CONFIDENCE REPORT:

Trailer Aerodynamic Devices

ABSTRACT

This report documents the confidence that North American Class 8 trucking should have in pursuing Trailer Aerodynamic Devices for improved fuel efficiency. The study team engaged the entire industry in the data that is presented here. Thanks to all of those who contributed to this important work.

The North American Council for Freight Efficiency (NACFE) works to drive the development and adoption of efficiency enhancing, environmentally beneficial, and cost-effective technologies, services, and operational practices in the movement of goods across North America. NACFE provides independent, unbiased research, including Confidence Reports on available technologies and Guidance Reports on emerging ones, which highlight the benefits and consequences of each, and deliver decision-making tools for fleets, manufacturers, and others. NACFE partners with Rocky Mountain Institute (RMI) on a variety of projects including the Run on Less fuel efficiency demonstration series, electric trucks, emissions reductions, and low-carbon supply chains.

Acknowledgements

Original Study Team:
Rick Mihelic, NACFE Program Manager, Mihelic Vehicle Consulting LLC
Dave Schaller, NACFE Engagement Manager
Mike Roeth, NACFE Executive Director

Original Study Editor:
Tessa Lee, Carbon War Room

Update Team:
Frank A Bio, FABio Transportation Consultation
Mike Roeth, NACFE Executive Director
Rick Mihelic, NACFE Director, Emerging Technologies, Mihelic Vehicle Consulting LLC
Denise Rondini, NACFE Communications Director, Rondini Communications

Revision Date: August 12, 2020
Original Release Date: February 26, 2016

NACFE Technical Advisory Committee:

Tim Dzojko, Air Products	Jordan Spradling, Pilot Travel Centers
Steve Orbanski, Bison Transport	Steve Jarosinski, Schneider
Randy Cornell, CFI	Dennis Elford, UPS
Matt McLelland, Covenant Transport	Mike Roeth, NACFE
Dan Deppeler, Paper Transport	David Schaller, NACFE
Bruce Stockton, Miller Truck Lines	Yunsu Park, NACFE
Guy Welton, Werner	Rick Mihelic, NACFE
Ken Marko, PepsiCo	Frank A. Bio, NACFE

Table of Contents

Table of Figures

NACFE
NORTH AMERICAN COUNCIL FOR FREIGHT EFFICIENCY

TRAILER AERODYNAMICS CONFIDENCE REPORT

This report is an update of a previously published report on trailer aerodynamics in order to examine new technology that has emerged in the meantime. See NACFE's reports here.

The fuel costs faced by the tractor-trailer industry held steady from 2012 to 2014, with fuel costing more than drivers' wages and benefits. In 2019 diesel fuel costs were $0.433 per mile, compared with $0.65/mile in 2013. Fuel is now the second-highest operating cost, slightly more than half the yearly cost of drivers' wages and benefits but still a significant amount. 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.

Aerodynamic improvement of commercial tractors and trailers has significantly reduced fleet operating costs and harmful emissions by decreasing the amount of energy needed to move vehicles down the road. Whatever powers the vehicle—whether traditional diesel, natural gas, propane, hydrogen, electricity, or combinations of those as hybrid vehicles—the efficiency of converting energy into motion always depends heavily on aerodynamic design. A simple example of this is when a child puts a hand out the window of a moving car and feels how hard the wind pushes back when the palm is facing the wind, and then turns the hand edgewise into the wind, eliminating most of the force. Aerodynamic improvements impact efficiency at every speed, the extent of benefit increasing with speed. At highway speeds, modern tractors with aerodynamic trailers are capable of exceeding 10 MPG fully loaded compared with their non-aerodynamic predecessors that were lucky to get 6 MPG.

Aerodynamics is a numbers game as well. Improving from 6 MPG to 10 MPG for one diesel truck means 6,667 fewer gallons of fuel burned over a 100,000-mile year, a 40% reduction in costs and emissions. That translates to over 666,000 gallons not burned in a year for a fleet of 100 trucks. At $3.00/gal, that one fleet is saving $2 million. For an industry that has perhaps 1.7 million tractors pulling freight, that equates to a savings of $34 billion, as well as significant reductions in both carbon and particulate emissions from not burning the fuel in the first place. Aerodynamic improvement is a major part of that.

Fortunately, myriad technologies that can cost-effectively improve the fuel efficiency of Class 8 trucks are readily available on the market. Unfortunately, multiple barriers have stymied industry adoption of these 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 exist today publicly. 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) collaborated with Rocky Mountain Institute to deliver tools and reports to improve trucking efficiency. The work includes producing a series of Confidence Reports, of which this report on technologies to improve the aerodynamics of trailers is one. This is an updated version of the report that was originally published in February 2016.

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

FUEL SAVINGS AND OTHER BENEFITS OF TRAILER AERODYNAMICS

Trailer aerodynamic devices help increase fuel efficiency by lowering air resistance so that it takes less fuel to move the vehicle down the road as speed increases. The per-vehicle fuel economy benefit of trailer aerodynamic devices can be high, ranging from 1% to more than 10%, depending on the devices chosen. Given these potential savings, trailer aerodynamics can significantly increase fuel efficiency. However, there are quite a number of technologies within trailer aerodynamics, and it can be complicated to determine which technologies to adopt. Trailer aerodynamics also improve stability and rollover, splash and spray, and driver fatigue.

CHALLENGES OF TRAILER AERODYNAMICS

The challenges of integrating trailer aerodynamic technologies into a fleet's operation include:

- Added weight
- Complicated methods for testing device performance and difficulty in comparing them
- Confusion between precision and accuracy, and the impossibility of obtaining accuracy in aerodynamics testing

METHODOLOGY

NACFE's research for this report included interviewing key people with firsthand knowledge of aerodynamics and aerodynamic devices at fleets, manufacturers, and industry groups. The full report includes a list of references to assist readers interested in pursuing more detail. These references were researched with the same diligence and thoughtful processes NACFE uses with its other technology Confidence Reports and Guidance Reports.

- Variance among aerodynamic device manufacturer information
- The need to optimize tractor-trailer ratios
- Questions of device reliability and/or durability
- Other minor concerns

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 lbs. Even the most aggressive aerodynamic fairings for trailers add less than 2,000 lbs. today, so the maximum miles-per-gallon reduction due to the weight of aerodynamic fairings would be less than 1.2%. This is much less than the 10% MPG (or greater) gain offered by advanced trailer aerodynamic systems in on-highway hauls for typical van trailers.

The main challenge preventing adoption is the perceived complication of improving trailer aerodynamics. The physics involved in testing trailer aerodynamic device performance can be complex, and there are multiple ways of measuring and evaluating performance; these are described in the *Determining Efficiency Report*. Additionally, fleets will see the greatest benefit from adopting multiple aerodynamic devices. However, 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 on their paybacks.

TRAILER AERODYNAMIC TECHNOLOGIES

All fleets are concerned with freight efficiency, but to date

the focus of aerodynamic trailer technology development (and of rulemaking) has almost exclusively been on van trailers since they are the most common, travel the most miles, are "large boxes" with wheels, and are most easily adapted to aerodynamic improvement. Reducing the aerodynamic drag of a basic van trailer comes down to adding one or more devices onto three key areas of the trailer: the gap, the underbody, and the rear.
The Confidence Report details devices for improving the aerodynamics of these three key areas, as well as more novel options, such as vortex generators, wheel covers, and mud flaps.

"Data shows that trailer aerodynamic devices help fleets save fuel. The priority for device adoption is side skirts, rear devices, and then gap."

— Rob Ulsh, Vice President, Dealer and International Sales, Great Dane Trailers

For the underbody, trailer skirts are the most popular devices for addressing drag. All trailer underbody skirts serve to extend the trailer side walls much closer to the ground, preventing wind from ducking in under the trailer and running into the non-aerodynamic trailer bogie. Trailer skirts offer 1% to more than 5% more fuel savings than non-skirted trailers.

Devices to mount at the rear of trailers are generally called boat tails or trailer wake devices. They modify the air flow as it leaves the trailing edge of the side and top surfaces of the trailer. The goal in all trailer rear devices is to reduce the wake field following the trailer, which can affect air some distance from the back of the trailer. Trailer tails are the most common device in use to improve aerodynamics at the rear of the vehicle, but they have deploying and retracting challenges. Second-generation trailer tails are coming on the market, and they seem to be addressing some of the challenges of the first-generation devices.

Finally, tractor-to-trailer gap management devices are relevant for a subset of the industry, in large part due to the evolution of the current aerodynamics of many tractors. Highly aerodynamic tractors have largely reduced the importance of trailer aerodynamic gap devices. However, many older tractors and day cabs that require a higher tractor-to-trailer gap for maneuverability would still benefit from trailer devices that address drag in the gap. Even the newest models can benefit from active devices that completely close off the gap at highway speeds.

Feedback from trailer and component manufacturers gives evidence of a robust market for aerodynamic technologies for both new and used trailers. In addition, the cost of trailer aerodynamic technologies—particularly side skirts—has decreased significantly in recent years, due to far more market entrants driving cost competition and much higher deployment volumes reducing cost per unit and availability of devices directly from the trailer manufacturers.

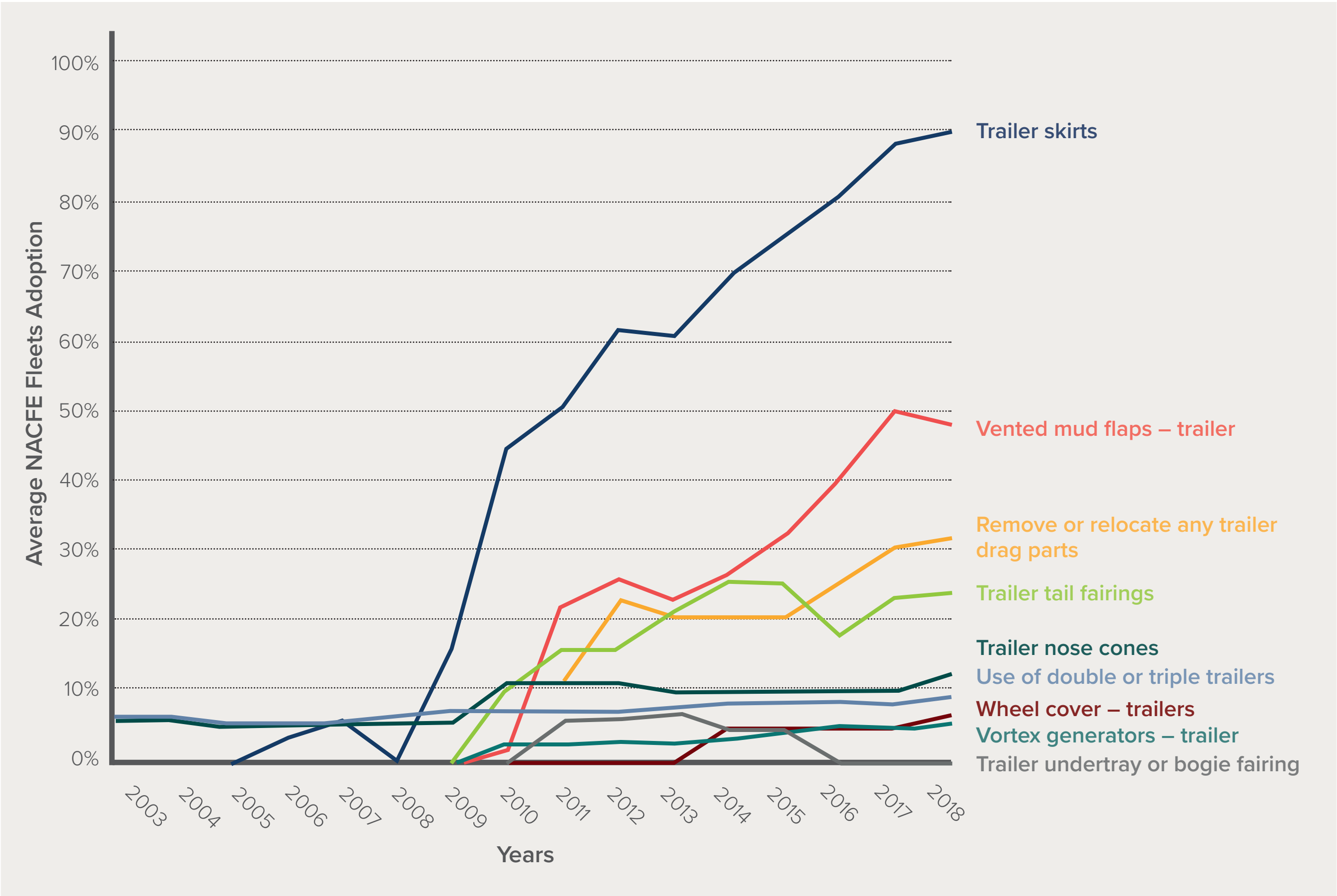
CURRENT INDUSTRY TRENDS

Tractor and trailer aerodynamic design concepts have been around for a very long time. A series of trends over the past 20 years has moved the industry from asking "why should my fleet use trailer aero devices" to "when and how will my fleet implement trailer aero devices?"

The most recent NACFE *Fleet Fuel Study* found that, since 2008 or 2009, fleets began ramping up their investment into trailer aerodynamics, most notably trailer skirts, as shown in Figure ES1.

FIGURE ES1

ADOPTION RATES FOR TRAILER AERODYNAMIC DEVICES



While the desire to save fuel in an era of volatile and often high fuel prices motivates the adoption of trailer aerodynamic devices, regulations also play a major role in this technology space. In the last half of the 1990s, regulatory focus dramatically increased on truck engine emissions standards, including the Environmental Protection Agency's (EPA) Clean Air Act emissions regulations and Phase I Greenhouse Gas (GHG) rules. These rules initially focused on engines and components but evolved into vehicle-level standards.

In parallel with ever-more demanding emissions rules came federally legislated reductions in the sulfur content of fuels, as well as the introduction of "no idle" rules in many geographies. Nearly all these requirements have resulted in increased tare weight or other changes that worsened fuel economy.

With respect to tractor aerodynamics, original equipment manufacturers (OEMs) have continually introduced new and improved models, helping the tractor side of the industry achieve net improvements in fuel economy. Yet both government and industry have recently realized that tractor efficiency improvements alone could only go so far toward saving fuel. The EPA GHG Phase II rules, which require trailer aerodynamics, have been released and are in effect. Other regulations, such as rules enacted in 2008 by the California EPA Air Resources Board, which mandated the use of SmartWay-certified tractors and trailers in California, are likewise driving investment

in trailer aerodynamics. Improving the aerodynamic performance of trailers is an excellent option for the industry looking to meet regulations and offset other fuel economy losses.

The EPA and National Highway Traffic Safety Administration's (NHTSA) GHG Phase II rules initially required the use of aerodynamic devices for new van and refrigerated trailers longer than 50' in 2021, with voluntary compliance that began in 2018. Final implementation of the trailer rules has been delayed pending legal and regulatory reviews. In coming years, regulation is likely to continue to drive adoption of trailer aerodynamic devices.

PERSPECTIVES FOR FUTURE SYSTEMS

Trailer aerodynamic technologies and strategies are constantly and rapidly evolving. The options detailed in this report are currently in use in the market today, and most are mature with a good track record of functionality, though they may be more or less economical depending on the specifics of a fleet's operations. 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
- On-Board Aerodynamic Sensing
- Aero Adaptive Cruise Control and Routing Systems
- Automation Systems
- Trailer Geometry Morphing
- Trailer-Tractor Ratio Reduction
- Dedicated Truck Highways and Lanes
- Hybrid Electric Vehicles
- Combining Technologies

"Manufacturers of trailer aero devices are working hard to make them lighter, less expensive, and more durable. In the case of rear devices, current iterations have eliminated many of the maintenance costs, challenges, and driver interaction of the first generation."

— Brent Nussbaum, CEO, Nussbaum Transportation

RECOMMENDATIONS

The study team has the following recommendations for those engaged in adopting or providing aerodynamic devices:

- Both aerodynamic device suppliers and fleet end-users need to have better communication on performance.
- Manufacturers and trailer integrators should increase development efforts to improve the total cost of ownership/payback of the devices.
- Research into advanced aerodynamic technologies should continue.
- Organizations like the Society of Automotive Engineers, Technology & Maintenance Council, EPA, and CARB need to push for improved aerodynamic assessment and correlation to real-world numbers.

The table below suggests aerodynamic actions fleets should consider prioritizing.

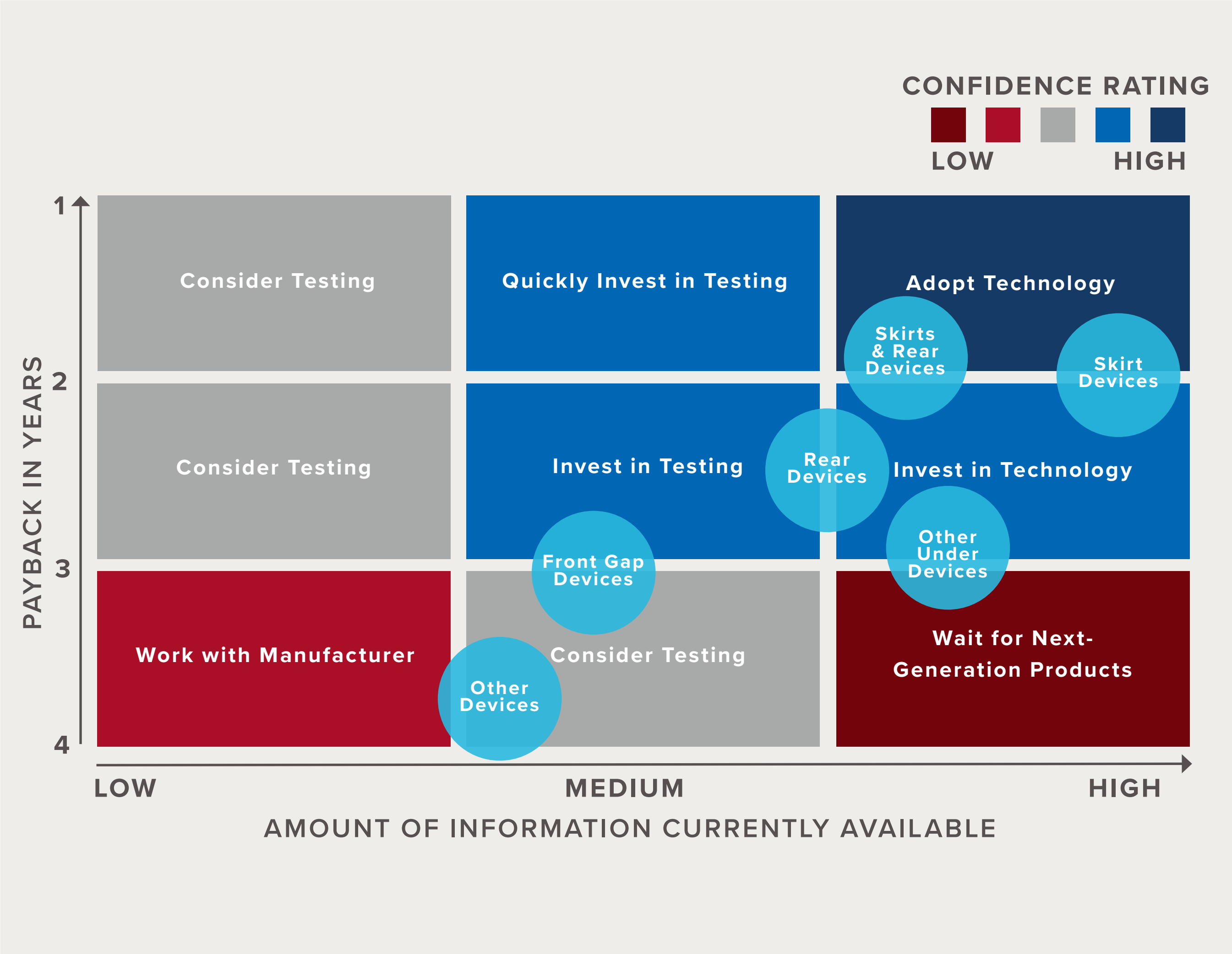
If you are currently running this trailer configuration:	This might be your best next step for better trailer aerodynamics:
Aero tractor with typical dry van trailer	Add trailer skirts
Trailer with side skirts	Add trailer rear device
Trailer with side skirts and manually deployed rear boat tail	Convert to second-generation trailer rear devices
Trailer with side skirts and rear boat tail	Add trailer front nose fairing and/or automatic gap closure device
Trailer side skirts, rear boat tail, and nose fairing	Start investigating other minor areas such as wheel covers, license plate position, and vented mud flaps
Day-cab tractor with large tractor-trailer gap	Add trailer-mounted gap device

CONFIDENCE RATING

For each of the Confidence Reports completed by NACFE, 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 NACFE 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 NACFE has high confidence in those short payback times, usually because the technology is more mature or has a more substantial track record of results. (See Figure ES2.)

FIGURE ES2

CONFIDENCE MATRIX



NACFE is highly confident that all fleets should be considering the aerodynamics of their trailers, and the adoption of devices that will improve those aerodynamics, as a major opportunity to save fuel. The best device or package of devices to adopt will depend on a fleet's unique duty cycle. But overall, available savings are likely quite high, up to 10%, for the majority of fleets running 53' dry box trailers. Moreover, many regulations are likely to mandate the adoption of trailer aerodynamic devices in coming years, so fleets that have not even begun to consider this opportunity will be wise to do so in anticipation of mandates.

CONCLUSIONS

This report focuses primarily on sleeper tractors pulling van trailers on-highway in North America. It describes both individual and combinations of technologies and practices available to fleets in pursuit of fuel economy improvement, operating cost reduction, and greenhouse gas emissions decrease through the use of trailer aerodynamic devices. The study team came to the following conclusions with respect to fleets, truck and trailer OEMs, manufacturers, and others concerning the adoption of trailer aerodynamic devices:

- Trailer aerodynamic devices save fuel. The priority for device adoption by fleets is side, underbody, gap, and then other devices. The EPA SmartWay program provides the industry with a structure for cataloging and ranking trailer aerodynamic devices. It should be considered a foundation for further improvement in performance evaluation.
- Devices have matured and will continue to improve. Skirts have become lighter, less expensive, and more robust, improving their payback. Other devices are maturing but need continued development to improve their total cost of ownership.
- There are unique challenges, including trailer-to-tractor ratio, that limit the miles per trailer; some cases of the trailer aerodynamics purchaser not buying the fuel; and that devices should be driver passive: no driver interaction is required to deploy or stow.
- Performance for each fleet is difficult to determine. Performance of any device is subject to many variables, and each operator will likely have their own experiences. Although most fleets can measure tractor efficiency very closely, they do not have the tools to monitor the trailer efficiency at all.
- Regulations will drive greater adoption. GHG Phase II and California Air Resources Board (CARB) rules will drive much greater adoption of trailer aero devices in the near future, taking them from being add-on options to being standard equipment. However, the primary motivation for aerodynamic technology investment remains a business one, with fleets demanding a two-year or less payback for technologies.
- Aerodynamic devices must work without driver intervention. History has shown that devices that need driver intervention—such as first-generation trailer tails—are not effective solutions. Second-generation rear devices are addressing some of the challenges of the earlier versions of those devices.

