage, in fact it likely decreased. The combination of driver hours of service rules and the reported driver shortage may have contained per vehicle mileage, i.e. existing drivers and vehicles are not able to add capacity under current regulatory conditions.

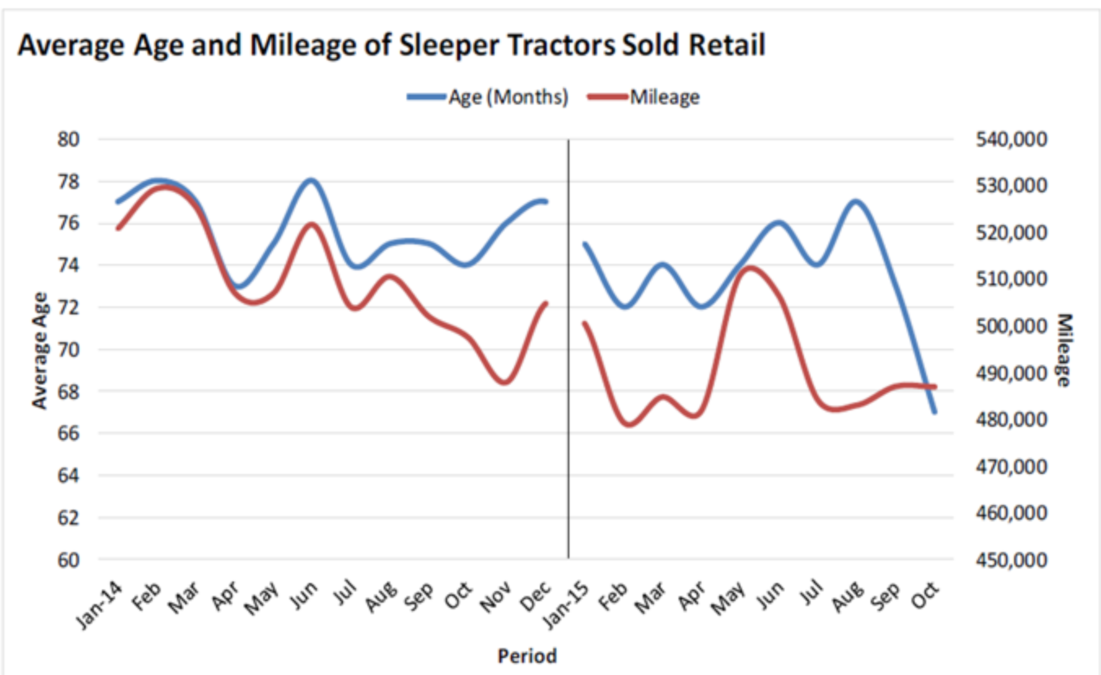


Figure 62 NADA Average Age and Mileage of Sleeper Tractors Sold

Adding capacity per driver and per vehicle may therefore require considering rule changes such as longer trailers and long combination vehicles (LCV), which, in turn, though perhaps inadvertently, could improve the overall aerodynamics and resulting fuel efficiency of freight transport. The DOT Map-21 Size and Weight study that completed in 2015, as well as the 2016 Federal Budget agreement, have put any national changes to size and weight rules on the back burner for the near term, but this may change.

The ATA stated in a position statement on LCVs that “Federal one-size-fits-all regulation prevents trucking companies from using their safest, cleanest, most pavement-friendly vehicles where such use would be appropriate. ATA believes that states, not the federal government, are in a better position to determine whether these more productive vehicles should be allowed to operate on their highway systems. Congress should reform federal law to give states greater flexibility.”

7. Perspectives for Future Systems

One thing that became very clear to the study team in the course of compiling this Confidence Report is that aerodynamic technologies and strategies are constantly and rapidly evolving, and that tractor OEMs are continuously improving the aerodynamics of their models. This report has focused on the options which are currently available today; the following section explores nine likely future developments in technologies for improving freight efficiency via aerodynamics. The ability for the tractor/trailer to be more self-aware is fundamental to these and other future improvements.