NACFE
NORTH AMERICAN COUNCIL FOR FREIGHT EFFICIENCY

NACFE

The North American Council for Freight Efficiency (NACFE) works to drive the development and adoption of efficiency-enhancing, environmentally beneficial, and cost-effective technologies, services, and operational practices in the movement of goods across North America. NACFE provides independent, unbiased research, including Confidence Reports on available technologies and Guidance Reports on emerging ones, which highlight the benefits and consequences of each, and delivers decision-making tools for fleets, manufacturers, and others. NACFE partners with Rocky Mountain Institute (RMI) on a variety of projects including the Run on Less fuel efficiency demonstration series, electric trucks, emissions reductions, and low-carbon supply chains.

www.nacfe.org

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

ROCKY MOUNTAIN INSTITUTE

ROCKY MOUNTAIN INSTITUTE

Rocky Mountain Institute (RMI)—an independent nonprofit founded in 1982—transforms global energy use to create a clean, prosperous, and secure low-carbon future. It engages businesses, communities, institutions, and entrepreneurs to accelerate the adoption of market-based solutions that cost-effectively shift from fossil fuels to efficiency and renewables. RMI has offices in Basalt and Boulder, Colorado; New York City; the San Francisco Bay Area; Washington, D.C.; and Beijing.

www.rmi.org

GET INVOLVED

NACFE provides an exciting opportunity for fleets, manufacturers, and other trucking industry stakeholders.

Learn more at: www.nacfe.org

Or contact: Mike Roeth at mike.roeth@nacfe.org

1 Introduction

This Confidence Report forms part of the continued work of the North American Council for Freight Efficiency, (NACFE) and Rocky Mountain Institute (RMI) highlighting the potential of fuel efficiency technologies and practices in over-the-road (OTR) goods movement. Prior Confidence Reports and initial findings on nearly 85 available technologies can be found at www.nacfe.org.

The fuel costs faced by the trucking industry have been extremely volatile over the past decade. By 2015, through an unexpected combination of world political and economic forces, fuel prices 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 shows the impact of fuel prices on fleets' operating costs. [1, 2]

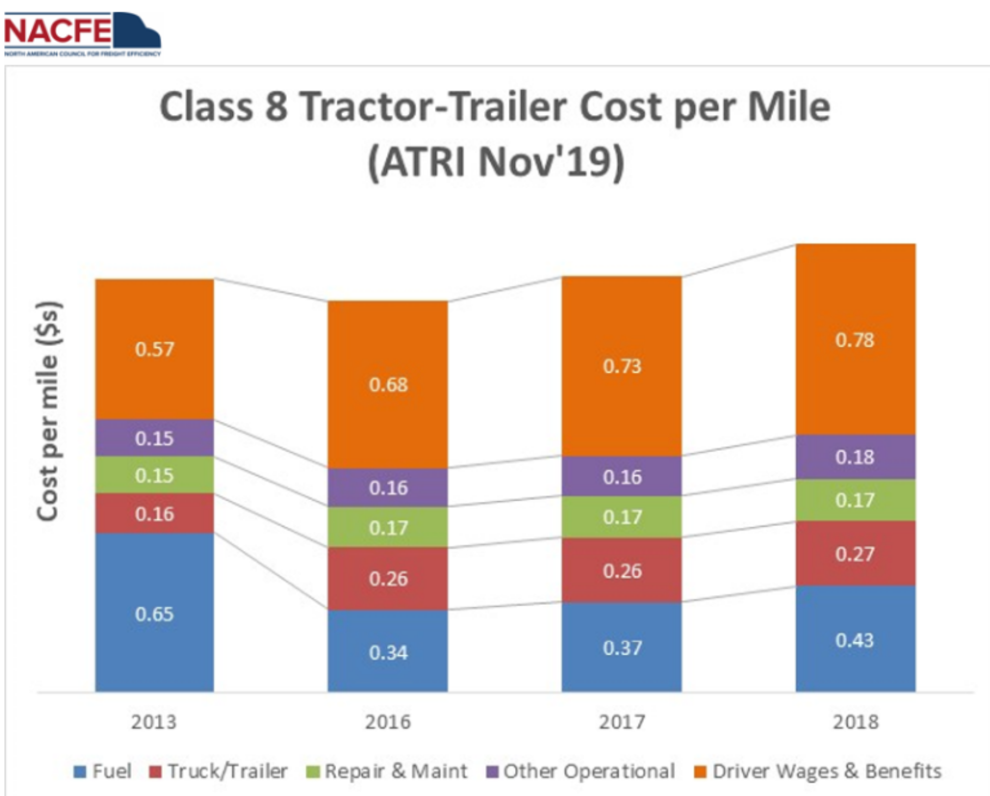


Figure 1: Trucking Operational Costs per Mile

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

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 85 fuel efficiency technologies currently available for Class 8 tractors and trailers. [3] Rob Reich, EVP, Chief Administrative Officer, Schneider commented on the report, saying, "I look forward to this report and read it each year within days of it being published. It is important to Schneider's efforts and it can be a critical resource to any fleet or owner/operator as well as manufacturers and others who are working to improve Class 8 efficiency."

The primary finding of the *2019 Annual Fleet Fuel Study* is that the 21 fleets studied are increasing their rate of adoption of these technologies, and that they are enjoying improved fuel economy as a result. (See Figure 2 for the names of fleets that participate in the study.) [3] The overall adoption rate for the technologies studied in this report has grown from 17% in 2003 to 45% in 2018. Not all technologies can be applied to a single tractor-trailer, as some are clearly an either/or decision. In 2018, there was an increase in fuel cost at the pump with diesel fuel, which powers a large majority of this fleet, averaging \$3.18 per gallon for 2018, up from 2017 at \$2.65. [1] This is a 20% increase, year over year and \$0.88 per gallon increase from 2016. The 2011 to 2014 four-year average was \$3.89, meaning that fuel costs annualized in 2018 is within \$0.71 of that level. (See Figure 3.)

Figure 2: 2019 Annual Fleet Fuel Study Participants

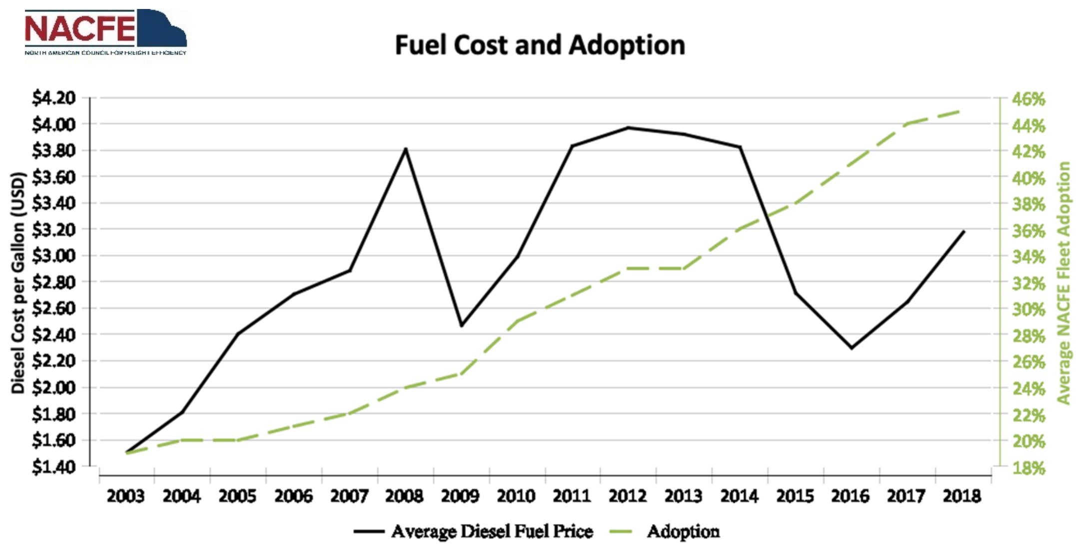


Figure 3: Price of Diesel and NACFE Fleets Adoption

The average fleet-wide fuel economy of the trucks in the *Fleet Fuel Study* was 7.27 MPG in 2018 — a slight increase from the 7.23 in 2017. There is variability in each fleet's yearly fuel efficiency depending on many factors. [3]

For the 16 years of this study, the average rate of improvement in MPG has been 2.0%. Figure 4 shows the average fleet-wide fuel economy for the combined population of trucks in this study compared to the overall U.S. truck population. A business-as-usual (BAU) line is included for comparison. The BAU shows a projection of what average MPG might have been given the combined impact of 2002, 2007, and 2010 emission regulations, and the effect of the 2014 and 2017 Greenhouse Gas (GHG) base powertrain improvements. In other words, this suggests the level of efficiency had the 21 fleets not purchased the technologies that are available to them as options. [3]

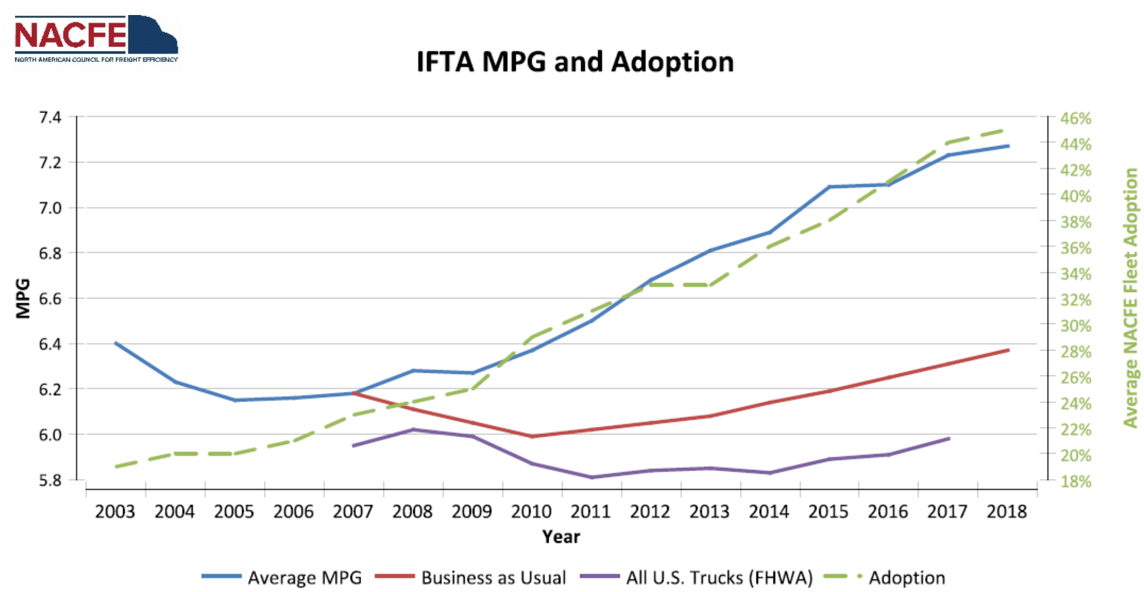


Figure 4: Fuel Savings per Truck

The fuel savings in 2018 between the BAU of 6.37 MPG and the NACFE fleets average of 7.27 MPG amounts to $6,492 per year per truck, at the $3.18 per gallon fuel cost over the average tractor mileage of 105,041. The fleets are saving $9,912 over the national average of 5.98 MPG. If fuel costs had been at the four-year average of $3.89 per gallon, the savings would have been $7,941 and $12,124, respectively. And finally, the 21 fleets operating 73,844 trucks saved $895,318,953 in 2018 compared to the average trucks on the road. [3]

The study reached the following conclusions:

- Multiple factors are influencing fleet adoption. New factors have emerged that influence decisions by fleets to improve efficiency including the current cost of fuel, potential future cost, federal and local regulations and increasing public demand for more sustainable operations
- Fleets continue to adopt fuel-saving technologies. Specific technologies adopted vary by fleet duty cycle, business models, fleet size and other factors.
- Manufacturers accelerated delivery of technologies
- Other advancements come both as novel technologies that provide the same function in a different way and new technologies that address areas not considered in the past.
- A significant gap to best-of-the-best still exists.

NACFE's goal is for the information shared in this study to provide fleets a roadmap for navigating the many available technologies that can have a positive impact on lowering fuel expenses.

1.1 NACFE's Confidence Reports

NACFE hoped its Fleet Fuel Studies alone would spur additional investment of freight efficiency technologies. However, in the course of conducting the studies, it became clear that some technologies still are only being adopted by the most progressive or innovative 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 RMI began this series of Confidence Reports, which 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 in order to centralize an unparalleled range of testing data and case studies on a given technology set.

Trailer aerodynamic devices options represent one such technology set. The most recent *Fleet Fuel Study* found that fleets have begun ramping up their investment in trailer aerodynamics, most notably trailer skirts. (See Figure 5.)

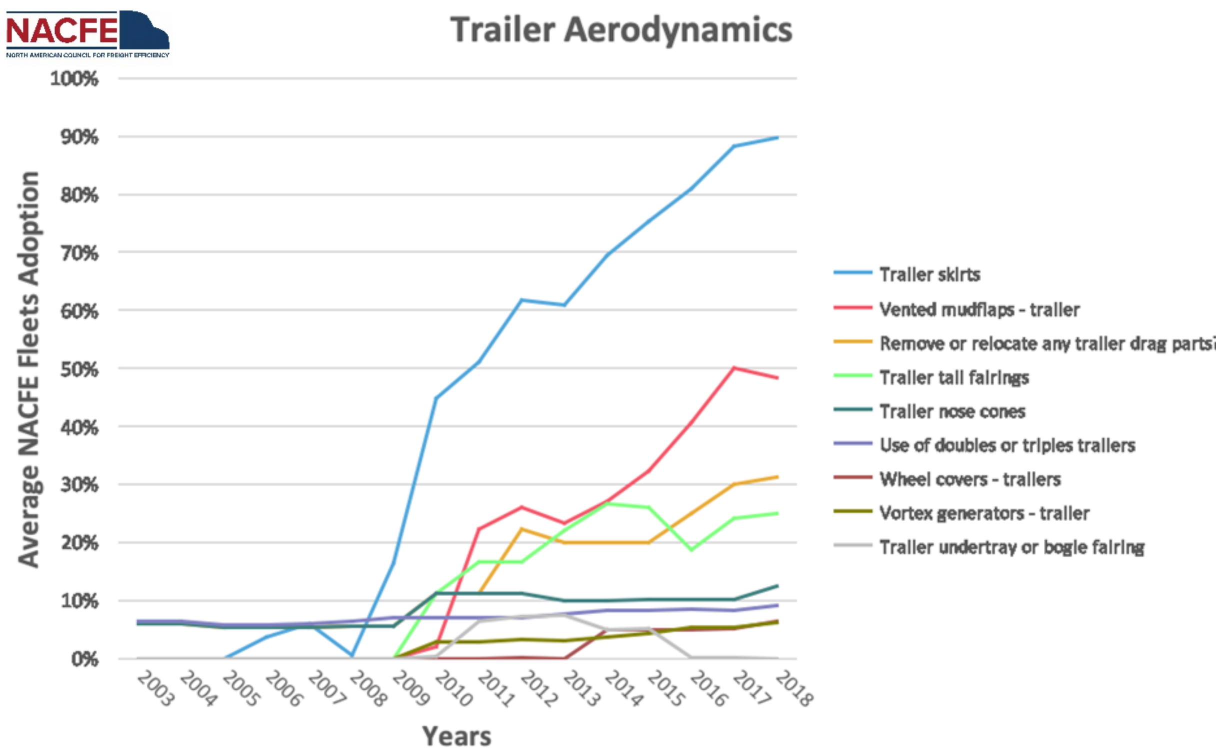


Figure 5: Trailer Technology Adoption (NACFE)

Trailer aerodynamic devices help to increase fuel efficiency, in two ways:

- They lower air resistance, so that it takes less fuel to move the truck down the road as speed increases,
- They allow carriers to downsize other weight sensitive specifications such as fuel tank size and engine horsepower rating, thereby reducing overall vehicle weight and offsetting the added weight of the aerodynamic devices themselves.

The per-vehicle fuel economy benefit of trailer aerodynamic devices can be high, ranging from 1% to over 10%, depending on the devices chosen. 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 lbs. [6] Today, even the most aggressive aerodynamic fairings for trailers adds less than 2,000 lbs., so the maximum mile-per-gallon reduction due to the weight of aerodynamic fairings would be less than 1.2% , much less than the 9%+ MPG gain offered by SmartWay *Elite* trailer aerodynamic systems in on-highway hauls for typical van trailers. [7]

Given these potential savings, trailer aerodynamics is an excellent technology set for significantly increasing fuel efficiency. However, it is also quite a large technology set, and can complicate the decision about which devices to invest in.

The goals of this Confidence Report, therefore, are as follow:

- To give the industry a foundational understanding of trailer aerodynamic devices
- To provide an unbiased review of available trailer aerodynamic technologies on the market today

- To increase investment into cost-saving trailer aerodynamic technologies

This NACFE Trailer Aerodynamic Device Confidence Report is one in a series of NACFE focused reports on configuring vehicles and operations to improve their fuel efficiency. (See Figure 6.) Visit https://nacfe.org/report-library/confidence-reports 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, preventive maintenance and determining efficiency testing methods.

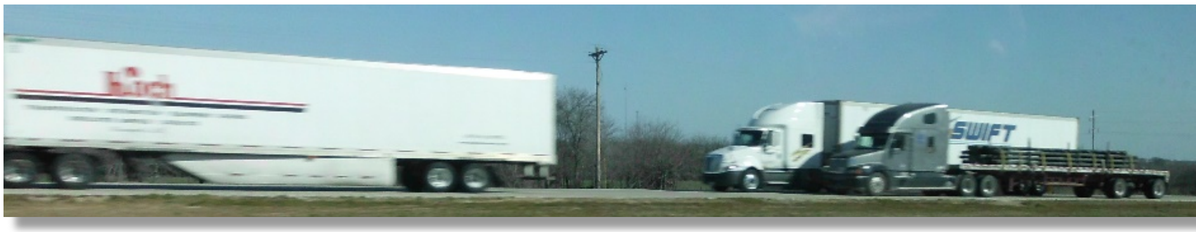


Figure 6: Aerodynamic Tractor and Trailers are Major Contributors to Fuel Efficiency

2 History of Trailer Aerodynamics

Tractor and trailer aerodynamic design concepts have been around for a very long time. A series of trends over the last 20 years have moved the industry from asking "why should my fleet use trailer aero devices" to "when and how will my fleet implement trailer aero devices?"

Early trailer designs in the 1930s and 1940s, as shown in Figure 7, featured rounded front ends, and the U.S. patent office documents a significant number of supposed aerodynamic-performance-enhancing inventors' concepts over the subsequent decades. [33, 34]

Figure 7: Early Aerodynamic Trailers

For example, the 1930s and 1940s trailers had rounded front ends as seen in Figure 8. While not practical for loading and unloading pallet-based freight, they do serve perhaps as inspiration for integrating aerodynamics into future trailer designs.

Figure 8: Rounded Front Trailers in '30's & 40's

But few if any of these ideas ever made it into production before the year 2000, and those that did rarely saw commercial success. One exception is the tractor roof fairing which was first developed through extensive work in 1953 by the University of Maryland with Trailmobile, and by Rudkin-Wiley in 1965-67. It came into significant use in the 1970s as a result of reactions to the 1973 Oil Embargo. The cab roof fairing was a single add-on device with significant and obvious drag reduction benefits that could be easily visualized and easily measured in terms of reduced-fuel-costs over time. Figure 9 shows how the roof fairing aerodynamic function was easy-to-explain to fleets as improving on the trailer's basic box front shape. [5]

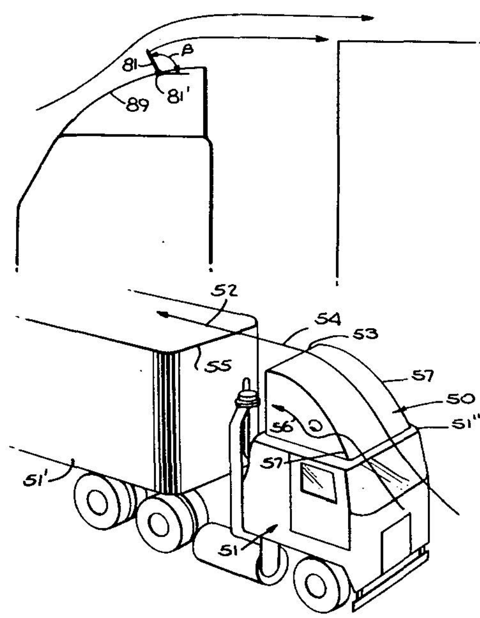


Figure 9: COE Easily Visualized (TrailMobile)

Still, adoption was slow. By 1975, government estimates found that only 11% of tractors had roof fairings, and the stabilization of fuel prices meant that the market penetration for roof fairings stayed small. The

1974 enactment of the 55 mph National Maximum Speed Limit (NMSL) also limited uptake of aerodynamics, as it capped highway speeds at 55 mph. Such road speed limitations reduce the potential fuel savings offered by aerodynamic devices, as aerodynamic drag, while a factor at every speed, increasingly determined fuel burn above 50 mph.

This is illustrated in a typical horsepower versus speed graph (Figure 10) that apportions required engine power between mechanical drag (rolling friction and accessories) and aerodynamic drag. (Figure 10, as, published in 2000 in the *Technology Roadmap for the 21st Century Truck Program*.) [4, 41]

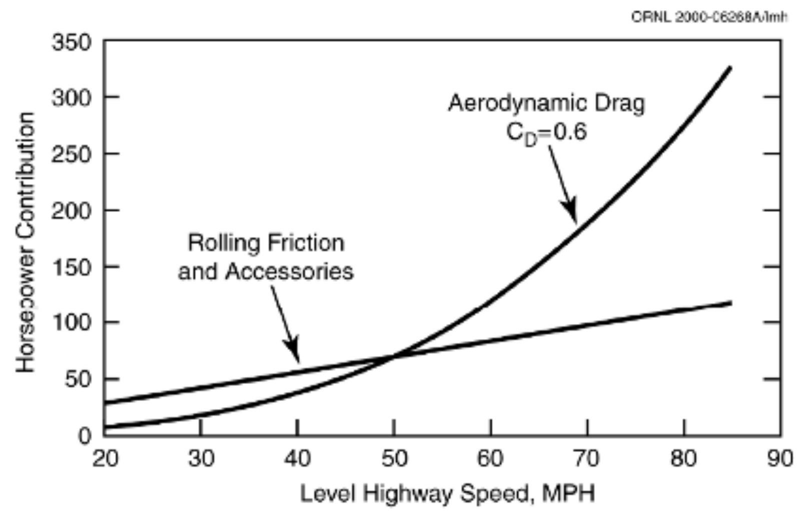
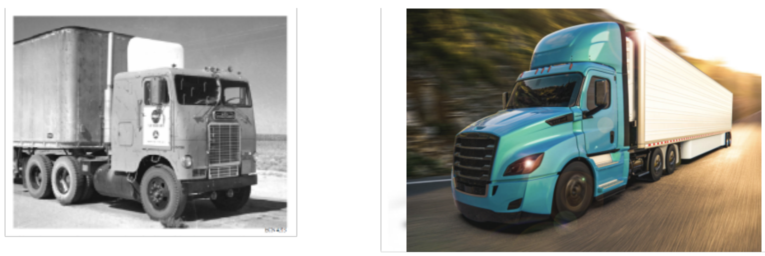


Fig. 4.2. Horsepower required to overcome aerodynamic drag and rolling friction/accessories as a function of travel speed for a typical Class 8 tractor-trailer.