1) Active Flow Control Systems

Tractor aerodynamics is currently determined by static fairing surfaces, namely, passive, robust devices that alter the tractor shape to reduce drag. The next phase of aerodynamic refinement will include active systems which can adapt and respond to conditions to better optimize performance. For example, extenders may reposition themselves automatically, based on the local crosswind conditions, vehicle speeds and/or traffic. More sophisticated solutions might inject or remove air to manipulate flow for better performance.

2) On-Board Aerodynamic Sensing

Obtaining accurate current conditions for a vehicle has thus far been limited to measurements of simple factors like ambient temperature. Advances in on-board vehicle anemometry (actual relative wind speeds and angles), fuel use, and load-sensing technologies will open up new opportunities to optimize vehicle operations based on real-time aerodynamic factors. Current work on precise fuel flow meters and laser based anemometry for limited track testing will evolve into marketable options for use in daily operations.

3) Aero Adaptive Cruise Control and Routing Systems

Cruise controls are becoming more sophisticated, with the ability to maintain set distances from other vehicles using a variety of sensing technologies and real-time data. These systems will eventually mature to include aerodynamic factors, in order to optimize fuel efficiency. Enabling this maturation will be innovations in on-board vehicle aerodynamic instrumentation, as well as cloud-based real-time local environment and traffic data that is combined with route planning and terrain mapping. For example, a hauler may choose an alternate route and set speed from Dallas to Chicago based on a better fuel economy projected from cross wind conditions, vehicle aerodynamics, terrain, traffic and desired time of travel, rather than just the information available that day about traffic or roadwork.

4) Automation Systems

Vehicle automation is a growing automotive technology set that will migrate into trucking. Tractor OEMs have already displayed working prototypes that minimize or eliminate human driver control, or that allow for one driver to control multiple vehicles (platooning). These prototypes all include efforts to optimize for fuel efficiency, but they generally do not yet address including specific aerodynamic factors. Simplistic platooning concepts improve aerodynamics by maintaining two vehicles at a prescribed separation distance, but as yet, do not optimize that distance based on aerodynamic inputs. Predictive cruise control systems adapt vehicle speeds to terrain to optimize fuel economy, but struggle with adapting to surrounding traffic and do not yet adapt to ambient weather conditions. Future innovations will incorporate these real-world situations and prioritize vehicle operation, possibly similar to how some cars can have multiple suspension settings or performance settings depending on driver selection.

5) Geometry Morphing

Currently, the tractor and trailer are one shape at all times. In the future, technologies may allow for the geometry of the vehicle itself to morph in certain ways to improve aerodynamics in certain conditions. For example, kneel-down suspension systems have an ability to alter the critical cross sectional area seen by the wind to reduce drag. Other technologies can morph the shape of the tractor or trailer roof or side to achieve performance gains. An example would be a system that lowers the rear of the trailer roof when at speed, taking advantage of trailer space not typically filled with freight, but still ensure the trailer is accessible to allow forklift access when docked.

6) Trailer/Tractor Ratio Reduction

Advancements in routing and load management software systems could decrease the number of trailers required for sustainable operations, which would improve net freight efficiency per active trailer, as each would be on-road a greater percentage of time. A company with a 4:1 trailer to tractor ratio means each trailer only sees ¼ of the annual mileage, hence only ¼ of the possible aerodynamic efficiency gain from any investment in new technologies. But the core issues of the tractor/trailer ratio are more complex than just supply and demand for freight hauling. Trailers are also used as temporary warehousing in many operations creating WIP inventory and artificial factory floor space that may not be tracked as such. Businesses need to evaluate their entire supply chain systems to spot opportunities to improve freight efficiency. Innovations in business data mining and analysis tools can open the door to additional fuel savings from aerodynamics, particularly on trailers.

7) Dedicated Truck Highways and Lanes

The interaction of automobiles and trucks causes high usage of braking systems and constant accelerations/decelerations, which reduce fuel efficiency. Several efforts are studying the use of dedicated truck highways or lanes, which would improve aerodynamics by establishing more uniform operations and reducing acceleration/deceleration events.

8) Hybrid Electric Vehicles

Conventional cab-behind-engine-tractors designs conform to practical needs that put the cooling modules, fans, engine and transmission in one line. This likewise dictates the position of the driver and cab. Electric motors could greatly change this paradigm, allowing for a significant reshaping of the tractor and opening up opportunities for revised trailer designs. An example of what may be possible can be found in the Peterbilt/Walmart concept and the Volvo concept shown in Figure 63.

Figure 63 Electrics Offer Shape Change Possibilities (Peterbilt/Walmart/Volvo)

9) Combining Technologies

Given advances in vehicle automation, it is possible that the future may see the driver operating a drone terminal, similar to the driving simulators currently in-use and shown in Figure 64. This would allow the tractor and trailer to be completely redesigned. An example of such a tractor can be found in current port container carriers that operate robotically or remotely, as shown with the Toyota AGV unit in Figure 65.

Figure 64 Driving Simulator Could Be Drone Controller (TranSim)

Figure 65 Container Handler (Toyota)

Concepts that combine automation technology, hybrid electric technology, aerodynamic feedback systems, and dedicated highway lanes could make possible significant trailer redesign as the Renault example shows in Figure 66. Taking redesign even further, road trains are possible with independent units connecting and disconnecting in transit, as envisioned by Volvo's slipstream concept in Figure 67.

Figure 66 Possible 66 Foot Aero Trailer with Drone? (Renault)

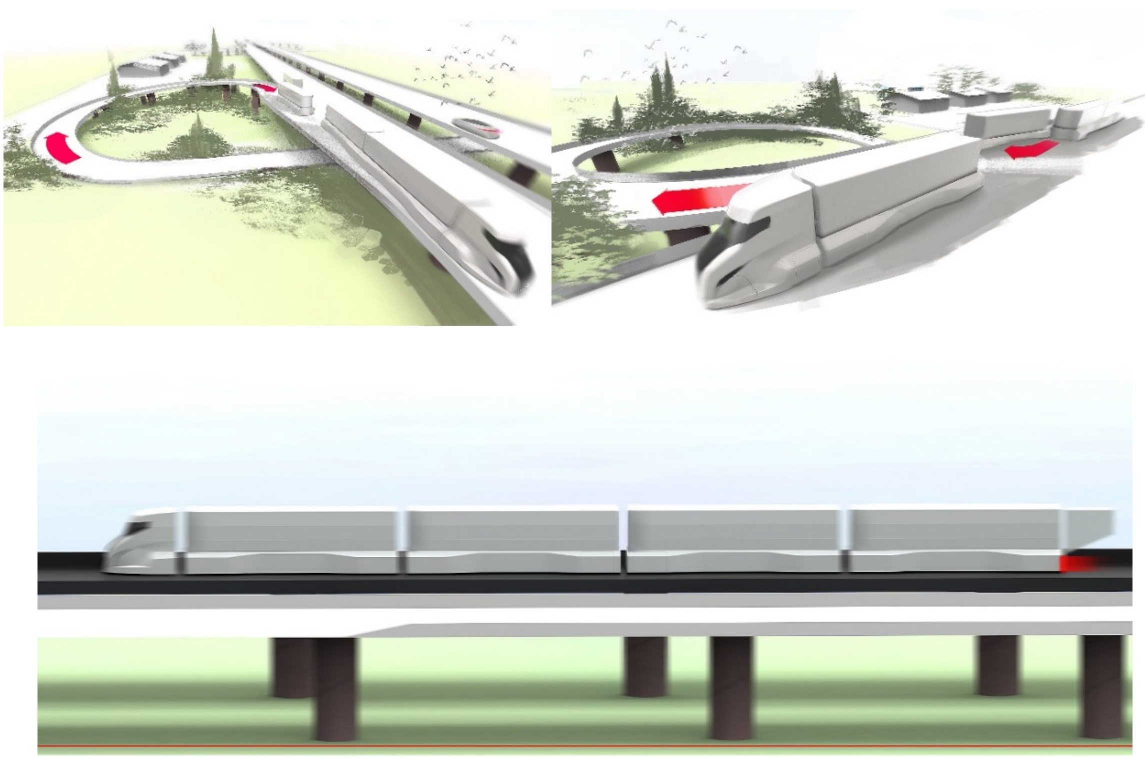


Figure 67 Volvo Slipstream Road Train

7.1. Near-term: Platooning, Long Combination Vehicles, and Longer Trailers

A report on how to improve truck fuel efficiency via aerodynamics would be incomplete without a discussion of alternatives to the ubiquitous 53’ dry van trailer. Technology is rapidly improving the ability of vehicles to analyze and adapt to surrounding traffic conditions. Devices like adaptive cruise control, collision avoidance systems, automatic braking systems, GPS-based predictive cruise control, automatic routing, and platooning and proposed autonomous vehicle technologies all can improve safe vehicle operations while offering other benefits to a fleet’s bottom line.