Figure 10: Horsepower Required Overcoming Opposing Forces

Fleet use of aerodynamic tractors began as early as the 1980's, some say with the launch of the Kenworth T600 (Figure 11). It took the introduction of the Surface Transportation Assistance Act (STAA) of 1982, which opened the door for the replacement of the cab-over tractor design with the hooded conventional design, and the lengthening of van trailers to increase usage of 53 footers. The STAA act really kick-started the long evolutionary path of aerodynamic performance from cab-overs to today's very aerodynamic conventional tractors (Figure 12). [5]

Figure 11: 1985 Kenworth T600 (PACCAR)



79% COE
72% Van Semitrailers
11% Cab-Mounted Deflectors

1975

98%+ Conventional
53% Van Semitrailers
95% Roof Fairing

2020

Figure 12: Significant Evolution in Tractor Shape Started by STAA Legislation

Then, in 1995, Congress repealed the National Maximum Speed Limit and returned full authority to set speed limits back to individual states. Thirty-three states quickly upped their speed limits, paving the way for market forces to demand better aerodynamic performance from tractor OEMs. [50]

Moreover, this increase in speed limits coincided with the start of increasingly dynamic fluctuations in fuel prices, as shown in Figure 13. [1]

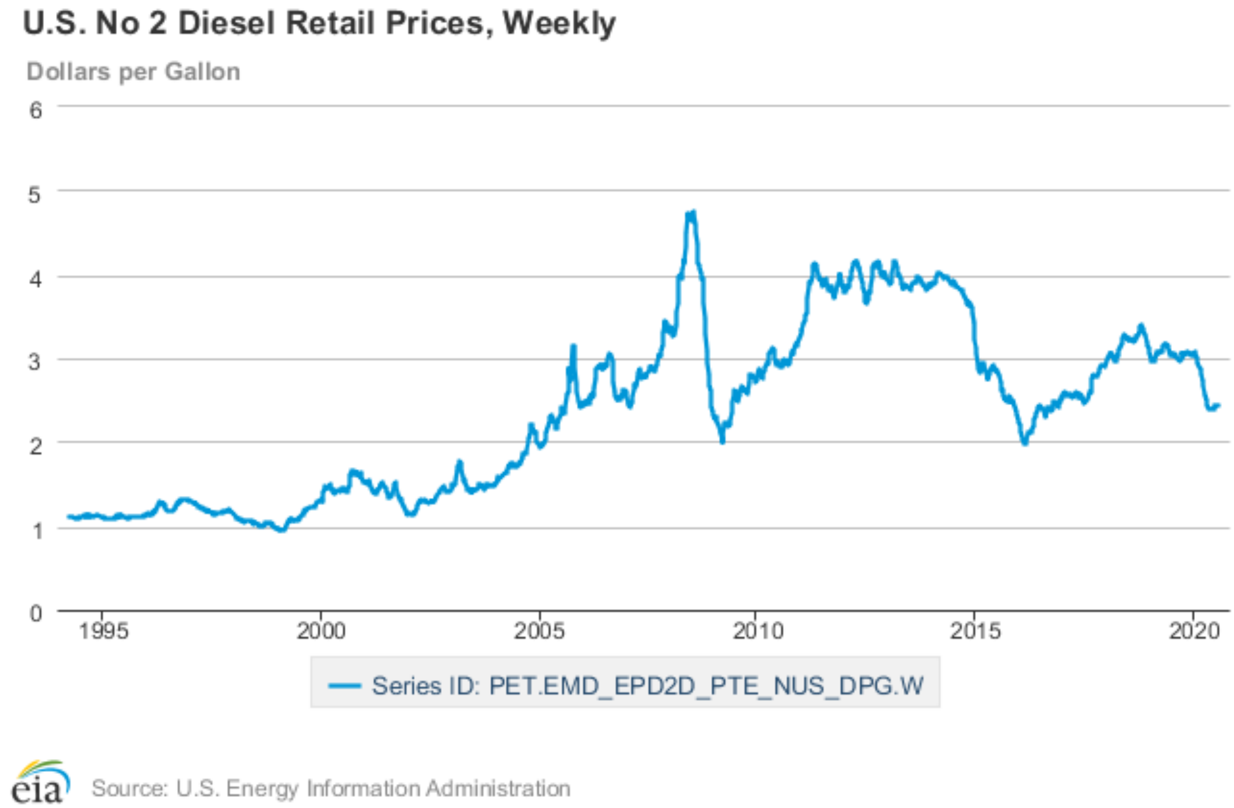


Figure 13: U.S. Diesel Fuel Price History

Higher speeds and high fuel prices combined to cause the industry to push tractor OEMs to release an unprecedented number of new, more aerodynamic models (Figure 14), including the Freightliner Century (1995), the Ford HN80 Aeromax (1996), the Kenworth T2000 (1996), the Volvo VN (1996), and Peterbilt 387 (1999). The aerodynamics of trailers, however, were left largely unchanged during this period, as both customers and OEMs focused aerodynamic improvement exclusively on tractors.

Figure 14: Late 1990's Aerodynamic Tractor Launches:
Ford HN80, Kenworth T2000, Freightliner Century, Volvo VN, Peterbilt 387

The 1990s saw significant changes in engine technology with the implementation of electronically controlled engines. Truck fuel economy performance became more predictable because of pre-defined software algorithms in the engine controllers. This enabled emissions regulation.

2.1 Impact of Recent Regulations

In the last half of the 1990s, regulatory focus dramatically increased on truck engine emission standards. In 1995 the Environmental Protection Agency (EPA), the California Air Resources Board (CARB), and the leading manufacturers of heavy-duty engines reached agreement on engine emissions reductions. They established a goal to have new standards that would halve NOx emissions of new trucks and buses. In parallel with this, the 21st Century Truck Partnership was initiated by the Department of Energy (DOE) as an on-going research effort to improve vehicle performance and investigate potential policy and technical improvements. [4, 9, 10, 11, 32, 41]

What followed were increasingly stringent EPA Clean Air Act emissions regulations beginning with the release of rules in 1997. These forced tractor and engine design changes roughly every two to four years, through 2017 when EPA's Phase I Greenhouse Gas (GHG) rules were fully implemented. These rules initially focused on engines and components but evolved into vehicle-level standards. Still, trailers were excluded from these emissions management efforts through 2017. The EPA implemented trailer aerodynamics as part of its GHG Phase 2 rule making. [11, 32]

In parallel with these ever-more demanding emissions rules came federally legislated reductions in the sulfur content of fuels, which changed in 1993 from 5,000 parts per million (ppm) sulfur to 500 ppm Low-Sulfur Diesel and then in 2006 to 15 ppm Ultra-Low-Sulfur Diesel (ULSD) with 15 ppm sulfur. These changes to fuel required additional design and performance changes to the engines and vehicles. Finally, federal, state and regional authorities in various locations began introducing "no idle" rules over the last decade. These often require the use of automatic engine shut down devices and promoted investment in idle-reduction technologies. (See NACFE's *Confidence Report on Idle Reduction*). [47]

Nearly all of these requirements have resulted in increased tare weight and/or devices which occupied critical space on the tractor chassis. In many cases these changes worsened fuel economy. Then OEMs attempted to offset the weight by improving tractor-trailer aerodynamic performance through the use of lower rolling resistance of tires and lightweighting efforts. With respect to tractor aerodynamics, OEMs have continually introduced new and improved models over the last 20 years as each of these emissions mandates took effect. See Figure 15 for the latest product introductions from the truck OEMs.

Figure 15: OEM Product Aerodynamic Progression

Top to bottom, left to right: Peterbilt 386 (2005), Navistar ProStar (2006), Mack Pinnacle (2006), Kenworth T660 (2007), Freightliner 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), Peterbilt 579 EPIQ (2015), Mack Anthem (2017), Navistar LT (2017), DTNA Cascadia (2018), Volvo VNL 860 (2019)

In general, the tractor side of the industry has achieved net improvements in fuel economy over the last 20 years, even as regulations increased. Figure 16 maps FHWA data to show that by 2005 tractor-only net freight efficiency improvements, taken in concert with all the other vehicle factors, was beginning to level out. Trailer aero devices had made minimal market penetration in this time period. [6]

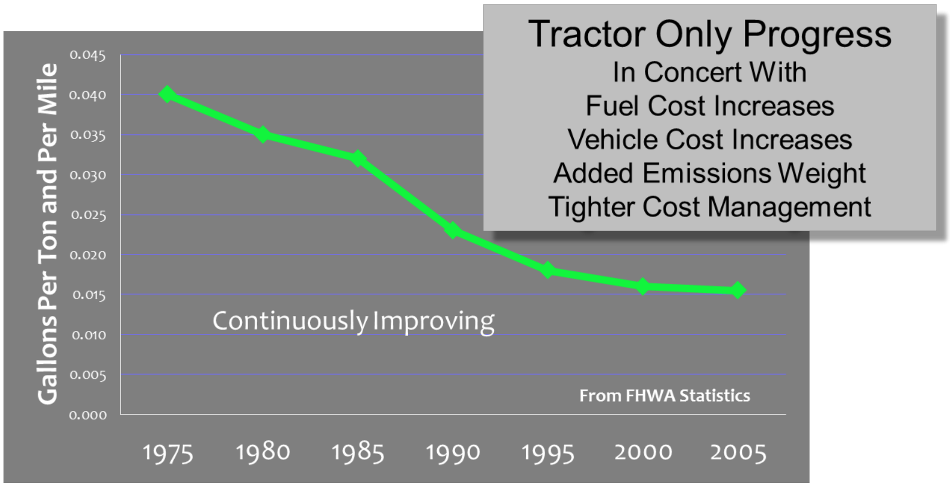


Figure 16: FHWA Freight Efficiency Improvement to 2005

Yet both government and industry realized that tractor efficiency improvements alone could only go so far toward saving fuel. In 2004, the EPA introduced the SmartWay program. a voluntary freight initiative with the goal of providing industry guidance on vehicle option selection with a focus on fuel economy improvement, including aerodynamic devices. SmartWay in turn deployed a Technology Verification program in 2005, which identified the key attributes of a highly fuel-efficient heavy-duty truck and included recommendations for 53' van trailer technologies. The EPA SmartWay's program and its thinking on trailer aerodynamics is discussed in detail in Chapter 7 of this Confidence Report. [7]

Though voluntary SmartWay recommendations attracted some early adopters to trailer aerodynamic devices, in 2006, trailer aerodynamic device market penetration was still nearly zero. Some fleets were experimenting with them, such as in the Great Dane/Walmart collaboration shown in Figure 17. [8]

Figure 17: 2006 Great Dane/Walmart Prototype Aero Trailer (DOE)

Significant market penetration only began with the rules enacted in 2008 by the CARB, which mandated the use of SmartWay-certified tractors and trailers in California. The rules initially applied to new 53' van trailers, beginning with Model Year 2011, but phased in full compliance requirements for older trailers by

2017. Additionally, CARB pursued a mostly parallel path with the EPA on vehicle emission regulations and are lockstep now with EPA GHG Phase I and GHG Phase II rules. Similar efforts are in process in Oregon where complete fleet trailer aerodynamic compliance has been in discussion since 2009. [9, 10, 11, 32, 43]

Overall, the recent regulatory environment at the state and national levels are tending to force technology choices regarding aerodynamic factors. Some of these rules directly apply to end users by requiring particular tractor configuration, such as the CARB and EPA rules just discussed. Other rules are being imposed on the OEM tractor manufacturers, requiring them to tailor their production to favor more aerodynamic configurations, per the EPA Phase I and Phase II GHG rules. [9, 10, 11, 32]

By 2015, in excess of 30% of new trailers were being equipped with trailer aerodynamic devices. Various state legislations and other voluntary incentive programs are likewise driving existing trailers to be retrofit with aerodynamic devices. Finally, competitive forces are driving adoption, as the benefits of investing in trailer aerodynamic technologies show up in the bottom line of company balance sheets.

In coming years, regulation is likely to continue to drive adoption of trailer aerodynamic devices. As mentioned, the EPA and NHTSA have released rules, commonly termed GHG Phase II rules, which initially required the use of aerodynamic devices for new van and refrigerated trailers longer than 50’ in 2021, with voluntary compliance that began in 2018. The GHG Phase II rules as finalized would have required increasing levels of trailer aerodynamic production starting in 2021, with additional increasing levels in 2024 and 2027. [11, 32]

Final implementation of the trailer rules has been delayed pending legal and regulatory reviews, specifically between the Truck Trailer Manufacturers Association and the EPA. There continues to be at the time of this report no timetable for the possible tweaking, repealing or leaving in place the joint rule.

The GHG Phase II rulemaking partitions the types of trailers into 10 categories, and aerodynamic improvement requirements will apply to all but the last four, Short Box dry and refrigerated Non-Aero Box and Non-Box trailers. The rules additionally note that “the partial-aero box trailers would have similar stringencies as their corresponding full-aero trailers in the early phase-in years, but would have separate, reduced standards as the program becomes fully implemented.”

- Long box (longer than 50’) dry vans
- Long box (longer than 50’) refrigerated vans
- Partial-aero long box dry vans
- Partial-aero long box refrigerated vans
- Partial-aero short box dry vans
- Partial-aero short box refrigerated vans
- Short box (50’ and shorter) dry vans
- Short box (50’ and shorter) refrigerated vans
- Non-aero box vans (all lengths of dry and refrigerated vans)
- Non-box highway (tanker, platform, container chassis, and all other types of highway trailers that are not box trailers).

EPA and NHTSA define “non-aero” trailers in the GHG Phase II rules as:

> *(i) For trailers 35 feet or longer, a manufacturer may designate as “non-aero box vans” those box vans that have a rear lift gate or rear hinged ramp, and at least one of the following side features: side lift gate, side-mounted pull-out platform, steps for side-door access, a drop-deck design, or belly boxes that occupy at least half the length of both sides of the trailer between the centerline*

of the landing gear and the leading edge of the front wheels. For trailers less than 35 feet long, manufacturers may designate as "non-aero box vans" any refrigerated box vans with at least one of the side features identified for longer trailers.

Partial aero trailers are defined as:

(ii) A manufacturer may designate as "partial-aero box vans" those box vans that have at least one of the side features identified in paragraph (a)(1)(i) of this section. Long box vans may also qualify as partial-aero box vans if they have a rear lift gate or rear hinged ramp. Note that this paragraph (1)(ii) does not apply for box vans designated as "non-aero box vans" under paragraph (1)(i) of this section

Non-aero trailers include three axle trailers. Non-aero trailers are estimated at 20% of the regulated van trailer market per EPA/NHTSA. These types of trailers have no GHG aerodynamic requirements, only the need to install qualified low rolling resistance tires. Partial aero trailers have requirements to adopt some aerodynamic devices along with low rolling resistance tires.

3 What is Trailer Aerodynamics?

Trailer aerodynamics describes how air flows around the trailer, and provides mechanisms to quantify and then rank performance of both individual devices and combinations of devices. The physics involved in testing trailer aerodynamic device performance can be complex, and there are multiple ways of measuring and evaluating performance; these are described in NACFE's *Determining Efficiency Report*. Fundamentally though, reducing the drag of a basic van trailer comes down to adding one or more devices onto three key areas of the trailer: the gap, the underbody, and the rear. [12]

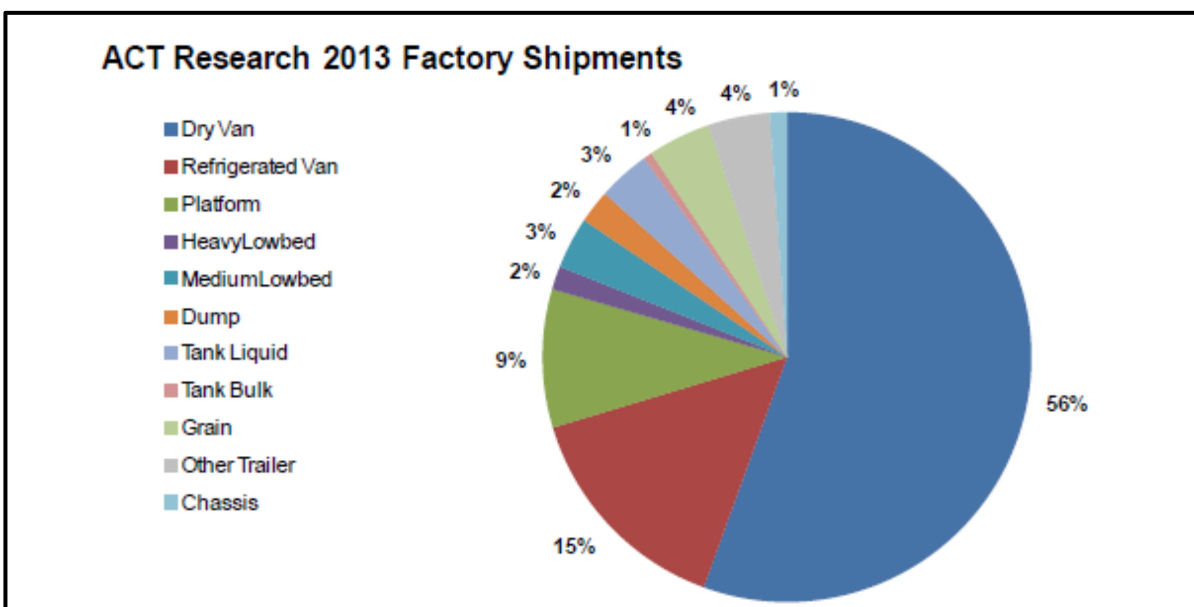
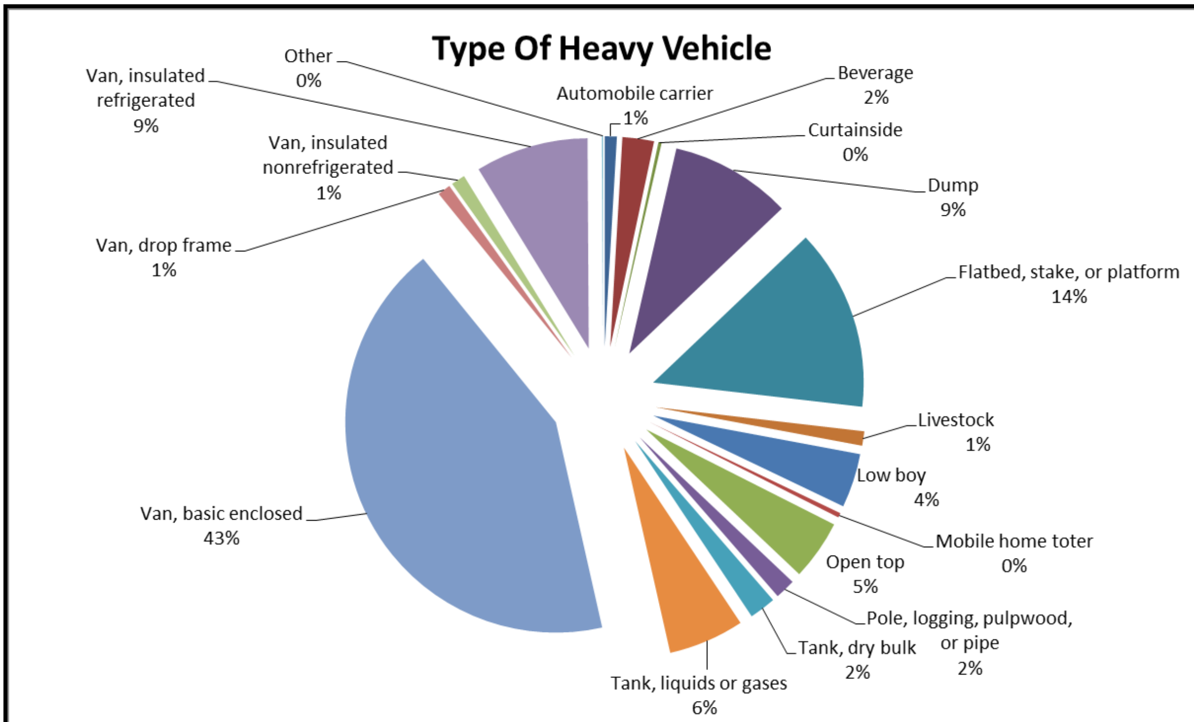


Figure 18: 2013 Factory Shipments (ACT Research)

There are a wide variety of trailer types and uses in North America. The U.S. Census Bureau had a program to track the transportation sector through the periodic Vehicle Inventory and Use Survey, or VIUS. The last report from 2003 showed trailer types and uses segmented into a wide range of configurations, as summarized in Figures 18 and 19, with the largest segment of roughly 52% described as van trailers and refrigerated van trailers. [51] Today's segmentation is similar in complexity as shown in 2013 ACT data reported by the EPA, which found that van and refrigerated units claim a 70% share of the market.



US Census Vehicle Inventory & Use Survey 2003
All Trailers Specific Service Types Shown For 60,000 - 80,000 lbs. GVWR

Figure 19: Trailer Type Distribution 2001

Obviously, all fleets are concerned with fuel economy and freight efficiency, but to date the focus of aerodynamic technology development (and of rulemaking) has almost exclusively been on van trailers; since the van trailer is simply a large box with wheels, it lends itself most easily to aerodynamic improvement.

Figure 20: Typical 53' Van Trailer Is Box Shaped On Purpose

The reason most trailers are just boxes, rather than some more aerodynamic shape, stems from the fact that packaging is largely a rectilinear world. Products are moved in boxes and on the ubiquitous 40”x 48” pallet (setting interior trailer width), which must be loaded by forklift (setting the interior trailer height) from warehouse docks (setting the trailer floor height). Meanwhile exterior width is set by the maximum permissible by highway lanes, and exterior height is set by highway underpasses and bridges.

Length is managed by various rules and regulations for safe roads. The lane width and bridge heights are effectively “go/no go” gauges, and trailer exteriors are pushed out to these maximums to provide the maximum rectangular floor space for pallet loads. The overall length of the trailer is the only variable that has the potential to increase freight space, but it is constrained by a myriad of state and federal highway rules tied to pavement life, bridge loading design and traffic safety, such that the two axle 53’ van trailers dominate trucking today in the United States. It is important to note that longer units and combination trailers are safely operated in various states and Canada under permits, and that there is a growing industry effort to reevaluate size and weight restrictions that may change the status of 53’ van trailers, which themselves evolved from 28’, 40’ and 48’s units in the past.

The basic box shape of the trailer shown in Figure 20 is thus fairly well-constrained at present to be what it is, a 53’-long, approximately 102”-wide, 13.5’-tall unit with floor/dock height between 46” and 52”. It is estimated that there are 8 million such van trailers in service today. EPA testing shows that “there is very little difference in performance between trailer manufacturers for their basic trailer models.” That said, there are trailer features that reflect better attention has been paid to aerodynamics. Most trailers do have some integrated aerodynamic structural treatments, like rounding the front vertical corner posts. Other options include the following:

- Increasing the size of the radius reduces drag on the front side and top edges
- Smooth sides and top surfaces, as structural seams and stiffeners can present gaps or steps to the air flow
- Flush rivets
- Hinges at the rear doors that are recessed or present minimal protrusions off the side surface
- Recessed structures found on roll-up doors, as these are more aerodynamic than flush base doors
- Eliminated or minimized rain gutters
- Rear edges that are chamfered inward
- Roofs that are level or that slope down toward the rear

- Sides that are parallel to the direction of travel
- Minimized tractor-trailer gaps

The basic box shape also lends itself easily to adding on aerodynamic devices. The length itself is a key factor for better aerodynamics. Longer trailers tend to make more uniform flow along the sides and roof, although for non-skirted trailers the extra length can allow more air to hit the trailer bogie than on shorter ones or straight trucks.