But due to concerns around truck length and weight as it relates to highway wear-and-tear, as well as safety, the one area that government, industry, and public groups have made little progress on since the STAA Act in 1982 is making any significant increase in the amount of freight carried per tractor. Where the other freight hauling industries including ships, airplanes, and trains, have all dramatically increased freight per crew and freight per motive unit, U.S. trucking has made no significant progress.

Improvements in the ratio of tractors to freight hauled, which in turn will require allowing greater usage of longer combination vehicles. While the addition of a second 53’ trailer to a vehicle increases its drag versus a single trailer unit, the net freight efficiency is dramatically improved by doubling the freight carried and halving the number of required tractors and tractor mileage. A recent SAE paper, 2015-01-2897, Aerodynamic Comparison of Tractor-Trailer Platooning and A-Train Configuration, highlights that for a wide range of key comparison factors, the double has significant advantages over two singles as outlined in Figure 68, including for safety.

Possible Comparison Factors

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

		
Net Capital	More	Less
Net Operating Costs	More	Less

Figure 68 Comparison Factors (Mihelic)

John Woodrooffe of the University of Michigan Transportation Research Institute and others have presented data showing that accident rates are based on number of driven miles and number of vehicles. Both these factors are halved by use of a double trailer versus two singles, with corresponding decreases in accident rates. Operations running LCVs in Canada, Oregon, and Idaho have documented that accident rates for individual LCVs are not significantly different than those of singles, so reducing the total number of miles driven by half and the number of vehicles being driven by half has a direct reduction on accident rates. These same reports have shown no significant difference in infrastructure maintenance costs, while documenting significant reductions in cost of operations, fuel used, and corresponding reductions in emissions.

The discussions on LCVs has proponents and detractors, but there is little argument that significant fuel economy gains and freight efficiency gains are possible with LCVs. Rather than discussing, for example, the benefits of saving 200 pounds by switching from steel to aluminum on a part, or of gaining 5% on fuel economy by adding aerodynamics to a trailer, the discussion in the future could be around the benefits of adding 30,000 pounds of freight to the same tractor.

8. Study Conclusions

The study team through its research as described above has the following conclusions pertaining to Class 8 tractor aerodynamics for van trailers.

- Tractor manufacturers have developed and offer as standard, sleeper aerodynamic packages. Fleets should use them for over the road operation and only divert with there are justifiable reasons.
- Fleets operating day cab tractors should consider higher adoption of aerodynamics, as their duty cycles offer value for them.
- Tractor and trailer heights should be matched for as many miles driven as possible as the fuel economy reduction is in excess of 10%
- Tractor manufacturers should design and make available aerodynamic features for day cab tractors, including those on natural gas tractors.
- Future EPA and NHTSA Greenhouse Gas regulations will continue to challenge tractor builders to continue to improve the aerodynamic drag of these vehicles.

9. Confidence Rating

For each of the Confidence Reports completed by Trucking Efficiency, the various technologies assessed therein are plotted on a matrix in terms of the expected payback in years compared to the confidence that the study team has in the available data on that technology – that is, not only how quickly fleets should enjoy payback on their investment but how certain Trucking Efficiency is in the assessment of that payback time. Technologies in the top right of the matrix have a short payback, usually thanks to their low upfront cost, and moreover are found to have high confidence in those short payback times, usually because the technology is more mature or otherwise has a more substantial track record of results.