On the other hand, other optional trailer devices can significantly worsen aerodynamics, or otherwise complicate the installation of aerodynamic technologies. Figure 21 highlights key examples of this potential complication.

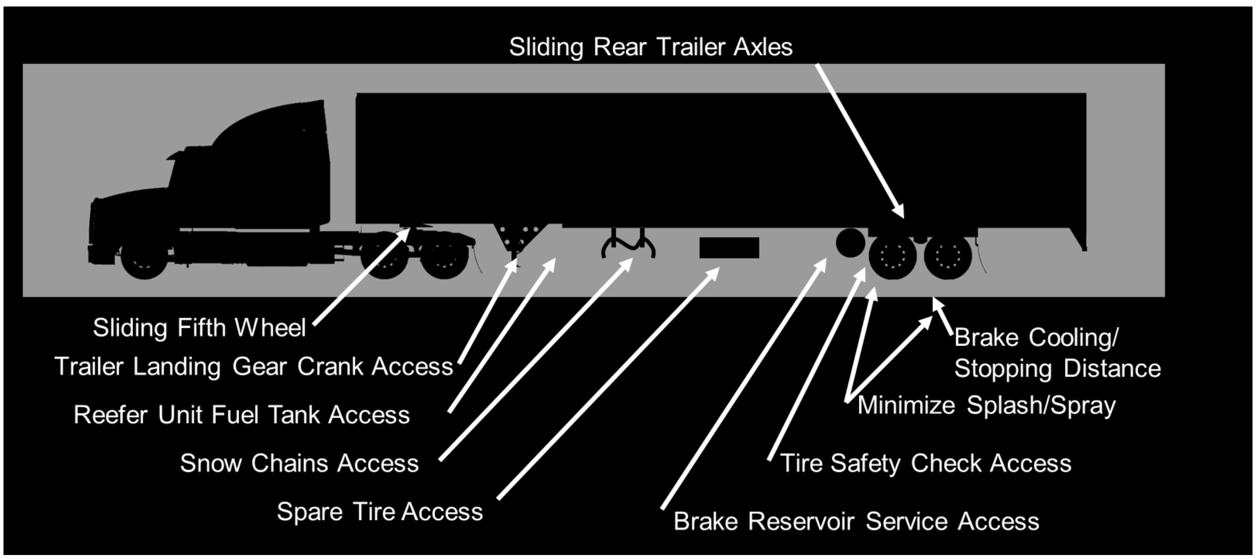


Figure 21: Optional Equipment Complicates Aero Configuration

Finally, note that a key aerodynamic element of the trailer is actually the tractor. The shape of the tractor, as illustrated in Figure 22, manages the way air is delivered to the trailer. In general, modern tractors are quite aerodynamic, as they have been extensively refined to provide smooth air flow around the trailer, dividing it into air over the roof, the sides, and the underbody. Much of the improvements in modern tractor aerodynamics have been to reduce air flow under the vehicle using bumper air dams, tractor side skirts that extend nearly to the ground, and more recently, work on tractor bogie fairings. A complete review of tractor aerodynamic devices can be found in the *Confidence Report on Tractor Aerodynamic Devices*. [49]

Figure 22: Aerodynamics of the Cab Affect the Trailer (Exa/Peterbilt)

4 Benefits of Trailer Aerodynamic Technology Adoption

The benefits of trailer aerodynamic technology adoption include:

- Improved fuel economy
- Improved tractor trailer stability
- Improved intervehicle safety
- Improved driver fatigue

4.1 Saves Fuel

Improving fuel economy is the primary motivation for using aerodynamic devices. The National Research Center of Canada (NRCC) estimated fuel economy savings for representative trailer devices in their 2015 study, *Improving the Aerodynamic Efficiency of Heavy-Duty Vehicles: Wind Tunnel Test Results of Trailer-Based Drag-Reduction Technologies*. [14] They based the estimate on an 80% at highway speed duty cycle and typical Canadian average miles per year and operational factors. Their estimates were that fuel savings for adding various trailer skirts should range between 766 gallons to 870 gallons per year. At $2.50 per gallon, that translates approximately to $1900 to $2200 in annual savings. Fleets are investing in these devices because they have adequate ROIs and payback periods.

4.2 Stability & Rollover

Trailer aerodynamic devices add surface area to the trailers and modify the trailer air flows. These can both slightly improve and slightly worsen rollover physics in severe crosswind conditions. Skirts which are mounted below the center of gravity of the trailers can partially counter rollover forces in severe crosswinds. On the other hand, the skirts may also route additional air flow over the top of the trailer creating slight lift forces as the roof edge can act a bit like an airplane's wing. The net results are likely offsetting. Boat tails add surface area at the rear of the trailers, and in severe crosswinds this may slightly increase side forces resulting in an additional tendency for trailer off-tracking. In headwinds or tailwinds, the underbody and rear devices may help the tractor-trailer maintain its lane better than a non-aero equipped trailer. Conversely, in severe crosswinds, the trailer aerodynamic devices may make the vehicle more sensitive to gusts. Anecdotal driver feedback is that aerodynamically equipped trailers are generally more stable requiring less lane correcting.

4.3 Splash & Spray Reduction

Aerodynamic device equipped trailers reduce drag by improving air flow around the vehicle, which also helps to reduce splash and spray. Passenger vehicles passing trailers in rain have perhaps the best first-hand perspective on whether trailer aero devices reduce splash and spray, but there are no clear measurement systems. A peer reviewed 2003 study prepared for the AAA Foundation for Traffic Safety concluded: “An improvement in the aerodynamics of a tractor-trailer configuration can significantly reduce the amount of spray generated by large trucks in wet weather.” A September 2015 article in *Heavy Duty Trucking* discusses that likewise *TMC’s Recommended Practice (RP) 759, Splash and Spray Suppression Guidelines*, stated that: “for regular box vans and refrigerated trailers, the main generators of spray are the landing gear, rear axle, suspension, tires and mud flaps, the RP notes.” [15, 16, 17] All of these are areas of high aerodynamic drag, so both drag and spray will be mitigated by adding aerodynamic devices. The RP concluded that: “taking steps to improve the aerodynamics of any trailer can significantly cut the volume of road spray generated by a Class 8 tractor-trailer.”

4.4 Driver Fatigue Reduction

Anecdotal feedback from drivers suggests that trailers equipped with aerodynamic devices are generally less taxing and maintain their lane with less frequent steering correction by the driver. Several drivers contacted by NACFE confirmed that aerodynamic-equipped trailers were more stable in most situations, and one fleet volunteered, “some of their drivers prefer the stability of the trailers with aero devices.” Another contributor to driver fatigue is ambient noise level. Anecdotal feedback is that the more aerodynamic tractors tend to have lower interior noise levels.

5 Challenges of Trailer Aerodynamic Technology Adoption

The challenges of integrating trailer aerodynamic technologies into fleets operations include:

- Added weight
- Complicated methods for testing device performance and difficulty in comparing between them
- Confusion between precision and accuracy, and the impossibility of obtaining accuracy in aerodynamics testing
- Variance among aerodynamic device manufacturer information
- The need to optimize tractor-trailer ratios
- Questions of device reliability and/or durability
- Other minor concerns

5.1 Added Weight

Aerodynamic improvement for today’s dry van and refrigerated trailers involves adding on fairings, which means adding tare weight.

In its *Confidence Report on Lightweighting*, NACFE found that over the next 5-10 years, denser freight will be requested by shippers in each load (Figure 23), and the all segments of the industry should expect to gross out (reach their maximum weight) more frequently. [4, 18, 41]

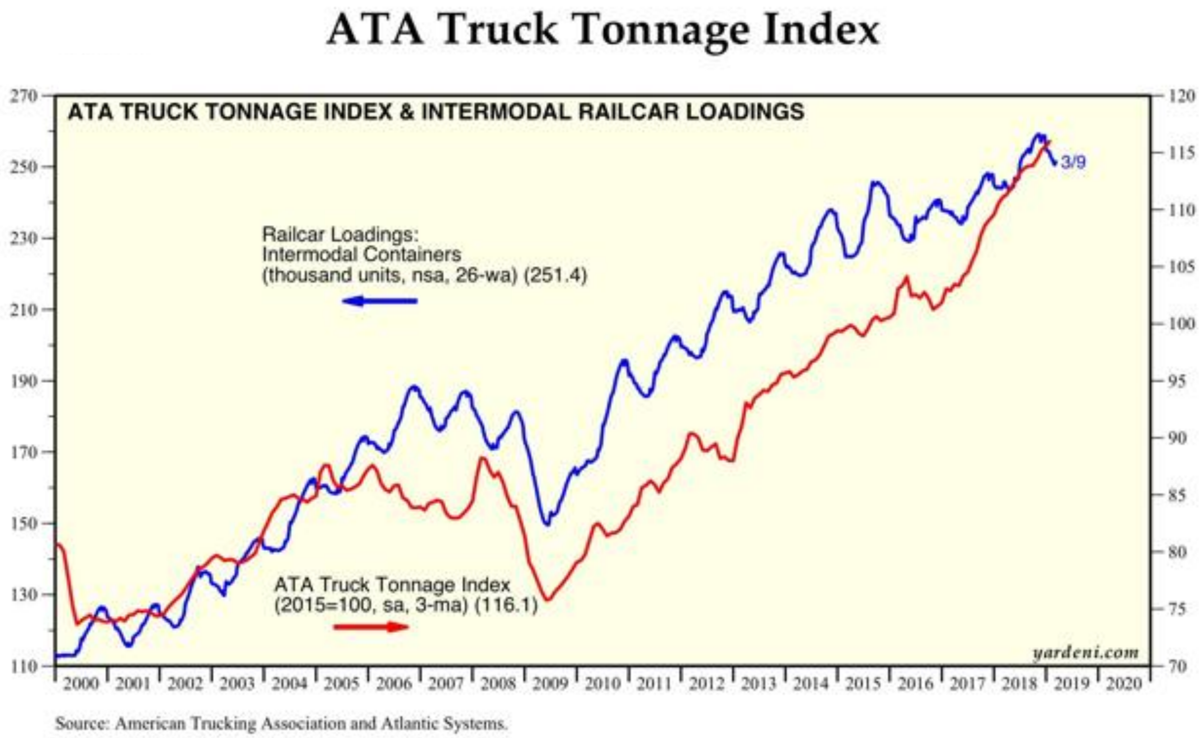


Figure 23: Tonnage per Load (ATA and Atlantic Systems)

As trailer aerodynamic devices also add weight the critical trade-off between aerodynamic performance improvement and increasing tare weight will depend on the weight-sensitivity of the fleet in question. It is important to keep in mind that weight's impact on fuel economy is just 0.5% - 0.6% per 1,000 lbs. of weight, and even the most aggressive/comprehensive suite of aerodynamic fairings for trailers today adds less than 2,000 lbs. while offering up to 9% fuel savings (but only sacrifice about 1% from the added weight). Even fleets that are highly weight sensitive may see overall fuel savings from a combination of trailer aerodynamic and lightweight technologies.

Another reason for this is that aerodynamic improvement devices can result in performance gains that allow for downsizing other systems on the vehicle. The Peterbilt/Cummins SuperTruck, for example, was able to "right-size" its tractor fuel tanks as a result of the improvements from aerodynamics, allowing a reduction in on-board fuel weight and tank size to cover the same distances and freight loads. That program also showed that switching to a higher aluminum content production trailer, and switching to aluminum single wheels from steel duals, could provide weight reductions to offset the addition of the aerodynamic devices. While there are generally additional costs associated with these options, and payback may vary with fuel costs, this goes to show that it would be a mistake to assume that aerodynamics will necessarily result in tare weight increases.

Additionally, aerodynamic improvement in some areas of a tractor-trailer can be accomplished by combining the aerodynamic functions with other functions, reducing the weight impact of the aerodynamics alone. An example is the integral sleeper roof which effectively replaced the separate add-on aerodynamic roof fairing as illustrated in Figure 24. This combined the benefits of greater headroom in the sleeper with better aerodynamics. Similar integrations have occurred with the shaping of hoods, bumpers and mirrors so that secondary add-ons, and the weight they entail, are no longer required.

Integration of aerodynamic functions with other functions on trailers is a future trailer design opportunity area as aerodynamic devices become standard.

Figure 24: Aero Design Integration from Discrete Fairing and Sleeper to Integral Aero Sleeper

The following two case studies help to put the potential trade-offs between aerodynamics and weight in perspective.

5.1.1 Hypothetical Case Study: Beverage Hauler

The hypothetical example illustrated in Figure 25 is of a beverage hauler operating at the maximum 80,000 GVWR, that therefore would need to reduce its load of beverages to add 500 lbs. of trailer skirt fairings. This case assumes the fleet's average fuel economy (before adding skirts) is 7 MPG, and average fuel price is $2.50/gallon. Those trailer skirt fairings are estimated to save 6% on fuel when driving at highway speeds the whole route. If the fleet travels a route from Denver to Dallas, approximately 800 miles, and assuming it can stay at highway speeds the entire route, then the new trailer skirts would save $16.17 in fuel on one run. However, the paying freight load was reduced by 500 lbs., say, from 45,000 lbs.to 44,500 lbs. At a freight rate of $1.75/mi the fleet would lose $15.73 in paid freight per run.

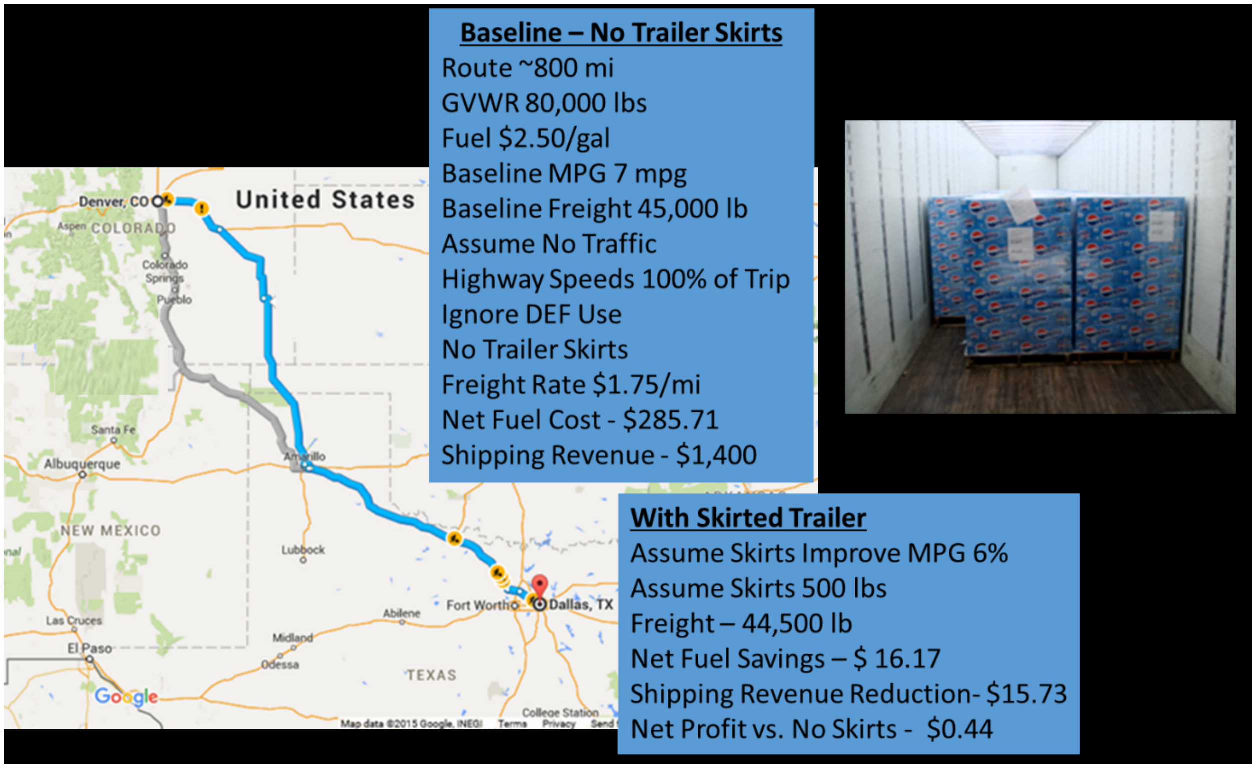


Figure 25: Beverage Hauler Aero vs. Weight Evaluation

Extrapolated over a year of operations, averaging 130,000 miles traveled, 162 trips between Denver and Dallas, ignoring deadheading and assuming this was a typical run, this translates to the trailer skirts saving $2,620 in fuel costs, but the reduction in paid freight income equally $2,556, for a net annual savings of just $64 (and industry-wide, a likely increase in fuel use, as those beverages would still need to be hauled on a truck somehow).

This shows that this beverage hauler would need to find other tare weight reductions to offset the weight of the trailer skirts, perhaps by choosing a lighter-weight aluminum trailer, and/or moving to wide base tires with aluminum wheels. Investing in such a suite of fuel efficient technologies on the trailer could net this hypothetical beverage hauler cost-effective fuel economy increases without sacrificing paid freight capacity.

5.1.2 Hypothetical Case Study: Furniture Hauler

The hypothetical example illustrated in Figure 26 is of a furniture hauler operating at 65,000 GVWR, that cubes out before it grosses out given the size of the load. In this case, the addition of the aerodynamic skirts does not alter the amount of paid freight carried; it only adds net weight to the vehicle. Taking the same route hauling the 800 miles from Denver to Dallas, the operator's typical fuel economy is instead 7.07 MPG (increased 0.07 MPG because of the 14,000 lb. lighter freight load of 31,000 lbs.) With the 500 lbs. of trailer skirts, total GVWR goes to 65,500 lbs. This added weight reduces fuel economy by 0.25%, but the new trailer skirts improve it by 6%, giving a net fuel economy improvement of 5.75%, and a net improvement in fuel cost of $15.38 per trip.

Figure 26: Furniture Hauler Aero vs. Weight Evaluation

Expanding this to a year's operation of 130,000 miles broken into 162 trips, again with the same qualifiers of no deadheading and assuming all trips are the same, the furniture hauler's net annual savings would be $2,492.

In sum, adding trailer skirts saved the beverage hauler just $64 in fuel costs for the year, compared to the $2,492 saved by the furniture hauler. This illustrates how weight and aerodynamics are inseparable when making decisions on how to configure trailers. A weight-conscious fleet will need to find additional significant weight savings in the trailer body to rationalize also adding the trailer skirts. But less weight-sensitive fleets, like the furniture hauler, can realize substantial paybacks with an aerodynamic device like trailer skirts from day one.

5.2 Aerodynamic Technology Test & Analysis Methods

There are many published methods and references for testing or analyzing aerodynamics technology for tractor-trailer configurations. [20, 21, 23, 24 25,, 26, 27, 28, 39, 40] The fact that there is such multitude of testing methods, each with unique contexts and applications, makes comparing between them on paper challenging and confusing, and extrapolating their findings to the real world even more so. Fleets need to feel confident in how a technology will perform in their operations, in order to be assured that they will enjoy a payback that covers the cost of adopting new technologies. But, especially for aerodynamic technologies, given the hundreds of interrelated factors which will determine their ultimate performance, it can be hard to know which test data is most relevant to a fleet, and how closely test findings will match real world performance.

The NACFE *Determining Efficiency Report* discusses these methods in detail. The report identifies key factors to consider in reviewing test information, comparing results between methods and in expanding those results to real world experience. [12]

Each of the methods for estimating aerodynamic drag can and typically do produce different results for a vehicle as illustrated in Figure 27 from the 2013 SAE COMVEC Plenary presentation on *Heavy Duty Tractor/Trailer Aerodynamic Testing Technology*. Each method will have its own precision value with respect to the specific test procedure. The relevance of that specific test procedure with respect to estimating the specific real-world operational values may not be known.

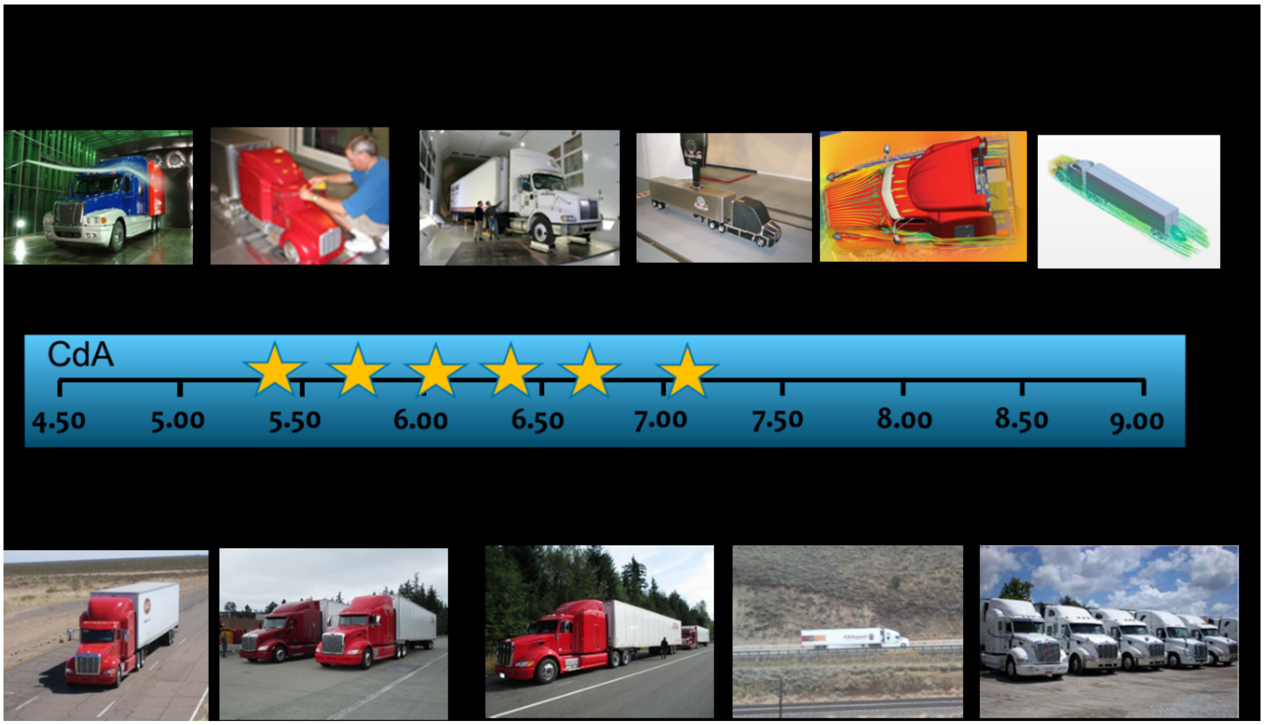


Figure 27: Aerodynamic Evaluation Has Many Different Methods Producing Different Results

The EPA documented one example of this in the *Regulatory Impact Analysis for the Phase I Greenhouse Gas Rules.* They attempted to pick a particular tractor-trailer configuration and evaluate it using coast down testing, various scale models in wind tunnels (including a full scale one), and with different Computational Fluid Dynamics analyses. [24, 25, 39, 40] One of the immediate challenges is that each of these approaches is actually measuring different metrics in different ways. So, while they are attempting to arrive at the same value, they are not measuring the same thing. But all the methods can arrive at an estimate of CdA (Coefficient of Drag x Area) for what was evaluated. EPA published this comparison of results shown in Figure 28.