CONFIDENCE MATRIX FOR TRACTOR AERODYNAMICS

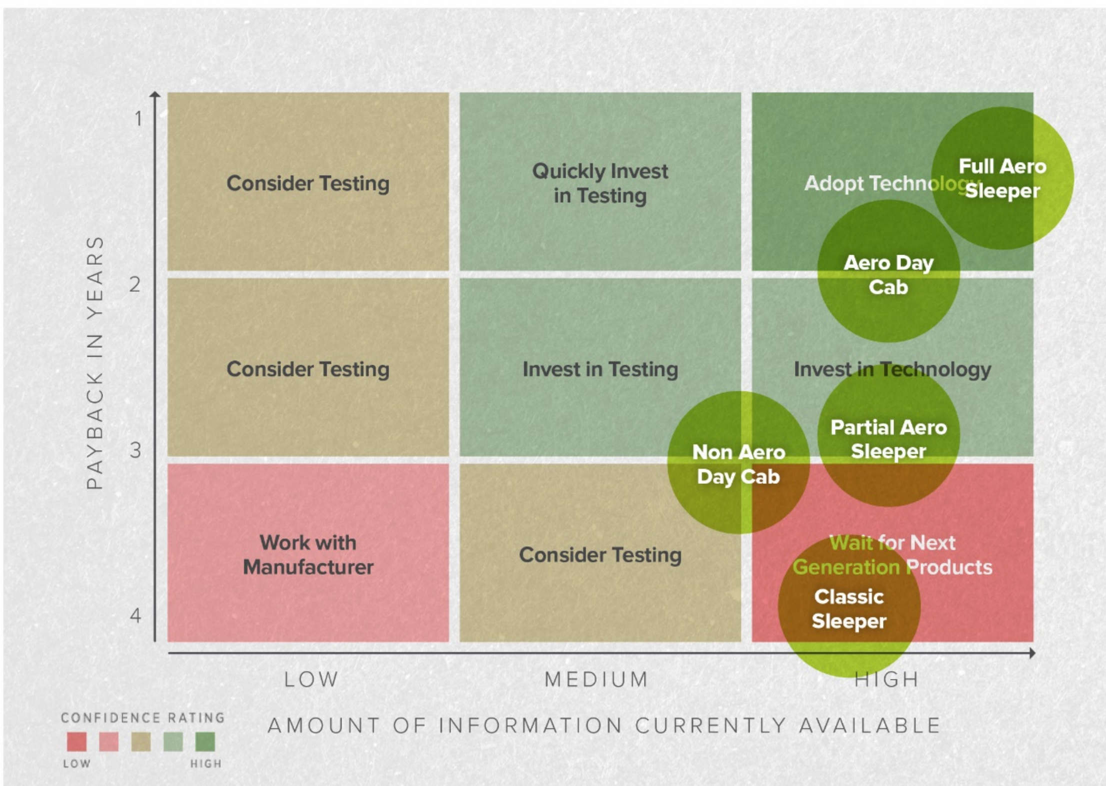


Figure 69 Confidence Matrix of Aerodynamic Tractors for On-Highway Van Trailer

Appendix A – References

First Occurrence	Reference	Source
Figure 1 U.S. Diesel Fuel Prices	Mihelic, R., "Heavy Truck Aerodynamics Beyond 2025," presentation at SAE 2015 COMVEC Session 15CVA2000 Aero Keynote, Oct. 2015, raw data from DOE.	Contact Author for copy
Figure 2: Trucking Operational Costs per Mile	Roeth, M., North American Council for Freight Efficiency (NACFE) graph from data from American Transportation Research Institute (ATRI), "An Analysis of the Operational Costs of Trucking: 2015 Update," Sep. 2015,	http://atri-online.org/wp-content/uploads/2015/09/ATRI-Operational-Costs-of-Trucking-2015-FINAL-09-2015.pdf
Figure 3: NACFE Fleet Fuel Study Fleets	Roeth, M., North American Council for Freight Efficiency (NACFE), "2015 Annual Fleet Fuel Study," May, 2016,	http://nacfe.org/wp-content/uploads/2015/05/NACFE-2015-Annual-Fleet-Fuel-Study-Report-050115.pdf
Figure 4: Fuel Savings per Truck	Roeth, M., North American Council for Freight Efficiency (NACFE), "2015 Annual Fleet Fuel Study," May, 2016,	http://nacfe.org/wp-content/uploads/2015/05/NACFE-2015-Annual-Fleet-Fuel-Study-Report-050115.pdf
Figure 15 Aerodynamic Technology Adoption by Category (NACFE)	Roeth, M., North American Council for Freight Efficiency (NACFE), "2015 Annual Fleet Fuel Study," May, 2016,	http://nacfe.org/wp-content/uploads/2015/05/NACFE-2015-Annual-Fleet-Fuel-Study-Report-050115.pdf
Figure 16 Day Cabs (left) and High Roof Sleepers (right)	Western Star and Kenworth	http://www.westernstartrucks.com/_Assets/Trucks/TL-LTL/5700/Media/5700YellowDayCabFrontQuartRight_1200.jpg http://mms.businesswire.com/bwapps/mediaserver/ViewMedia?mgid=316486&vid=4&download=1
Figure 17 Different Duty Cycles Result in Different Tractor Design	Caterpillar and Freightliner	http://www.trucknews.com/wp-content/uploads/2015/05/CT680-with-trailer.jpg https://www.freightlinertrucks.com/Content/media/trucks/models/cascadia/cascadia-performance.jpg
Figure 8 Elements of a Modern Aerodynamic Tractor	Peterbilt	
Table 1 EPA Designated SmartWay Tractor Models	SmartWay Tractor Designations in February 2016	http://www3.epa.gov/smartway/forpartners/technology.htm
Page 13	Determining Efficiency Confidence Report - NACFE	http://www.truckingefficiency.org
Figure 10 Day Cabs & Sleepers Are Related	Freightliner	https://www.freightlinertrucks.com/Trucks/On-Highway-Trucks/Day-Cabs/
Figure12: Day Cab to Sleeper Production Mix	Obtained from ACT Research	http://www.actresearch.net/
Figure 13 Examples of Day Cab Drive	Dave Schaller	Contact Dave Schaller for information

Cycles		
Figure 14 Example No-Aero Device Day Cab	Rick Mihelic photograph	
Table 2 Proposed EPA/NHTSA Phase II Aerodynamic Bins (EPA)	EPA/NHTSA Greenhouse Gas Rule Phase 2 Proposed Rulemaking	https://www3.epa.gov/otaq/climate/regs-heavy-duty.htm
Sproul	Market penetrations by EPA GHGp2 aerodynamic bins.	2015 SAE Comvec presentation
Figure 18 Odd Size Loads and Non Aero Trailers May Cancel Any Aero Benefits of Tractor	Odd loads	https://s-media-cache-ak0.pinimg.com/236x/ec/ce/dd/ecceddd665b757c620e980aff01412bc.jpg
Knight	Knight Transportation 2016 10-k	https://biz.yahoo.com/e/160229/knx10-k.html
Werner	Knight Transportation 2016 10-k	https://biz.yahoo.com/e/160226/wern10-k.html
Proposed duty cycles defined for industry and government use	Draft EPA GHG Phase II Regulatory Impact Analysis (RIA) issued in 2015	http://www3.epa.gov/otaq/climate/documents/420d15900.pdf starting on page 3-58
Table 5 EPA GHG Phase II Composite Duty Cycles	Composite Duty Cycles from EPA GHGp2 proposed rulemaking	https://www3.epa.gov/otaq/climate/regs-heavy-duty.htm
Figure 19 Horsepower vs. Speed	Horsepower vs Speed	*DOE circa 1998*
Page 23	Idle Reduction Confidence Report - NACFE	http://www.truckingefficiency.org
Figure 18: Sleeper cab with chassis options	Chassis options	http://apextrans.com/wordpress/wp-content/uploads/2015/01/colorado-vans-curbside-trucking1.jpg
NRC	NRC Wind Tunnel Tests	From NRC/SmartWay Presentation 1/6/2016, Evaluation of the Latest Drag Reduction Technologies for Heavy-Duty Trucks and Trailers by Brian McAuliffe
Mack	Aerodynamic Packages and resale value	http://www.fleetequipmentmag.com/buying-for-resale/
Freightliner	Aerodynamic Packages and resale value	http://equipmentready.com/blog/wp-content/uploads/2012/11/2009FreightLinerCascadiaTandemAxleSleeperForSale.png