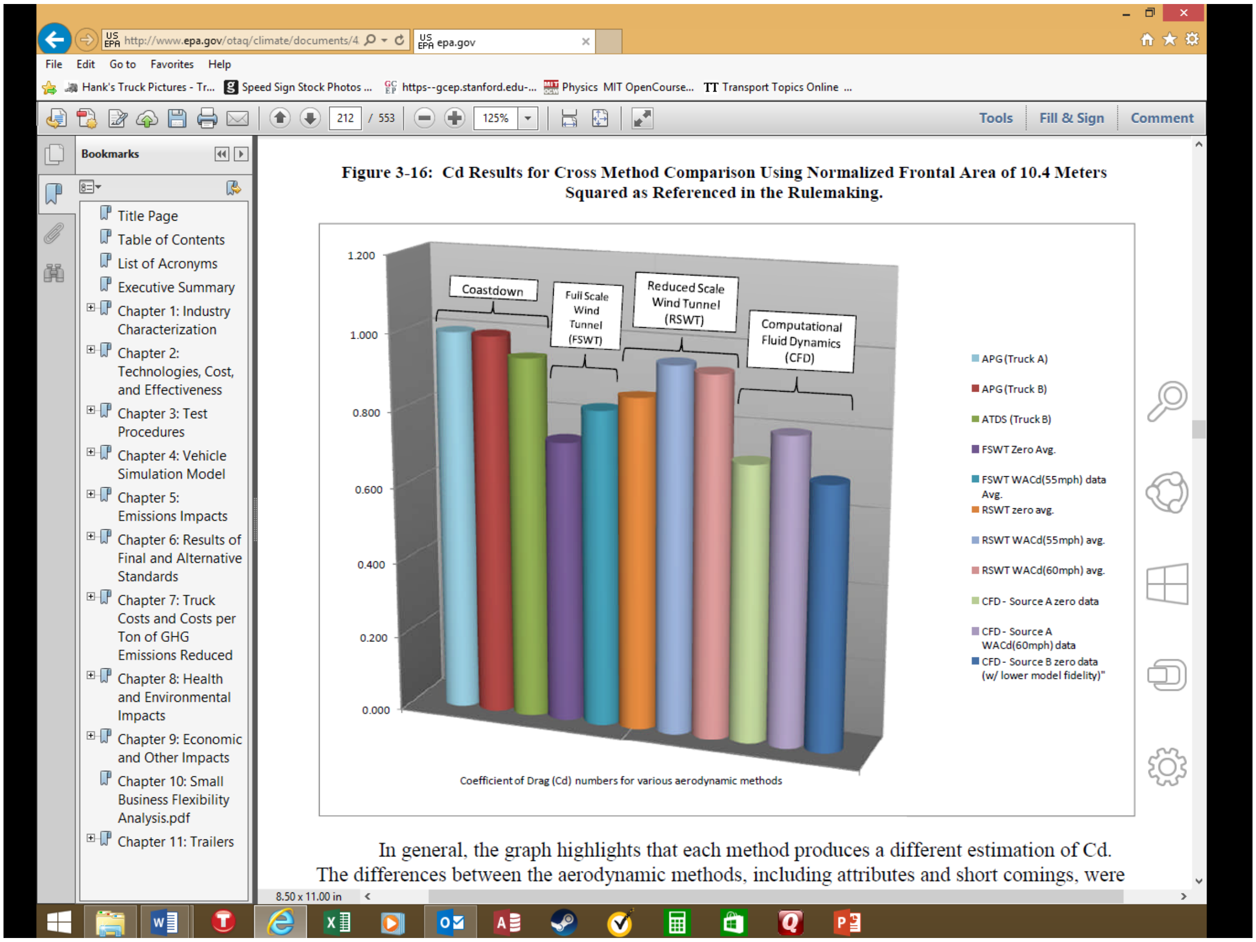


Figure 28: EPA Aero Evaluation Comparisons from GHG Phase I RIA

Each test method was done with an appropriate level of integrity and attention to detail, and for each method, some level of precision was obtained. This highlights that each method used correctly can and will provide different results for what is considered the same vehicle.

As tools, all these methods have their usefulness, and some are more appropriate at different times in the development of a tractor-trailer configuration. Their utility is really in making comparisons such as “is this new design better than that old design?” These are termed A-to-B comparisons.

What fleets considering trailer aerodynamics need to know is that every test and analysis methodology is some abstraction of the real world, because modeling and controlling the real world are very difficult. Each method has some degree of simplifying assumptions or an artificially controlled environment built into it, so that results can be repeatability obtained (i.e. “precise”). For example, wind tunnels eliminate natural and unpredictable crosswind conditions by testing inside of a controlled space. In other testing methods, the actual measured data is not aero drag force, but rather fuel consumption weight or volume, or road load based on vehicle deceleration rate data, and from these data points the aero drag force is estimated by being “backed into” from what is left over when all the other factors are estimated.

For reference, a short list of some of the more relevant aerodynamic testing methods is provided here. Note that each of these methods can spawn various permutations, as end users often must make simplifying assumptions or other engineering judgment calls on test configurations or environmental constraints to obtain adequate statistical precision.

- SAE J1321 Fuel Consumption Test Procedure Type II
- SAE J1526 Fuel Consumption In-Service Test Procedure Type III
- SAE J2971 Aerodynamic Device and Concept Terminology
- SAE J2978 Road Load Measurement Using Coastdown
- SAE J2966 Guidelines for Aero Assessment Using CFD
- SAE J1252 Wind Tunnel Test Procedure for Trucks & Buses
- SAE J3015 Reynolds Number Simulation Guidelines and Methods
- SAE J1264 Fuel Consumption Test Procedure Type I
- SAE J3156 Constant Speed Test Procedure for Trucks & Buses
- SAE J1263 Road Load Measurement Using Coastdown
- SAE J2263 Road Load Measurement Using Anemometry and Coastdown
- EPA Phase II Road Load Measurement Using Constant Speed Torque
- EPA Phase II Coastdown Test procedure
- EPA Phase II CFD Analysis methodology
- EPA Phase II Wind Tunnel Test Methodology
- TMC RP1102A Type II Fuel Consumption
- TMC RP1109B Type IV Fuel Consumption
- TMC RP 1103A In-Service Fuel Consumption Type III Test Procedure
- TMC RP1106A Evaluating Diesel Fuel Additives for Commercial Vehicles
- TMC RP1111B Relationships Truck Components & Fuel Economy
- TMC RP1118 Fuel Savings Calculator for Aerodynamic Devices
- TMC RP1114 Driver Effects on Fuel Economy
- TMC RP1115 Guidelines for Qualifying Products Claiming a Fuel Economy Benefit
- EPA/NHTSA 40 CFR§1037.521 GHG Phase I Revised Coastdown
- EPA/NHTSA 40 CFR§1037.521 GHG Phase I CFD
- EPA/NHTSA 40 CFR§1037.521 GHG Phase I Wind Tunnel
- CARB Wind Tunnel Test Procedure
- Others

Additionally, qualitative assessment methods exist, such as high-level fleet operation's reporting of fleet or individual vehicle fuel economy (miles driven vs. fuel gallons purchased), or the dashboard feedback on fuel economy gauges, or engine data downloads. [20, 21, 23, 24, 25, 26, 27, 28, 39, 40]

5.3 Precision vs. Accuracy

A fundamental point of confusion in interpreting the testing data of efficiency technologies (and in industry publications generally), is that the terms "accuracy" and "precision" are often used interchangeably with respect to reported results, when in fact these are two quite different metrics. [12, 30]

Precision is the ability to repeat a test or analysis and get the same result; it is a measure of the statistical spread of repeated results from the same exact test or analysis, and is typically represented as a bell curve, as shown in Figure 29. Fleets place a value on the precision of performance results, and should use the uncertainty values given to compare the results of multiple different tests. For example, if Test 1 has a value of 0.5 ± 0.15, and Test 2 has a value of 0.75 ± 0.15, the precision difference between these values would be 0.25 ± 0.30.

Meanwhile accuracy, also called "bias," refers to how closely a test value matches the "true" real world value. So, for example, since the real-world value of the aerodynamic drag factors of a truck is unknown, the "accuracy" of any testing method is likewise unknown. Since the absolute value of the aerodynamic drag coefficient of a vehicle is not known, any evaluation methods, even those that have received extensive scrutiny and improvement over the last decade, will necessarily be an estimate with respect to the real world. Measuring the specific aerodynamic drag of a tractor-trailer has required significant controls, assumptions and simplifications, and often the measurement systems themselves introduce further variations in results. Figure 29 shows accuracy (bias) as the difference between the test result and the true reference value. [12]

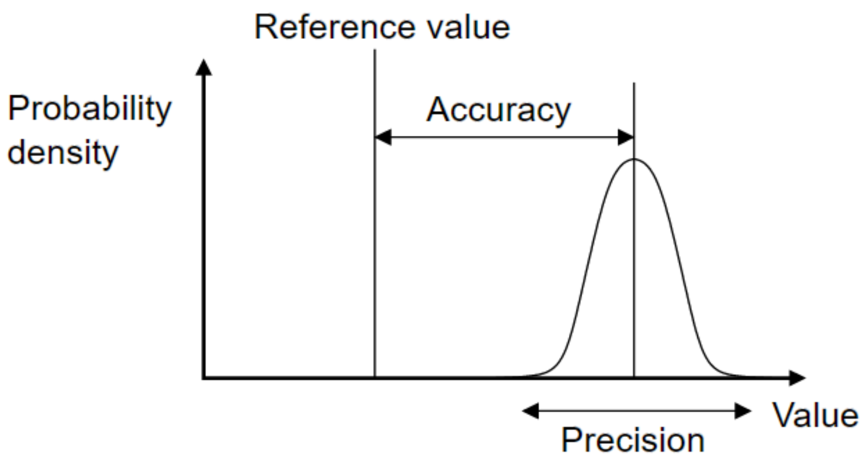


Figure 29: Precision vs. Accuracy

Why is accuracy often so difficult to measure? That is, why is the real-world reference value so often unknown? Because all measurement systems require a standard reference system, but there is no standard reference vehicle for aerodynamics or other efficiency technologies. An easy corollary from everyday experience is color — all of the sample swatches in Figure 30 are clearly different colors, yet could be described as "green," even, for some color blind people, the one on the right which most would describe as brown or yellow. [12]

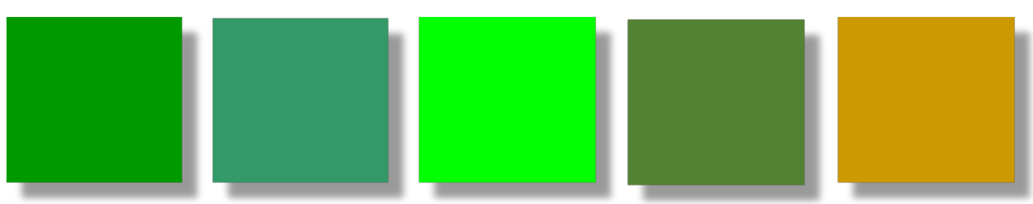


Figure 30: Different examples of Green

To add accuracy to any measurements of color, a method that describes color based on the wavelength of the light is used (Figure 31). In this system of reference values, each of the "green" swatches shown would have a specific and accurate wavelength that could be used to refer to it.

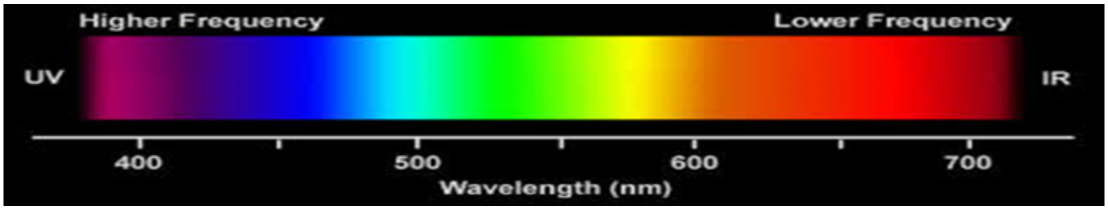


Figure 31: Colors Accurately Differentiated As Specific Wave Lengths of Light

Another example of an accurate absolute reference is a common tape measure or ruler. An inch or centimeter will be the same on every device, and if it is not, it can be easily deemed inaccurate, and by what degree. The accuracy of every length was once evaluated as compared to a specific platinum bar ruler stored in Paris, but is now defined internationally with respect to a particular accurately determined wavelength of light. [12]

5.4 Impact of Real-World Factors and Impossibility of Accuracy of Aerodynamics Testing

A key thing for fleets to understand is that no one can currently measure the actual absolute value of the reference vehicle for any tests of aerodynamics, so accuracy will never be obtained the way it could be with the examples of time or color in the previous section.

Instead, engineers calculate aerodynamic drag forces using this equation:

$$D = C_d \rho A V^2/2$$

Where D is the aerodynamic drag force, Cd is the dimensionless drag coefficient, ρ is the density of the air, A is the vehicle cross sectional reference area and V is the relative vehicle velocity, which must be squared, then divided by two. The velocity value includes both vehicle speed and atmospheric wind effects like crosswinds. [31]

A way to visualize aerodynamic drag is that as truck speed increases, so does the air pressure in the space into which it is being forced. Proportionately lower pressure exists behind the truck, creating a space that is vacuum-like in comparison.

However, air density is significantly affected by temperature and altitude; colder air is more dense, and higher altitude air is less dense. Many test methods try to limit test conditions to standard atmospheric conditions at sea level and at a nominal warm temperature. Others attempt to correct actual test data back to these conditions. But since not all evaluations are done at sea level and in the real world, these values vary from day to day and location to location. The difference in reported drag coefficient between a winter test at a facility in Arizona versus standard atmospheric conditions can exceed 0.5% just from altitude and temperature differences. End users of aerodynamic evaluation data should take care to understand what conditions are being reported in the evaluations.

The reference area, A, is likewise somewhat arbitrarily selected as a common factor in aerodynamic comparisons. One specific area used in evaluations is the width-based reference area value. A way to visualize this is that it is the area of the shadow a vehicle would make on a wall directly behind the vehicle if the light were projecting from directly ahead of the vehicle. (See Figure 32.) These values can differ. For example, a tractor pulling standard van trailers would differ from those pulling flat beds. Even for the same configuration, different sources may assign significantly differing values for area. The Phase I EPA Greenhouse Gas GEM emissions final modeling tool assigned a frontal area of 10.4 m2 to all high roof sleeper tractors with standard van trailers. [32] This value was revised by the EPA from an initial draft proposed value of 9.8 m^2. Computer analysis of one typical production tractor and trailer by an OEM showed this value was 10.6 m^2. The original EPA proposal resulted in drag coefficient difference greater than 8%. The final published value differs by nearly 2% for that one vehicle. Valid aerodynamic comparisons between different vehicles require the vehicles to have the same reference areas. Differences in defining area and vehicle changes that alter areas can confuse and complicate aerodynamic comparisons.

Figure 32: Width Based Reference Area for a Navistar ProStar with Van Trailer

It is not appropriate to directly compare aerodynamic drag factors where there are significant differences between vehicle geometries. So, for example, aerodynamic comparisons of double trailers to singles, day cabs to sleeper cabs, straight trucks to tractor-trailers, etc. all require extra detail and effort.

While the cross-sectional areas may appear similar, the lengths are substantially different. Similarly, aerodynamic comparisons between full-scale vehicles and sub-scale models are not consistent unless they are appropriately similar; meeting what is called geometric similitude. Care must be taken when the geometries being tested differ from the expected full-scale vehicle.

Rearranging the drag force equation gives one for the dimensionless drag coefficient.

$$C_d = \frac{\rho\ A\ V^2/2}{D}$$

Again, the math highlights that drag coefficient depends on air density, which depends on temperature and pressure, which vary by altitude, seasons and location. Drag coefficient is much affected by vehicle relative velocity, which includes ambient winds, crosswinds and other aerodynamic factors in addition to vehicle speed. Choice of reference area also determines reported drag coefficients. The drag force is estimated from measurements and is very dependent on the evaluation method. These differences will be discussed in subsequent sections of this Confidence Report.

The equation for aerodynamic drag force, and the rearrangement for drag coefficient should highlight that aerodynamic drag is always a factor when a vehicle is in motion. However, the shades of real-world differences accumulate and can be significant. What is needed in the future is an industry agreement on an absolute reference vehicle and a concerted effort by all to correlate each method to this absolute standard, along with continuous improvement and refinement of measurement methods to better match real world conditions. We are not there now, but innovation is constantly in process and we may get there in the next decade.

5.5 Variance among Aerodynamic Device Manufacturer Information

The NACFE research into trailer aerodynamic devices highlighted that the available information published by the device manufacturers varies greatly in content, format, and detail. The lack of uniform information on aerodynamic devices makes it difficult for fleets to make comparisons. In preparing the aerodynamic Confidence Reports over the years, NACFE attempted to survey as many of the manufacturers listed for trailer aerodynamic devices on EPA's SmartWay Verified Devices website. We requested from them what we consider to be a minimum amount of information on the supplier's device and company. [48]

NACFE recommends that customers request the same information from their aerodynamic device suppliers when performing their own evaluations. To this end, NACFE has provided a form as an example of what NACFE believes is the minimum a customer should request and be provided by an aerodynamic device supplier. (See Trailer Aerodynamic Device Requested Information Form on the next page).

Fleet owners and operators may want additional information in order to clarify the specifics of the tested vehicle configurations. These factors would include the specific vehicles used in the evaluations as follows:

- Specific tractor make, model and option content used in the evaluations
- Specific trailer make, model and option content used in the evaluations

Additionally, fleets may wish to request details of the specific test method, facilities and details of the evaluation conditions or assumptions such as average wind conditions, peak gusts, temperature, and altitude of test. Some suppliers provide this in the form of test reports and may have links to this information on their websites.

Trailer Aerodynamic Device Requested Information Form

EPA Officially Listed Device Name: ________________________

Alternative Device Names Used by the Manufacturer: _____________________________

EPA SmartWay Verified Aerodynamic Device Listed Category (shown below):

- 9% Elite Combination: __
- 5% Trailer Under Device: __
- 5% Trailer Rear Fairing: __
- 5% Other Trailer Device: __
- 4% Trailer Under Fairing: __
- 4% Trailer Rear Fairing: __
- 4% Trailer Other Device: __
- 1% Trailer Under Fairing: __
- 1% Trailer Rear Fairing: __
- 1% Other Trailer Device: __
- Not Listed by EPA Yet: __
- EPA Archived SmartWay Device: __

EPA SmartWay Verified Trailer Aerodynamic Device Listed Verification Method(s) (shown below):

- SmartWay Verifications Pre-2014: __
- Wind Tunnel (2014) Method: __
- Coastdown (2014): __
- SmartWay Track Test (2014): __
- CFD (Supplement): __

Indicate Any Other Test Methods Used and Mile-Per-Gallon Improvement Estimated

- Wind Tunnel: ___________________________
- Computation Fluid Dynamics (CFD) Analysis: ___________________________
- Track Test: ___________________________
- Fleet Testing: ___________________________

Trailer Aerodynamic Device Information

- Installed Weight for one trailer set (lbs): ___________________________
- Retail Cost to equip one trailer ($ USD): ___________________________
- Installation Labor (man-hours): ___________________________
- Estimated Annual Maintenance Cost ($ USD): ___________________________
- Standard Warranty Coverage: ___________________________
- Primary Materials Used: ___________________________

Include web link address to a publicly available photo or brochure on the specific device:

5.6 Trailer-Tractor Ratio and Trailer Aerodynamics

The investment decision of whether or not to adopt trailer aerodynamic devices is impacted directly by two key factors: the fleet's trailer-tractor ratio and the fleet's deadheading ratio. The first relates to how many miles a given trailer aero device will see in a period, while the second relates to how many of those miles actually are traveled while carrying freight. Note that these two qualifiers may be absent in reporting of individual technology performance estimates, but fleets will need to account for them.

The national industry-wide trailer-tractor ratio is reported by the Truck Trailer Manufacturers Association (TTMA). The average ratio reported in the last few years has varied between two and four trailers for each tractor, but that average hides the fact that some fleets operate with ratios of 1.5 to 1, and others may have 9 to 1. A review of the top 100 for-hire fleets by Transport Topics shows an average of 2.6 for fleets. (See Figure 33.) The average for the top 25 of those fleet is higher at 3.0, the national assumption. In summary, the industry-wide average is not important, what will matter for estimating fuel savings is the ratio of each individual fleet.

2019 Transport Topic Top 100 For-Hire Carriers				
2019 Rank		**Tractors**	**Trailers**	**Trailer-to-Tractor Ratio**
	Total Average of Top 100	**390,969**	**1,030,543**	**2.6**
1	UPS Inc.	19,732	106,481	5.4
2	FedEx Corp.	29,813	113,218	3.8
3	XPO Logistics	14,438	25,689	1.8
4	J.B.Hunt Transport Services Inc.	15,808	33,510	2.1
5	Knight-Swift Transportation Holdings	19,156	69,544	3.6
6	YRC Worldwide	14,100	45,000	3.2
7	Schneider	13,700	37,800	2.8
8	Landstar System	10,599	16,743	1.6
9	Old Dominion Freight Line Inc.	9,254	35,729	3.9
10	TFI International	15,992	26,487	1.7
11	Hub Group	3,800	5,000	1.3
12	Estes Express Lines	7,569	29,519	3.9
13	ArcBest	4,273	22,680	5.3
14	Werner Enterprises Inc.	7,860	25,255	3.2
15	Penske Logistics	3,491	10,162	2.9
16	Roadrunner Transportation Systems	3,422	5,563	1.6
17	Prime Inc.	7,226	13,524	1.9
18	NFI	4,000	9,700	2.4
19	U.S. Xpress Enterprises	6,909	16,000	2.3
20	Daseke Inc.	6,144	13,824	2.3
21	UniGroup Inc.	5,022	5,607	1.1
22	R+L Carriers	5,084	15,675	3.1
23	CRST International	6,052	14,077	2.3
24	Saia Inc.	4,834	15,483	3.2
25	C.R. England Inc.	4,287	6,494	1.5

Figure 33: 2019 Transport Topic Top 100 For-Hire Carriers

The tractor-trailer ratio will indicate the trailers actual annual mileage and the return on investment from the adoption of trailer aerodynamics. Aerodynamic trailers that do not move do not offer improved performance or fuel savings. One large fleet contacted by NACFE for this Confidence

Report calculates their ROI for trailers in “miles to payback” rather than months, noting that some of their trailers see an average of only 24,000 miles per year while their tractors see 115,000 to 130,000 miles per year.

A hypothetical fleet that averages four trailers for every tractor, means each trailer, on average, will see one-quarter of the highway miles seen by the tractor. This in turn means that in order to obtain the SmartWay advertised 9% improvement in trailer-tractor highway fuel economy performance for a single tractor operated entirely at highway speeds, the fleet must buy four sets of aerodynamic trailer skirts and boat tails for each tractor. This information can be translated to an ROI curve with respect to installing trailer aero devices linked directly to the tractor-trailer ratio (Figure 34).

Figure 34: Trailer Aero ROI Depends On Trailer/Tractor Ratio

Fleets that operate refrigerated trailers generally have lower trailer-tractor ratios, perhaps 1.25. However, these trailers can be more complicated with side doors and access ramp requirements, plus the additional equipment required for the refrigeration system. But if these units do see a significant amount of highway miles, the refrigerated fleet can still realize a swifter return on investment from trailer aerodynamic devices than a van fleet that might average a trailer-tractor ratio of four.

Deadheading, driving without any freight, is another significant qualifier on the fuel efficiency gains offered by trailer aerodynamic devices. The amount of deadheading at each fleet is sensitive information, but some publicly available information such as SEC Form 10-K data puts averages around 13% of driven miles, though each fleet will differ. This is where fleets may consider viewing performance in terms of freight efficiency as much more meaningful than looking at simply fuel economy, as trailers that haul no freight have zero freight efficiency.

A company that has a high percentage of deadheading overall should have higher fuel economy than an equivalent fleet that has a lower deadheading percentage, because moving freight requires more fuel than driving empty. Freight efficiency, however, directly includes the amount of freight along with the fuel economy to give freight tons per mile. The lower deadheading fleet would show higher net freight efficiency. This freight efficiency factor also addresses loaded trailer efficiency factors where one fleet may average 65,000 lbs. gross vehicle weight per trip while another averages 80,000 lbs. GVWR. However, Confidence Reports focus on fuel efficiency, as this figure will be more constant for a given vehicle, rather than varying highly from fleet to fleet.

The trailer-tractor ratio and the deadheading percentage are two significant business qualifiers to estimating the effectiveness of freight and fuel efficiency improvement technologies. End users of performance evaluation data need to factor in data from their own operations when calculating the return on investment for these technologies, and likely should focus on freight efficiency metrics.

5.7 Reliability and Durability

The SmartWay program does not specifically address structural requirements for trailer aerodynamic devices, for example, there are no specific minimum loads or stress cycles, durability, etc. In addition, the Phase I Greenhouse Gas regulations do not apply to trailers, while the Phase II include trailers and installed aero devices and require that they "meet emission standards over the expected service life of the vehicles." Although Phase II is being challenged in court, various state and federal road safety requirements do require proper maintenance and safe operation, as described by DOT Federal Motor Carrier Safety Administration (FMCSA) regulations.

Title 49 CFR§ 396.7: Unsafe operations forbidden.

- General. A motor vehicle shall not be operated in such a condition as to likely cause an accident or a breakdown of the vehicle.
- Exemption. Any motor vehicle discovered to be in an unsafe condition while being operated on the highway may be continued in operation only to the nearest place where repairs can safely be affected. Such operation shall be conducted only if it is less hazardous to the public than to permit the vehicle to remain on the highway.

However, while not specifically defined in current U.S. regulations, aerodynamic device structural integrity is hugely important to both device providers and fleets considering adoption. The safe operation of commercial vehicles requires that aerodynamic devices be robust enough to survive normal daily operations and should be subject to regular driver inspection and other audits. To save both time and money, the industry prefers lower maintenance and repair requirements; aerodynamic devices must be as robust as other vehicle systems. Future emissions regulations linked to trailers will likely reinforce that aerodynamic trailer devices be properly maintained for the service life of the vehicle. European regulations on pedestrian underride protection may also influence future U.S. rulemaking.

5.8 Tire and Brake Temperatures and Aerodynamic Devices

Brakes and tires are cooled by a combination of convection, radiation and conduction. Aerodynamic devices can modify the air flow over the brakes and tires resulting in slightly higher operating temperatures. EPA track tests have seen wheel hub temperatures increase 10-15° F on trailers with skirts installed compared to non-skirted trailers. While 10-15 degrees may sound like a lot, a University of Michigan Transportation Institute study, *The Influence of Braking Strategy on Brake Temperatures in Mountain Descents*, documented brake temperatures on a non-aerodynamically equipped 80,000 lbs. GVWR tractor-trailer as reaching 350°F to 500° F while descending a long grade and pulsing the brakes. At such high temperatures and with such a wide range the addition of skirts actually has a small impact overall. Still, a 2012 National Research Council Canada study, *Review of Aerodynamic Drag Reduction Devices for Heavy Trucks and Buses*, offered advice for the adoption of wheel covers, saying that it is necessary to evaluate the effect on brake cooling "to ensure they do not restrict air flow to the brakes" – this is likely relevant for any aerodynamic treatments to the trailer. [13]

6 Trailer Aerodynamic Technologies

There are three primary "areas of opportunity" to address aerodynamic drag on a trailer, as shown in Figure 35 and as outlined by the EPA in Figure 36. They are at the front of the trailer, at the underside of the trailer, and at the back of the trailer. In some cases, there is also small space for devices to go on the sides and the roof, and there are also aerodynamic devices for wheel ends. Underbody devices are generally described as "fairings," which refers to any aerodynamically shaped surface. The general industry prioritizes adding trailer aerodynamic devices on the underbody, followed by the rear, followed by the gap, based on observation of on-highway use and discussions with manufacturers and fleets. [22]

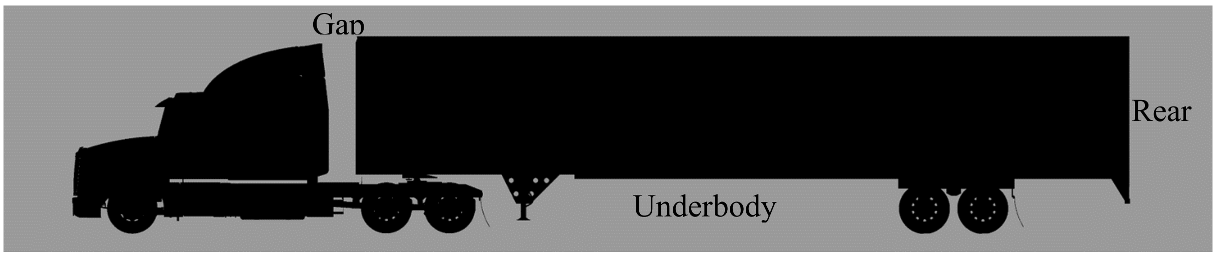


Figure 35: Three Primary Aerodynamic Opportunity Areas

LOCATION ON TRAILER	EXAMPLE TECHNOLOGIES	INTENDED IMPACT ON AERODYNAMICS
Front	Front fairings and gap-reducing fairings	Reduce cross-flow through gap and smoothly transition airflow from tractor to the trailer
Rear	Rear fairings, boat tails and flow diffusers	Reduce pressure drag induced by the trailer wake
Underside	Side fairings and skirts, and underbody devices	Manage flow of air underneath the trailer to reduce turbulence, eddies and wake

Figure 36: EPA's Description of Primary Trailer Aerodynamic Technologies

6.1 Devices to Prevent Under Trailer Aero Drag

Air flowing under the trailer body decreases fuel economy. However, aerodynamic drag under the trailer is complicated especially when ambient winds are not aligned with the tractor and trailer.

Aerodynamic trailer devices will not be beneficial in every single situation. The goal of adoption is that they will provide a net benefit over the course of all of the vehicle's operational conditions. That implies that statistics are involved to predict expected performance which in reality will continually vary. This is perhaps most easily understood by looking at what aerodynamicists call a yaw curve, a wishbone shaped graph showing drag as a function of wind angle. The example shown in Figure 37 is from a 2004 historical overview by Kevin Cooper of the National Research Council of Canada, *Commercial Vehicle Aerodynamic Drag Reduction Historical Perspective as a Guide*. The graph plots drag coefficient versus the yaw angle of the vehicle into the wind. In the wind tunnel, this is done by rotating the vehicle on a platen as shown in the photograph. Each wishbone curve represents the drag coefficient at each wind angle for different configuration of devices. [33, 34]

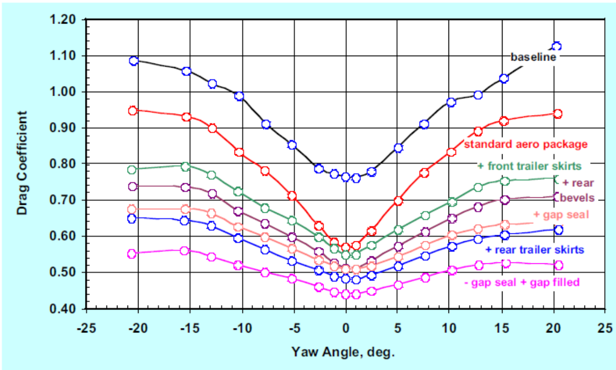


Fig. 8: Low-drag Development of the NRC Tractor-trailer

Figure 37: Drag Varies by Wind Yaw Angle (NRC)

The variability of actual wind speeds and angles is unpredictable, but over time, weather measurements can be averaged to come up with a way to approximate and estimate average conditions. Aerodynamicists report results as Wind Averaged, which usually means they have taken nationally averaged wind conditions and applied a probabilistic weighting to each drag value at each angle to come up with an average estimated drag coefficient. Details on this can be found in SAE J1252 and background on it is discussed in a 1988 report by Kenworth and published by SAE titled *Heavy Duty Truck Aerodynamics*, report SP-688 (see also SAE 87001). [25]

6.1.1 Skirts

Trailer skirts are the most popular devices for addressing aerodynamic drag in the underbody. While some argument can be made that various rear devices may offer fuel savings equivalent to those of some underbody systems, the underbody systems are perceived by fleets and drivers as having fewer challenges in operational environments, since they are not “in the way” of moving freight in and out of the dry van trailer. This is not necessarily the case with some compartmentalized refrigerated trailers with side access doors where the access ramps may be stored underneath the trailer.

All trailer underbody skirts serve to extend the trailer side walls much closer to the ground, preventing wind from ducking in under the trailer and running into the non-aerodynamic trailer bogie. Figure 38 shows a typical set of wind streamlines taken at the height of the axles. The streamlines for an un- skirted trailer will bend after passing the tractor tires and go underneath the trailer and directly impinge on the bogie, increasing drag (the green area). Figure 39 illustrates how skirts keep the air flow efficiently aligned with the flow on the trailer sides. [35]

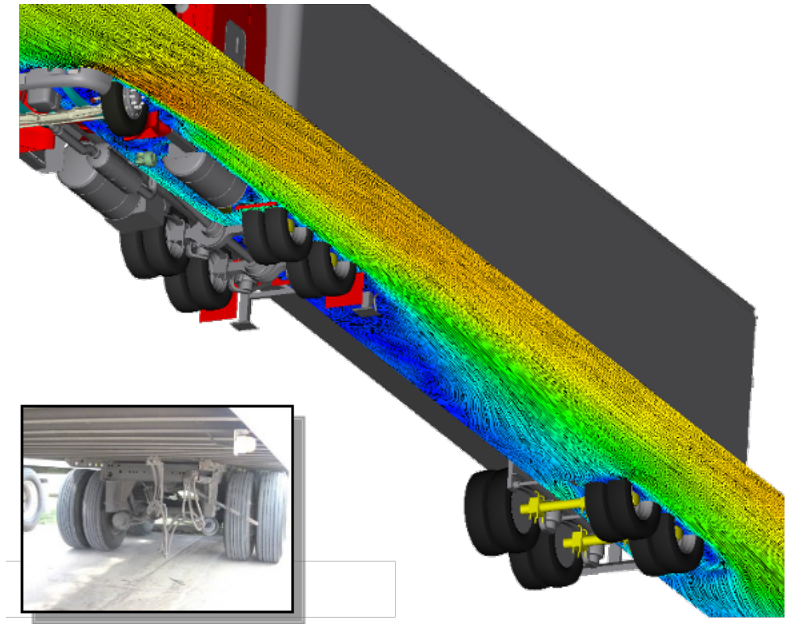


Figure 38: Streamlines for an Un-Skirted Trailer (PACCAR)

The simple view in Figure 39 seems to be an obvious improvement to the aerodynamics of the trailer. However, Figure 40 illustrates that air in some trailer areas can flow underneath an un-skirted trailer and not increase drag, whereas that same air flow could hit a skirted trailer and actually increase drag. In still other situations the ambient air flow will hit the trailer bogie just as before. All that is to say that the effectiveness of trailer skirts changes with the relative angle of the wind to the moving truck.

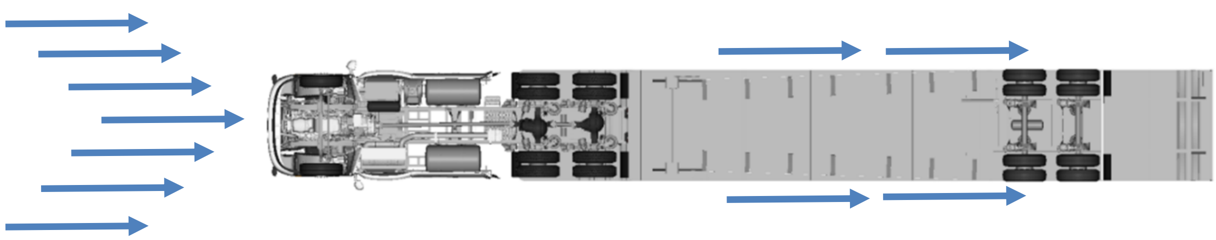


Figure 39: Trailer Skirts Keep Air from Impacting Trailer Bogie

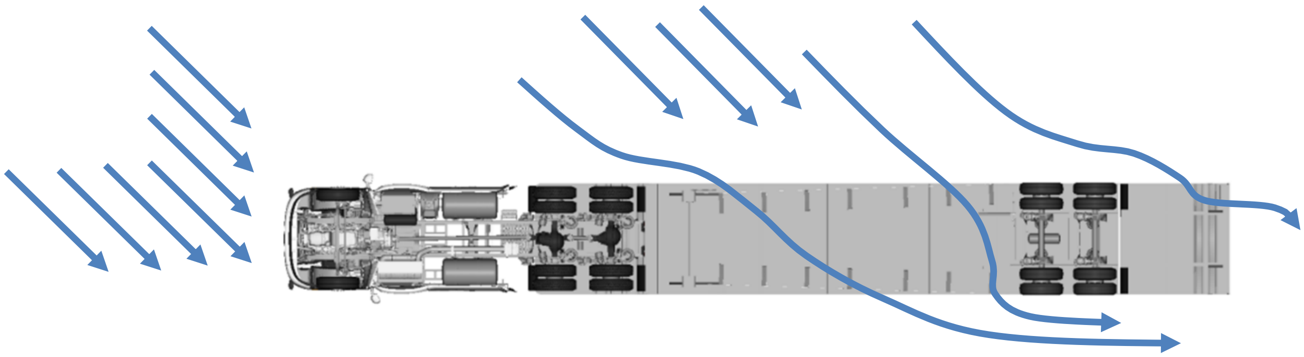


Figure 40: Off-Axis Un-Skirted Trailer Air Flow Example

Although skirts will vary in performance from ambient wind conditions, on balance the decades of extensive research and actual field performance finds that skirts will be of benefit to most operations by reducing overall fuel use. The absolute value of the savings will differ by user and depends on many factors which are described in more detail in the NACFE *Determining Efficiency Confidence Report*. [12]

The designers of trailer skirts focus on providing cost effective, lightweight, robust designs so that they hold up, especially as they are a very publicly visible technology. The trucking industry is not forgiving of devices that are easily damaged and require constant repair or replacement. Another key factor determining the industry's perception of skirts is their installation time and required technicians, as many installations occur in the aftermarket.

Most skirts on the market today are flat sheet materials bracketed to the underside of the floor structure of the trailers. The example shown in Figure 41 is by Utility Trailer. Sheets can be composite, metallic or both. Formed or molded panels are offered by some manufacturers as shown in Figure 42 from Laydon (now WABCO). Molded panels offer an ability to design in stiffness and features like the crank handle stowage recess. The brackets also can be composite plastic or metallic. Much of the innovation in skirts is in material selection and bracket design. (**Note:** Laydon was purchased by WABCO and now is marketed under the Opti*Flow* product line).

Figure 41: Example Skirt Installation (Utility Trailer)

Figure 42: Formed Skirts (WABCO)

For more skirt design detail, an SAE paper by Naethan Eagles, titled *A Parametric Assessment of Skirt Performance on a Single Bogie Commercial Vehicle SAE 2013-01-2415*, defines and quantifies several key geometric parameters. [35]

6.1.2 Underbody Devices

Another type of underbody device can be described as a bogie fairing. In somewhat the same way that a sleeper roof fairing moves the air around the blunt trailer front, these bogie fairings move the air away from the trailer bogies. A leader in manufacturing this type of device was SmartTruck. The company has since exited the market.

The company's computational fluid dynamics image (Figure 43) showed how this underbody system avoids air flow impinging on the trailer bogie.

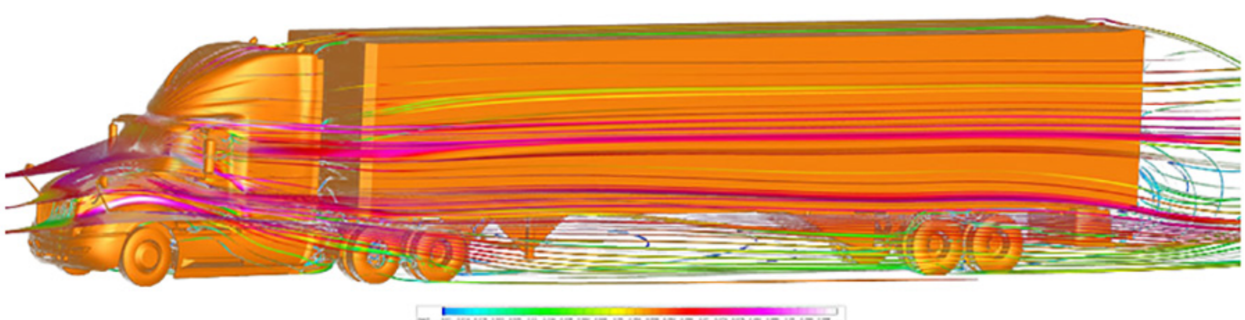


Figure 43: UnderTray Bogie Aerodynamic Improvement (SmartTruck)

The benefit of the bogie fairing type of system is that it provides greater clearance and access under the trailer than with full skirts. But these types of devices alone are generally less capable at reducing overall drag than skirts and may require additional systems to be installed. (See Figure 44.) The SmartTruck UT-1 UnderTray device generally must be paired with their roof top Aerodynamic Rain Gutter to achieve the SmartWay 5% rating held by many skirt systems, while the UT-6 system has the UnderTray, a Rear Diffuser, and the Aerodynamic Rain Gutter all needed to get the 5% EPA rating.

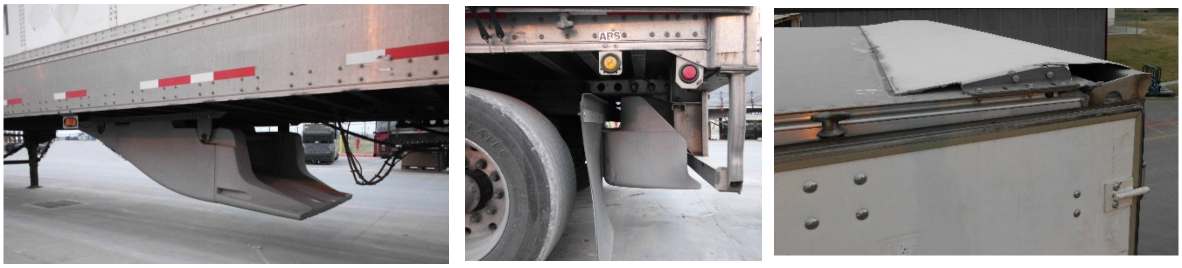


Figure 44: Various SmartTruck Aerodynamic Parts On Operating Trailer: UnderTray, Rear Deflector and Roof Mounted Device

Similar findings came from independent testing by Performance Innovations Technology (PIT), in tests run in Canada reported by *Heavy Duty Trucking* in October 2013. [36] They reported that, "The test results show that trailers with side skirts consumed an average of 6.69% less fuel than similar vehicles without skirts. Trailers with undercarriage aerodynamic devices consumed 1.43% less fuel on average than similar units without the deflectors." It is important to note, though that some owner-operators shared with NACFE that they had higher performance levels from UnderTray. As stated previously, the specific real-world results can and do differ from those reported from various controlled testing, and there can be legitimate disagreements on performance.

Other examples of underbody devices are the Airman AirWedge III and the EkoStinger shown in Figure 45.

Figure 45: AirWedge III by Airman Systems (top) and The Stinger System by EkoStinger (bottom)

In February 2019, Airman Systems announced the AirWedge III that it says is lighter and stronger and offers a modular mounting system for easy removal. The device is said to improve airflow characteristics with enhanced side wide benefits as a result of the addition of the company's AirKnife. The company says the AirKnife removes the drag winds from trailer tires.

EkoStinger designs and manufactures aerodynamic devices for 48' and 53' dry van and refrigerated trailers. The company says the undermount design allows the system to actively slide with the tandems. The company believes this Active Slider feature allows drivers to easily maneuver around tight turns and back into steep loading docks without damaging the unit. The Active Slider moves with varying tandem positions and since it attaches to the tandems, it can help protect trailer air lines and the suspension system. The unit consists of one piece of molded polyethylene. According to the company, fleets using the Stinger could see fuel savings of 6%.

A key takeaway from this example of skirts versus under trays is that fleets should investigate the complete set of parts and installation times that are required with any aerodynamic trailer system before making investments, as the complete system of parts may not be obvious from advertising or press releases.

6.1.3 Other Devices to Prevent Under Trailer Aerodynamic Drag

Still other new products are reaching the market that offer more clear space under the trailers than full skirts. A design discussed in a 2012 in SAE paper, *EPA SmartWay Verification of Trailer Undercarriage Advanced Aerodynamic Drag Reduction Technology, SAE 2012-01-2043*, uses a series of individual skirts spaced apart under the trailer to effectively accomplish the same performance as a monolithic full surface. [37] The Wabash Ventix DRS system is one similar concept (Figure 46) and is designated as an EPA SmartWay 5% device, similar to full skirts. Wabash's website claims that these can, in fact, perform better than traditional skirts. Care again should be taken to understand all of the parts in the system, for example this includes a fairing aft of the trailer wheels and one ahead of the trailer landing gear where the traditional base solid skirt is only ahead of the wheels and behind the landing gear. Some of the standard full skirts may also be optioned to include these longer installations so a more equivalent comparison can be made.

Figure 46: Segmented Skirt Aerodynamic Devices (Wabash)

A differentiating factor in skirt designs may be the size of the gap between the ground and the bottom edge of the skirt, and whether the bottom pieces of the skirt are solid materials or flexible rubber. Notably, warehouse apron crown clearance can be an issue with skirts, as can servicing access.

Figure 47: Ground Clearance Precaution with Aero Performance (Wabash)

Various manufacturers include a rubber flexible strip at the bottom of the skirts to help close the gap but deal with the occasional real-world issues like crown clearance, curbs, railroad crossings, and running over dunnage like pallets and 2x4 wood. Figure 47 shows one example from Wabash, their DuraPlate AeroSkirt with a flexible thermoplastic that maintains aerodynamic rigidity but absorbs impacts.

Skirt ground clearance also affects aerodynamic performance. The most aerodynamic installations tested in prototype development have nearly zero ground clearances, but these installations are not practical in the real world unless they can move out of the way in some of the situations just described. An example of such a technology is the Windyne Flip and Slide fairing system shown in Figure 48, which can hinge up while maneuvering around delivery docks, but then fold back into position for on-highway use.