Figure 32: Sleeper Chassis Fairings	*Sleeper Chassis Fairings – Peterbilt 579 full length with skirt, Mack Pinnacle with sleeper length skirt, Volvo VNL780 full length with steps, Western Star Sleeper length with extension.*	Peterbilt http://www.truckertotrucker.com/listings/281944.cfm Mack http://www.macktrucks.com/~/media/images/hero%20images/mack_truckseries_pinnacle_hero_blacktruck.ashx?as=1&h=600&la=en&w=1400 Volvo http://www.imanpro0.com/pub/co/mktruck/photo/283093/1.jpg Western Star http://pictures.dealer.com/e/eastgatefordtruckcentretc/1678/1dfed76b0a0e0acc2e111af69971cd78.jpg
Figure 33: Skirt Aerodynamics	Optimizing Skirt Aerodynamics - Recurring Themes in Highly Optimized Prototypes	Peterbilt SuperTruck at http://www.peterbilt.com/about/media/2014/396/ Freightliner SuperTruck at http://www.overdriveonline.com/photos-freightliner-unveils-futuristic-supertruck-concept/ WAVE at https://www.youtube.com/watch?v=NER9X4_gtYk 372 copy posted at http://www.trucknetuk.com/phpBB/viewtopic.php?f=35&t=98062&hilit=ERGO&start=1140 Volvo SuperTrucks at http://energy.gov/sites/prod/files/2014/03/f13/ace060_amar_2013_o.pdf and http://www.arb.ca.gov/msprog/onroad/caphase2ghg/presentations/1_4_roland_g_usdoe.pdf Mercedes-Benz concept http://www.tuvie.com/mercedes-benz-aero-trailer-concept-drastically-reducing-wind-resistance-and-fuel-consumption-of-semitrailer-tractors/ and http://www.truckinginfo.com/blog/trailer-talk/print/story/2012/09/aero-trailer-could-save-3900-a-year-in-euro-fuel-daimler-engineer-says.aspx Renault Concept at http://www.commercialmotor.com/big-lorry-blog/-and-so-its
Figure 35: Drive Wheel Fairings	FlowBelow Drive Wheel Aero Kit and Wheel Covers	Picture provided by Flow Below March 2016
Figure 36 Roof Fairing Patent Image	Trailmobile	Image from United States Patent 4,245,862, "Drag reducer for land vehicles," Buckley, Jr. January 20, 1981 also see W. Selden SAUNDERS and Rudkin-Wiley Corporation patents 3,241,876 1966 and 3,309,131 1967
Figure 38: Daycab Aero	Tractor with Cab Extenders and Roof Fairing	http://blogsdir.cms.rrcdn.com/10/files/2013/03/ProStar-copy.jpg
Figure 41: Cab	Examples of Aerodynamic Cab Mirrors and Mounting Arms	Peterbilt

Mirrors		https://etrucking.com/forum/attachment.php?attachmentid=6448&d=1427380503 Mack http://www.transportelatino.net/wp-content/uploads/2012/01/mack12.jpg Volvo http://www.volvotrucks.com/SiteCollectionImages/VTNA_Tree/ILF/Products/VN%20Series/670/landing/gallery/892x438_vnl670_8.jpg Kenworth http://fleetnewsdaily.com/wp-content/uploads/2012/11/Screen-shot-2012-11-08-at-11.30.27-AM.png Prostar http://www.imanpro0.com/pub/co/sac/photo/3769/1.jpg
Figure 55 Horizontal Exhaust	Photo by Schaller, TMC 2016	
Figure 56: Aftermarket Options	*Options May Alter Aerodynamic Drag versus OEM Optimized Configuration*	http://cdn1.traderonline.com/v1/media/569fab238bbd11736565e9f6.jpg?width=300&height=225
Figure 62 NADA Average Age and Mileage of Sleeper Tractors Sold	NADA Data on Used Trucks	http://img03.en25.com/Web/NADAUCG/%7Bcaf2c731-01cb-4eaf-8283-dc2a64a8016c%7D_Guidelines_CTG_201512.pdf
ATA	American Trucking Association (ATA) length and weight	http://www.trucking.org/article.aspx?uid=656fc826-9472-4ae6-bd91-a7a15f632440