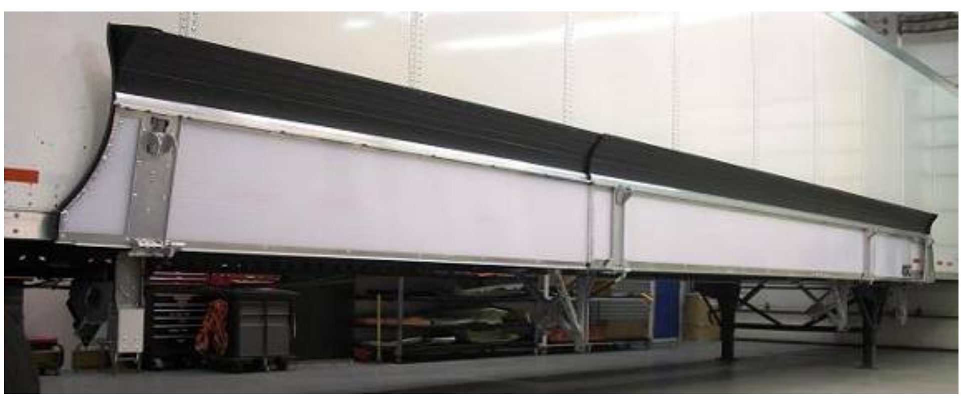


Figure 48: Articulated Skirts Allow Clearance at the Yard (Windyne)

Multiple evaluations have been done over the years on the sensitivity of the ground clearance and skirt length on skirt aerodynamic performance – as length increases, aerodynamic performance improves. But skirts that have too small a ground clearance see a high rate of damage and become less desirable in the market, while skirts that have too high a ground clearance see too little performance gain to justify adoption. One example study from wind tunnel work by Navistar is in *SAE 2007-01-1781, Practical Devices for Heavy Truck Aerodynamic Drag Reduction*. Ground clearance is one factor that will determine why some skirts on SmartWay's verified list are listed as 1% or better, others 4% or better, and many are at 5% or better.

The real world tends to force iterations in design over time. Two fleets contacted by NACFE said that when skirts were first introduced, everyone that could bend a bracket got into making them, so quality varied. They both also said that skirt quality has significantly improved in the last five to seven years. The sales feedback process tends to force iteration toward an acceptable balance between ground clearance damage rate and aerodynamic performance. Devices with a longer field history that have been through design improvement may be better tuned to customer's real-world requirements than those with less field history.

There is really no standard definition of "minimum clearance," or even of a "trailer skirt," so attention must be paid to details when comparing different claims, as the devices may not be similar in size or function. It is very unlikely that a manufacturer will guarantee a customer real performance values due to all the variables inherent in real world operations. This is where asking for data on warranty occurrence rates and actual performance from other fleets that are using the devices becomes important when talking to aerodynamic device suppliers.

Fleets should also know that underbody devices can collect ice and snow in winter conditions, and this can impact aerodynamic performance, as well as adding weight to the vehicle and reducing its freight load potential or resulting in overweight fines at inspection stations. This situation is experienced in aircraft so often that they are equipped with a range of systems to prevent ice build-up and are sprayed down with deicing mixes before some winter flights. At present there are no trailer underbody system options that similarly address ice or snow build-up automatically, so fleets must rely on the driver's inspection.

6.2 Rear Devices

Devices that mount at the rear of trailers are generally called boat tails or trailer wake devices. They modify the air flow as it leaves the trailing edge of the side and top surfaces of the trailer. Given that a raindrop is an optimally aerodynamic shape, with the tail of the drop opposite the direction of travel coming to a point; it may seem that the ideal trailer rear shape would come to a similar point. NASA aerodynamicists experimented with this as early as the 1970s as seen in Figure 49 from *A Reassessment of Heavy Duty Truck Aerodynamic Design Features and Priorities, NASA/TP-1999-206574.*

Figure 49: Trailer End Design Getting to the Point (NASA)

Several more recent research studies have also reached this conclusion; several are described in U.S. Patent 2007 #7,255,387 by Rick Wood. These shapes, however, present many challenges, including that they may exceed overall length rules, or create packaging challenges and issues at warehouse docks. The federal rules on overall length do allow for adding devices to the rear of trailers under 23 CFR Part 658.16, Truck Length and Width Exclusive Devices, but these devices cannot exceed five feet, cannot carry freight, must be flimsy enough to easily crush in a rear accident, cannot block required lighting, etc. Operationally trailer tails also need to get out of the way during the loading and unloading of freight. The reward for innovating a practical solution into this complex set of requirements is significant aerodynamic drag reduction.

The goal in all trailer rear devices is to reduce the wake field following the trailer, which can affect air some distance beyond the back of the trailer as shown in the computational fluid dynamics graphics.

The generally smooth air flowing along the large flat sides of the trailers detaches as it passes the sharp rear corners of the trailer box creating a series of vortices which create a low pressure region adding drag to the tractor-trailer as shown in Figures 50 and 51. Generally, the greater the wake field, the more drag the tractor engine has to overcome.

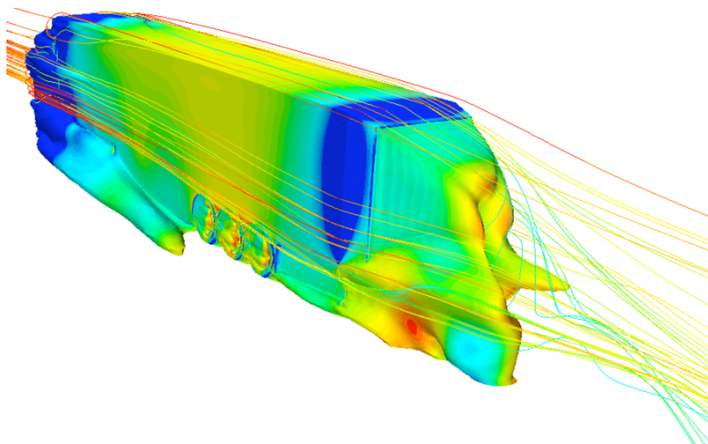


Figure 50: Wake Field Behind A Trailer

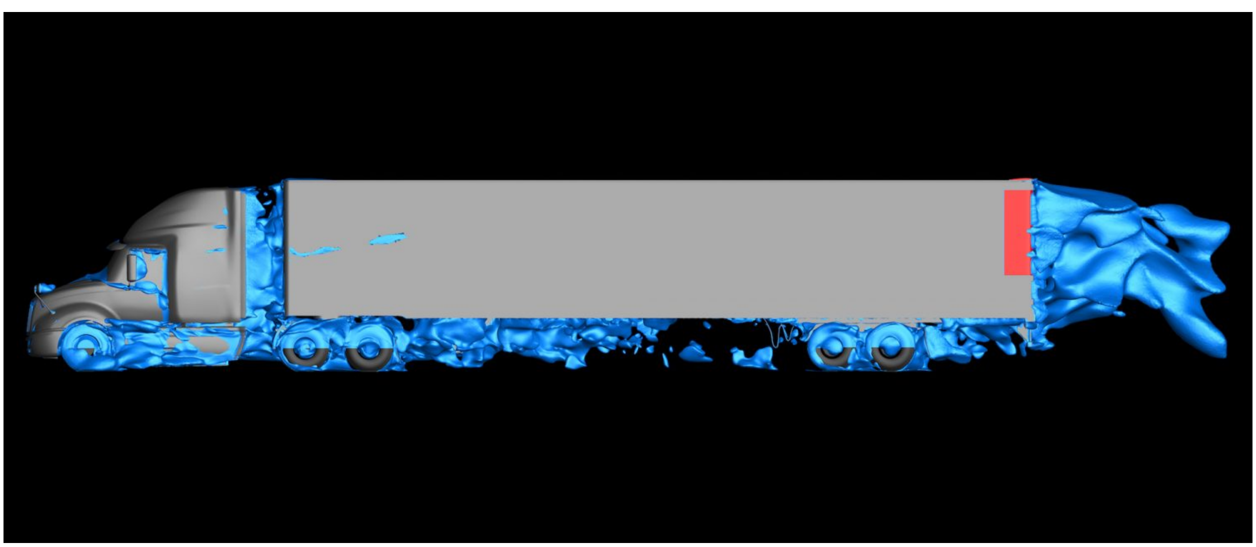


Figure 51: Wake Field Aerodynamics

For trucks operating primarily in one prevailing wind orientation, like crosswinds in a north-south mid-west corridor or aligned winds in an east-west mid-west corridor, tail device performance can vary significantly. A deeper dive into this is found in two SAE papers by Cooper et.al. titled *The Unsteady Wind Environment of Road Vehicles, Part One: A Review of the On-road Turbulent Wind Environment, SAE 2007-01-1236*, and *The Unsteady Wind Environment of Road Vehicles, Part Two: Effects on Vehicle Development and Simulation of Turbulence, SAE 2007-01-1237*. [39, 40]

6.2.1 First Generation Rear Devices

Many concepts have been developed to help get the air to wrap more efficiently around the trailer rear corners, reducing the size of the wake field and thus reducing the drag. Various flat panels, or ramps have been added to the rear edges, similar to tractor sleeper extenders but angled inboard, and ramps of different lengths and angles have been evaluated. In general, the best performance comes from the longest allowable ramp set at an appropriate angle as determined from aerodynamic studies. Various designs trade-off ramp length for other design factors, like ease of device storage, or clearance roll-up door openings for trailers with roll-up doors. Overall this is a very challenging design space to optimize.

One product that initially succeeded to capture market share was TrailerTail, (Figure 52) which was originally invented and offered by ATDynamics was later sold to STEMCO.. (Note: In February of 2020 STEMCO discontinued production of its TrailerTail product according to STEMCO's February 25 earnings report.) This system exemplified the challenges of tail devices. The aero surfaces stowed flat against the rear swinging doors of a typical trailer. An origami folding system allowed these to easily deploy to their on-highway configuration and lock in place.

To re-stow, the driver simply had to open the trailer swing door all the way to the side. The TrailerTail folded itself back up flat in the process of swinging the trailer door around. With the doors in their latched open position, the TrailerTail required no additional width when backing into tight freight docks. Upon leaving the dock, since the driver had to normally close and secure the trailer doors, there were no additional steps required. The series of photos in Figure 53 show various stages of the TrailerTail operation. The driver could choose to have the TrailerTail remain in its stowed position or he could deploy it. An automated system for deployment was developed.

Figure 52: TrailerTail by STEMCO

Market penetration of this device had grown such that a random sampling of trucks in 2014 driving on the Dallas-Oklahoma City corridor found that 3% to 5% of trailers were equipped with TrailerTails. That same random sample found that 15% to 30% of trailers had skirts, including all the TrailerTail-equipped vehicles observed. Few trailer gap devices were spotted. In the 2015 NACFE *Annual Fleet Fuel Study*, 19% of the new trailers bought by the 14 surveyed fleets had boat tails of some model, showing that many early adopters were increasing their purchase of these devices. As of the 2019 NACFE *Annual Fleet Fuel Study*, the 21 fleets report 25% utilization, while skirt use exceed 90%. While these numbers are somewhat anecdotal, the trend reinforced earlier statements that the priority for equipping trailers with aerodynamic devices is the underbody, then the rear, and finally the front. [3]

One of the complaints about these initial devices is that they required driver interaction to deploy them. STEMCO added a self-deploy option to the device but made the decision to stop producing the product indicating it was one of three underperforming products that STEMCO's parent company EnPro Industries decided to end its production.

These first generation rear devices had issues with maneuverability and docking. The large size of the tails made them prone to damage at loading docks. Drivers were also reluctant to manually open and close the devices in bad weather. The units typically featured dozens of moving parts which could break during use.

6.2.2 New Generation Rear Devices

Recognizing that rear of the trailer presents a good opportunity for aerodynamic savings, Wabash Trailers recently developed its own trailer rear device, the AeroFin XL shown in Figure 53. The device consists of lightweight composite panels that measure 24" by 113" and weighs 84 lbs. The Wabash tails are always deployed when the swing doors are closed, requiring no intervention by the driver. The company says the device will not interfere with trailer loading and unloading, so there is no adverse impact to freight operations.

Figure 53: Wabash AeroFin and AeroFin XL Rear Aero Devices (Wabash)

Because of its compact design, it can fold behind the door when in the holdback position and it is said to work with most door holdback devices.

According to the company, by managing airflow across the rear of the trailer, the AeroFin XL reduces aerodynamic drag behind the trailer. The unit's top panels direct high velocity airflow downward to reduce wake. The company says 4.2% fuel economy savings are possible when using the device alone and when used with aerodynamic devices approved within EPA's 5% category, the combination is verified as an EPA SmartWay Elite aerodynamic device combination providing 9% or greater fuel savings.

TransTex offers a trailer tail fairing called The EDGE TopKit shown in Figure 54, with a SmartWay designation as 5% or above. It is made of thermoplastic polyolen to withstand all weather conditions. This system improves the way the air transitions from the trailer's top and sides to the wake region by modifying the trailer's sharp rear corners. The roof mounted device also improves the air crossing a rain gutter that exists on the top rear of many trailer models.

Figure 54: TRANSTEX LeadEDGE and EDGE TopKit Products

In 2015 TransTex introduced a SmartWay-designated tail system called Edge Tail shown in Figure 55. The system extended 30" and had an auto deployment method above 45 mph. TransTex Edge Tail is listed by SmartWay as a 4% or above device. Since the initial release of this Confidence Report, the Edge Tail is no longer available, but some remain in operation.

Figure 55: Transtex Edge Tail (HDT)

WABCO offers OptiFlow Tail, an EPA GHG Phase II Bin III rear fairing solution. The company says use of the device results in a 4.3% fuel savings at highway speeds and a 4.0 ton reduction in CO_2 emissions per year.

It comes in two versions: ManualTail which uses for steps to deploy and retract. AutoTail deploys and retracts automatically via sensors that are linked to the company’s trailer anti-lock braking system. (See Figure 56.) The device automatically deploys at vehicle speeds of 45 mph and retracts at 10 mph.

Figure 56: AutoTail from WABCO

The devices side panels fold toward the trailer’s centerline which results in a 260 degree opening angle for trailer doors, depending on door construction. Each side of the device operates independently allowing individual trailer door access.

The panels and struts are made of thermoplastic and brackets, stiffeners, pneumatic cylinders and connectors are made from stainless steel and aluminum. Panels are 28.7” deep x 97.1” high x 103.3” wide.

Rocketail produces a rear drag reduction device for trailers that works by creating forward lift while it streamlines the rearward air flow. It claims a 3.36% fuel savings when fully deployed. (See Figure 57.) The device self deploys, has no moving parts and extends just 14” from the back of the trailer compared to first generation rear devices which could be as long as 4’. The company says the device solves all three D issues for trailer aerodynamics — drag, deployment and damage.

Figure 57: Rocketail Trailer Rear Fairing

The unit consists of two wings and a top element which is a spoiler on the roof line. The device is one solid piece of a high-impact, gas-infused polymer. The Wing itself is internally cross-braced with no additional external or internal moving parts it just needs two, industrial-grade steel “swing” hinges.

Wings deploy automatically when the trailer doors open or close. The company says the hinges automatically shift the wing flush with the side of the trailer each time the doors are opened, so trailer doors can swing their full 270 degrees without being blocked or impeded. The company says Rocketail is placed one inch away from the trailer wall, avoiding the boundary air layer to interact with higher volume, more uniform airflow. According to the company’s website, “The primary cause of drag is separation of airflow. When a solid object travels through a fluid, the area of fluid close to the solid surface is known as the boundary layer. Boundary layer separation occurs when the fluid flow becomes detached from the surface of the object, and instead takes the forms of eddies and vortices.”

The company goes on to explain, “As the trailer moves through the air, an area of low pressure forms directly behind the trailer creating separation and generating a turbulent airflow (i.e. back pressure). This turbulent airflow directly behind the trailer represents 16.25% of the energy consumed by the truck when it is traveling at a constant velocity on a level surface at highway speeds. The objective is to minimize separation and generate a laminar airflow to reduce tail-end drag.”

Michelin Energy Guard system is a combination of side skirts, trailer end fairings, mud flaps and a unique wake reducer located on the trailer doors. (See Figure 58.) Energy Guard is a complete system in which the components are designed to work together. The company says the trailer skirt can flex and bend around objects and will bounce back into place. The bracket and slider design is said to reduce the load on skirt panels.

Figure 58: Michelin Energy Guard

Trailer end fairings for the top and side of the trailer are said to accelerate and then turn airflow around the back to the trailer. The system's aerodynamic mud flaps are angled and feature progressive louvers, which the company said reduce vehicle drag and road spray.

The wake reducer is a rear-facing spoiler that can be used with swing and roll-up doors. The company says it reduces the size and effect of the primary recirculation zone behind the trailer. The wake reducer is always deployed and no driver interaction is required. According to the company, a 7.4% fuel savings is possible at 65 mph.

Reflecting the difficulty of designing a robust trailer rear device, Aerodynamic Trailer Systems patented its inflatable tail solution with work started in 2007.The company obtained SmartWay status at 5% or above and sold and fielded it over the years since, but decided to exit the market in late 2015. The innovative concept shown in Figure 59 has potential and may re-enter the marketplace in the future.

Figure 59: ATS SmartTail Inflatable Rear Aero System (ATS)

6.3 Gap Devices

Tractor-to-trailer gap management devices are ranked third in adoption priority in large part due to the evolution of the current aerodynamics of SmartWay verified tractors. These highly aerodynamic tractors have high roofs and well-tuned trailing edges which include cab extenders, trim tabs, and the bridge fairings that are being added to the rear of some roof fairings. These tractor devices have largely reduced the importance of trailer aerodynamic gap devices. Fleets that operate highly aerodynamic sleeper tractors have decreased the gap between the tractors and trailers as a fuel saving practice to reduce this gap. Many day cab operators choose to have much higher gaps as these tractors tend to operate in more regional haul operations with an increased need for maneuverability. At small gaps, damage can occur when the tractor and trailer come into contact in severe turning situations. This damage can be very expensive, into the thousands of dollars per instance.

These trailer-mounted devices are referred to variously as gap reducers or nose cones, although NoseCone is also a trademark for a particular brand of devices. However, there are still many non-SmartWay tractors in service in North America which are not necessarily equipped with roof fairings. These tractors have long lives of 12 to more than 20 years and multiple uses over many owners. There also is a large inventory of existing trailers. These two factors leave room for gap devices to be more significant contributors to performance than indicated by SmartWay's values.

NoseCone produces a family of devices as shown in Figure 60, from one that softens the blunt top edge of the trailer, to one that improves the exposed front of the trailer, to the full package that includes improved aerodynamic rounding of the trailer edges. These devices have very sound technical roots going back to the 1950s and 1960s, and provide significant savings for day cab tractors, mid-roof sleeper tractors, and older styled conventional tractors. As with the argument for adding trailer rear fairings, continuous improvement and fleets pursuing efficiency gains after they have installed underbody devices will need to consider these options as the next area of opportunity for aerodynamic improvement.

Figure 60: NoseCone Trailer/Tractor Gap Devices

WABCO also makes a trailer nose fairing system of parts, shown in Figure 61, which SmartWay lists as 1% or better. A challenge with trailer front and rear devices is that they generally require drilling the trailer surfaces, which makes these installation choices more difficult to change later if desired. This is compared to underbody systems, which currently have access to the floor structural members exposed on the underside of the trailers providing convenient locations and flanges for clamping brackets, such that no trailer drilling is needed.

Figure 61: OptiFlow Front Fairings by WABCO

A different type of trailer gap device uses the natural tendency for air to swirl in the tractor-trailer gap as shown in Figure 62. These natural vortices tend to prevent air from crossing from one side of the trailer to the other, essentially creating virtual fairings. These uniform opposing vortices destabilize toward the top of the tractor-trailer gap. The vortices also collapse as the tractor-trailer gap increases in length, so trailers with fifth wheel settings too far back will not see the aerodynamic benefits.

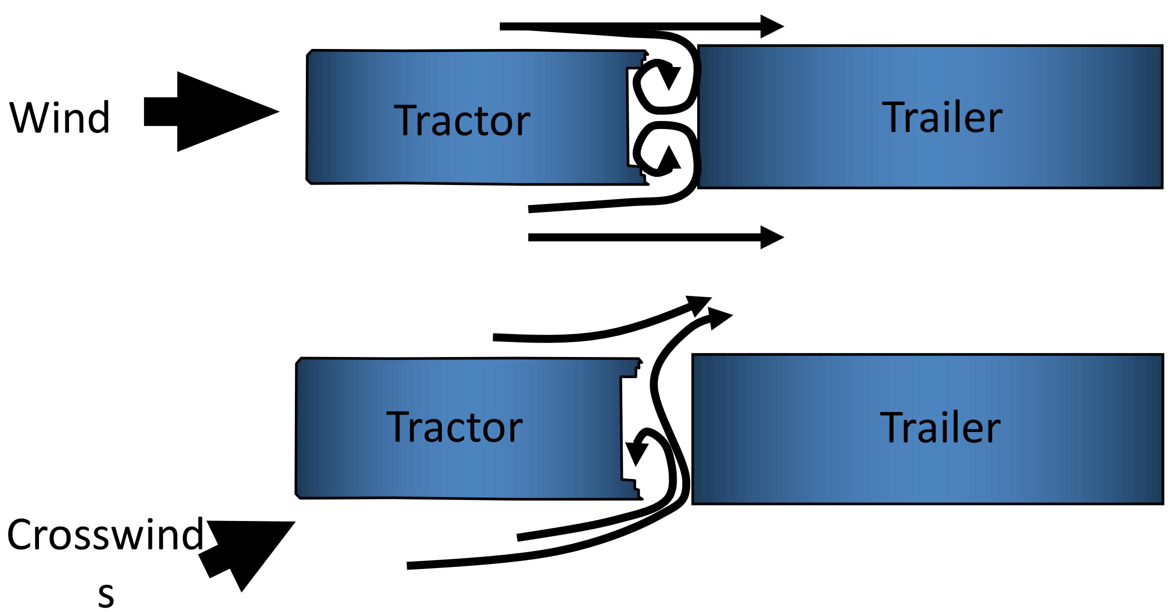


Figure 62: Gap Vortex Management Devices

One example of a device to help maintain these vortices is the WABCO Vortex Stabilizer shown in Figure 63. The device, by itself, is not SmartWay designated, but can be part of a complete Elite package. As previously discussed, the evolution of aerodynamic tractors has significantly improved tractor-to-trailer gap air flow and with shorter fifth wheel settings, this type of device is less necessary. For longer gap settings that may be required due to axle loading, there may be benefits from this type of device, especially in crosswind conditions. Many types of devices with similar purposes to this one have been evaluated with positive results, but they are currently very rarely seen on-highway. This stabilizer has not been commercialized and since the initial release of this Confidence Report WABCO Composites Ltd has been purchased by WABCO.

Figure 63: Vortex Stabilizer Device by WABCO

Another strategy that can be implemented to limit the drag caused by this gap is to employ a gap device on the back of the tractor. For information on those solutions, see NACFE's *Tractor Aerodynamic Confidence Report*. [49]

6.4 Trailer Axle Fairings

FlowBelow produces a trailer tandem fairing system that includes quick-release aerodynamic wheel covers, tandem fairings and flow through mud flaps designed to work together as a system. The AeroSlider is designed to address the airflow around exposed trailer wheels. Its purpose is to reduce turbulence and drag. (See Figure 64.)

Figure 64: FlowBelow Trailer AeroSlider

Each kit includes four aerodynamic fairings, two flow-through aerodynamic mud flaps, and four 'quick-release' wheel covers, which provide instant access to the wheel end via FlowBelow's patented "push and turn" latching system. The tandem fairings, mud flaps and wheel covers are made from 100% rust proof polyethylene and are engineered to maintain maximum durability even in known extreme weather conditions and temperatures, the company says.

According to the company, the AeroSlider can be used with our without other trailer aerodynamic devices like side skirts and boat tails. The system can be sued with most wheel and tire configurations, including wide base tires.

6.5 Wheel Covers

A variety of manufacturers produce aerodynamic wheel covers for use on both tractor and trailer wheels. 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. Small benefits can be shown 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 be 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 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 mud flaps." [13]

The devices are generally described in advertising and press releases as 1% or better type fuel economy devices. As with other claims, these values may relate to a specific controlled test conditions and methodology and the real-world improvement may be smaller.

A *2012* SAE Paper, *EPA SmartWay Verification of Trailer Undercarriage Advanced Aerodynamic Drag Reduction Technology, SAE 2012-01-2043*, [37] documents the evaluation of a Solus Wheel Cavity Cover, shown in Figure 65. The device attained a SmartWay rating of 1% or better in concert with various short trailer skirts. A key requirement for wheel covers is the need for drivers and inspectors to be able to view and access the wheels. This Solus device addresses this by providing an access hole.

Figure 65: Solus Wheel Cavity Cover

FlowBelow produces a closed wheel cover that can be readily removed by pushing the center release button as shown in Figure 66. The company says the stainless steel and TPO construction ensures a long lasting product life. Independent third party tests including SAE Type II fuel efficiency test procedures, wind tunnel testing, CFD models and on-road fleet tests have shown fuel consumption reductions of .7% to 1%, according to the company.

Figure 66: FlowBelow Wheel Cover

One challenge, however, with making wheel covers devices easily removable is that it also can facilitate theft when the vehicle is parked.

RealWheels Corporation offers a combination of wheel cover products that includes a closed wheel cover with clear panels to be able to view inside the wheel space as seen in Figure 67.

Figure 67: RealWheels Corporation (RWC)
Tandem cover with Viewing Panes (L) and Front Axle Covers

Steer axle wheels can also have covers. These are seen more rarely in the field than tractor drive axle and trailer bogie wheel covers.

The cost, weight, and installation time of wheel covers, is relatively small compared to other investments. One set of four covers for a trailer complete with mounting bracketry may add 20 to 50 lbs. 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 had 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.

6.6 Aerodynamic Mud Flaps

A variety of mud flap alternatives have been on the market for some years offering improved aerodynamic performance and fuel economy savings. As with the wheel covers, it can be challenging to prove significant savings with current testing methods. And again, the general consensus is that these devices should be beneficial, but the savings are hard to statistically prove in individual controlled tests, while fleet evaluations include many other factors that make it difficult to isolate 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, so that one size mud flap does not fit all. A mud flap that is too exposed to the air flow in fact will create significant drag and downstream issues (Figure 68).

Figure 68: Example Exposed Wide Mud Flap (Badger)

Aerodynamic mud flap concepts range from simply venting the flap to introducing louvers and aerodynamic surfaces. An example of a simple vented flap is shown in Figure 69. Variations get progressively more complex, for example the Fleet Engineers Mud Flap with actual tuned louvered surfaces and taking this further is the Mirrex Louvered Mud Flap, both shown in Figure 70.

Figure 69: Simple Vented Flap

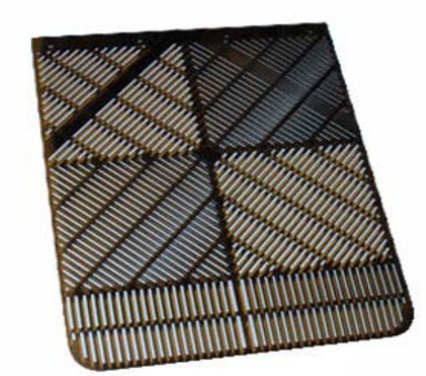


Figure 70: Fleet Engineers (left) and Mirrex Louvered Flap (right)

6.7 Vortex Generators

While the concept was briefly introduced in the section on gap technologies, a new product offering for the whole trailer is a vortex generator, which is basically a flow control device instead of fairing, and is offered as the VorBlade Wing system shown in Figure 71. SmartWay lists this system as 5% or better, but VorBlade's public information does not clearly define all the parts that are used for this designated configuration.

The system uses a series of individual devices mounted on the roof and other devices mounted on the trailer sides to moderate crosswind conditions, which VorBlade claims is where the drag reduction occurs. The devices add height and width to the trailer but are exempted from federal height and width constraints as energy conserving devices. However, U.S. bridge height infrastructure is less forgiving of height exemptions, so caution is advised with these devices. This is new technology and there has not been significant market penetration to date.

Figure 71: VorBlade Wing System

Meanwhile Aeroserve Technologies' LTD Airtab vortex generators, shown in Figure 72, have been on the market for over two decades. These devices are easily added to trailers and tractors through adhesive backing. Some fleets report MPG improvement from installing devices on the rear edges of tractors and trailers, while others have not realized measurable improvement and industry testing has reached mixed conclusions.

Figure 72: Aersoserve Technolgies LTD Airtabs

The SmartWay verified list also includes the Nose Cone Mfg. Co. AeroTrak VG Pro which is no longer offered. They said, "Over the road analysis of the technology did not support the test submitted to us as verification."

6.8 Refrigerator Units

It should be noted that refrigerated trailers have what effectively serves a trailer gap reducing device in the modern trailer refrigeration unit. EPA recognized this in its 2015 GHG Phase II draft *Regulatory Impact Analysis* (which has now been released), stating that the "The transport refrigeration unit (TRU) commonly located at the front of refrigerated trailers adds weight, has the potential to impact the aerodynamic characteristics of the trailer, and may limit the type of aerodynamic devices that can be applied." The EPA recognizes box trailers that are restricted from using aerodynamic devices in one location on the trailer as "partial-aero" box trailers."

6.9 Smaller Details

While skirts dominate as the leading candidate for single device selection, the DOE SuperTruck programs highlighted that attention to a range of small details can produce measurable improvements. Fleets that make the effort to address details, like matching mud flaps to tire widths, relocating license plates to avoid blocking air, adding wheel covers, etc. accumulate savings over time due to the miles multiplier on even small gains that may not be measurable in controlled tests. Comments from one NACFE fleet were that these companies also instill a performance culture that they are motivated to make performance improvements at all levels and that leaves a positive impression on their drivers.

An example of a smaller detail is the Bumper Bullet offered by Kodiak Innovations (Figure 73) which rounds the leading edge of the ICC bumper. Many of the trailer OEMs are now manufacturing trailers with softened bumper leading edges as shown in Figure 74 from displays at NACV 2019.

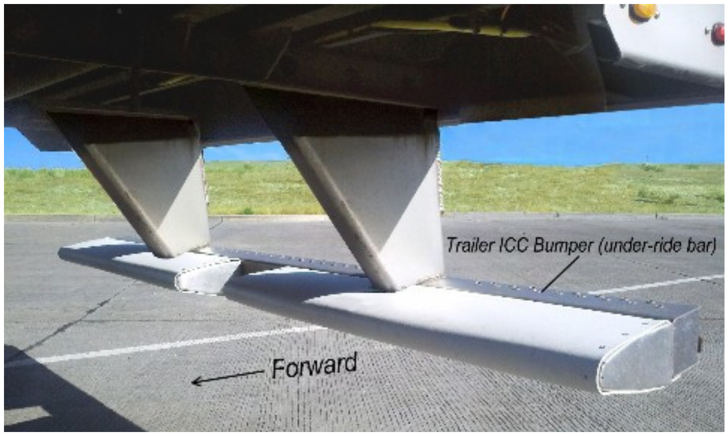


Figure 73: Bumper Bullet (Kodiak Innovations)

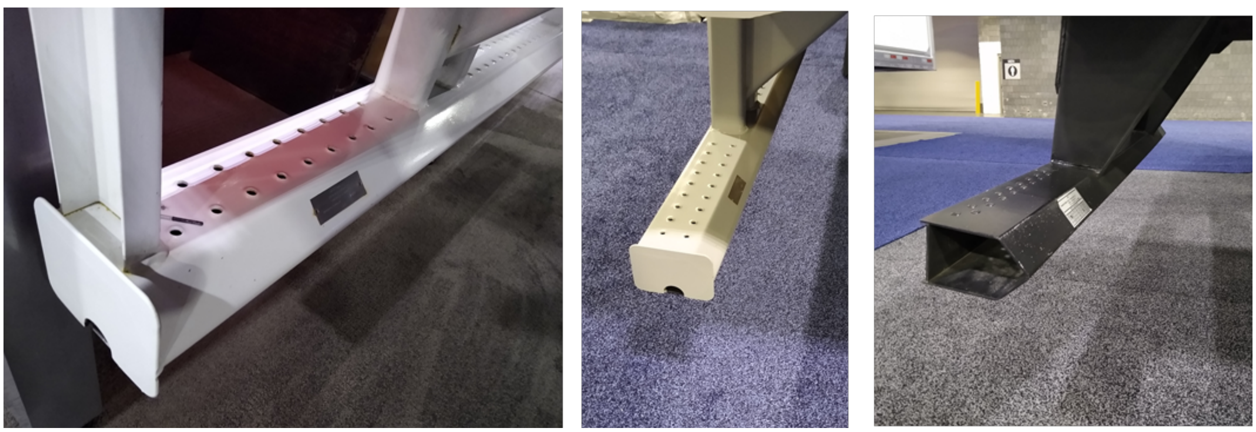


Figure 74: Aerodynamic detail of trailer bumpers displayed at NACV 2019 (Mihelic)

6.10 Combinations of Technologies

Where is the greatest opportunity on the trailer? Each area can reduce drag with the addition of aerodynamic devices, but as each device is added, the performance of other devices will be impacted.

Generally, the reason for this is that air flow over each device changes the operating conditions for the other devices. The performance of a combination of devices will not simply be the additive total of each device operating alone as they may interact positively or negatively. Both industry and government aerodynamicists have repeatedly shown that the maximum aerodynamic improvement comes from a combination of sealing the tractor-trailer gap, from sealing the trailer underbody, and from adding a boat tail — basically acting on all three of the key areas of drag identified. These very-optimized trailers have been demonstrated by OEMs in Europe and the U.S., as shown in Figure 75, most recently with the Department of Energy SuperTruck Program vehicles which achieved a greater than 50% freight efficiency improvement, with mile-per-gallons demonstrated in the 10 to 12 MPG range.

Figure 75: Optimizing Trailer Aerodynamics to the Extreme - Recurring Themes

The example graph in Figure 76 was reported in a 2009 SAE paper titled, *Understanding Practical Limits to Heavy Truck Drag Reduction SAE 2009-01-2890*. [42] The testing is based on a 25% scale model wind tunnel test examples of which are shown in Figure 76. This graph shows that the greatest drag reduction, (the lowest curve in green), came from having aero devices in all three regions and maximizing their drag reduction. While there is no guarantee the multiple devices will actually be more beneficial than individual ones in absolutely 100% of all operational situations or configurations, addressing the aerodynamics of all three points of drag should give the greatest fuel savings for the vast majority of fleets.

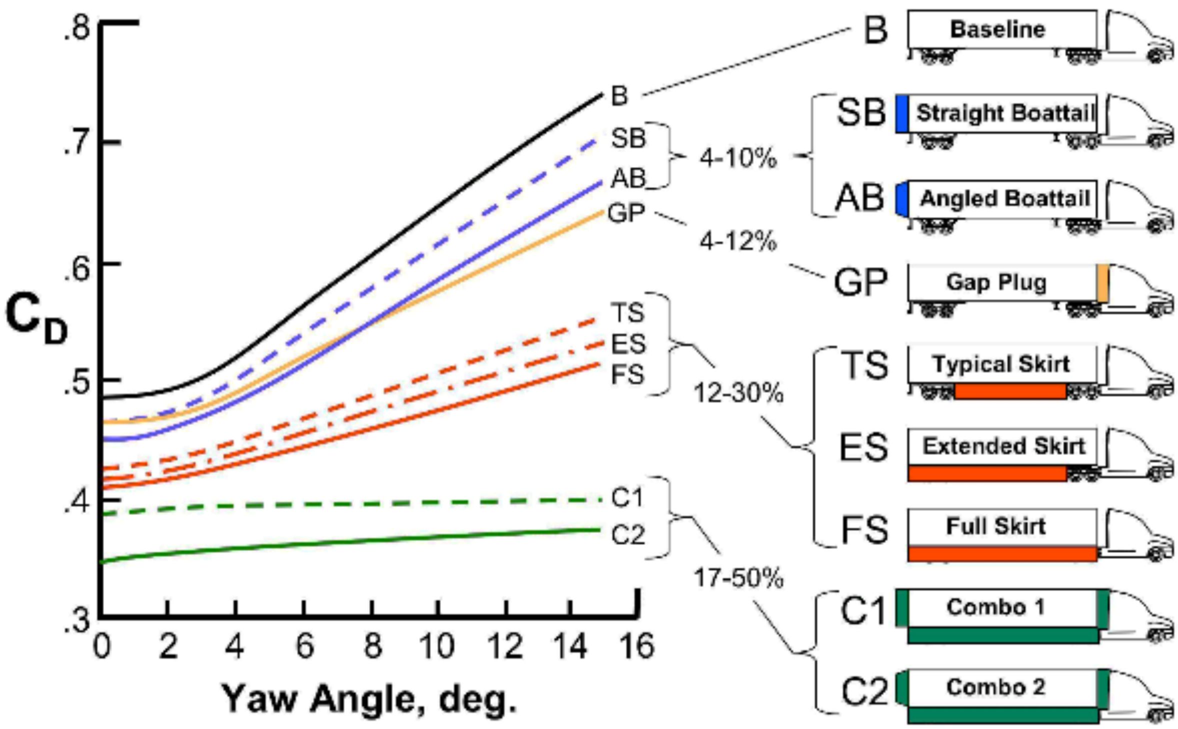


Figure 76: Best Aero Performance Comes From Treating All Three Opportunity Areas

A joint 2007 program of the DOE National Energy Technology Laboratory and the Truck Manufacturers Association OEMs, entitled *Test, Evaluation, and Demonstration of Practical Devices/Systems to Reduce Aerodynamic Drag of Tractor/Semitrailer Combination Unit Trucks*, has a number of similar examples to that shown in Figure 77, generated via wind tunnel tests, CFD, track, and on-road testing. [8, 42] One example set of data from that report for wind-tunnel-tested combinations of aerodynamic devices is shown in Figure 78 This graph also highlights, as the overall report itself concludes, "The total drag reduction as a result of device combination was not always equal to the sum of an individual device's drag contribution." [8]

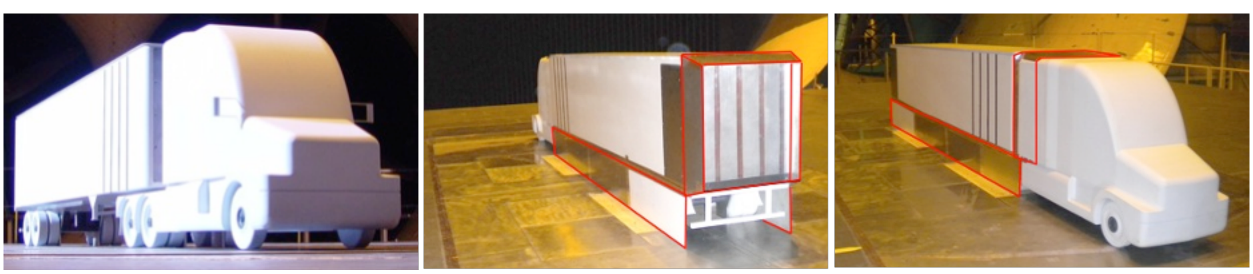


Figure 77: Scale Model Wind Tunnel Tests of Typical Aero Options

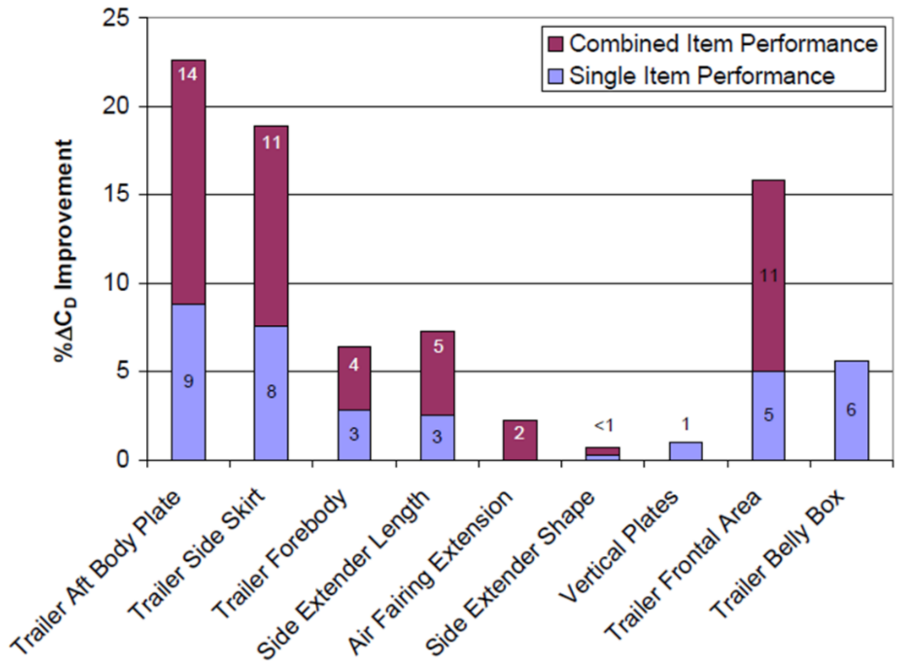


Figure 78: Total Aerodynamic Improvement May Be Greater Than Sum Of Parts

More recent work by EPA and NHTSA published in their *2015 GHG Phase II Regulatory Impact Analysis* (RIA), Figure 79, shows again that combining devices, in this case using both an underbody fairing skirt and a rear fairing tail, tends to reduce overall drag in a synergistic way and in this case found greater savings than the sum of the individual savings of each device alone.

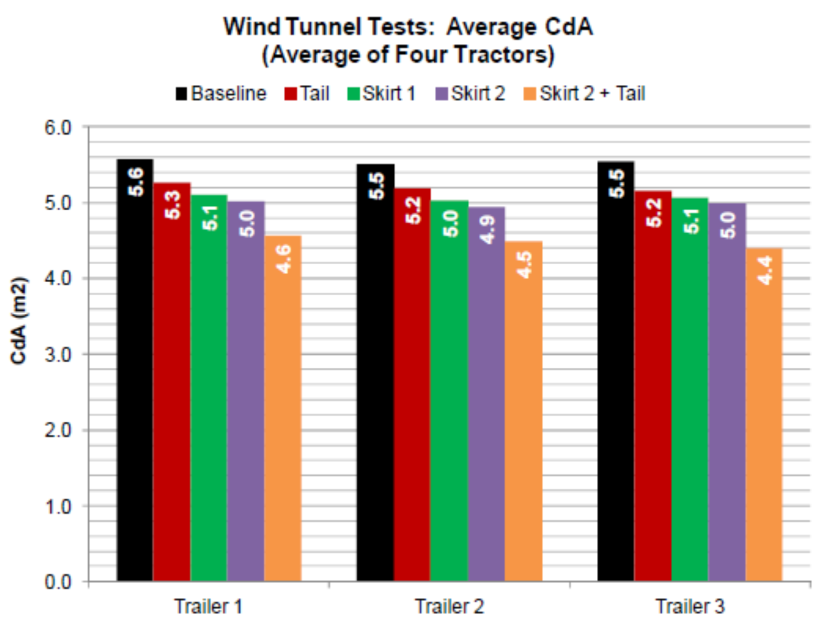


Figure 79: Recent Multiple Trailer Aero Device Testing for EPA:
Variation of Trailer Devices Due to Trailer Manufacturer

But the RIA also documented that values varied "depending on tractor type, device manufacturer and test method." This is shown in Figure 80, a graph published in the 2015 GHG Phase II RIA. The variation in results due to variables like tractor type, test method, and manufacturer is expected and the reasons for this variation is discussed in detail in NACFE's *Determining Efficiency Report*. [12] Likewise, the rules recognize that "It is important to note that the cruise speed results presented in SmartWay do not necessarily represent performance that would be observed in real world operation."

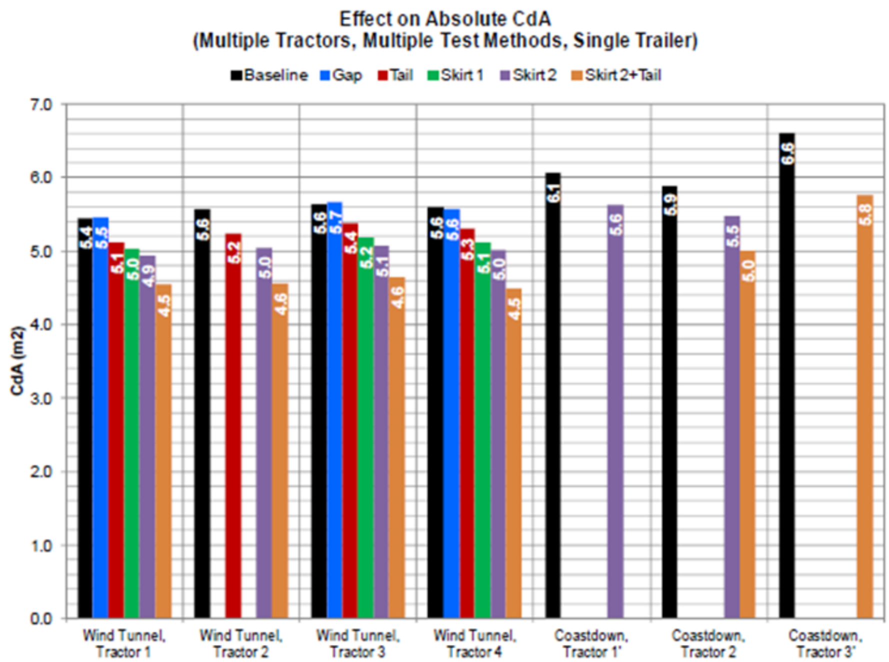


Figure 80: Tractor Choice Can Alter Results:
Variation in Aerodynamic Performance of Trailer Devices due to Manufacturer and Test Method

The EPA and NHTSA explained that relative aerodynamic performance improvement deltas were less variable than absolute values from these tests, noting, "The fact that an absolute test would require a specific standard tractor for testing to ensure an apples-to-apples comparison of all trailer test results and a delta CdA approach makes it possible to allow device manufacturers to perform tests on their devices and have them pre-approved for any trailer manufacturer to apply on their trailers." Recall from prior discussion on the challenges of adoption — no national reference tractor-trailer exists.

EPA has simplified combining listed devices and allowing end users to simply add categorized ratings to achieve differing SmartWay levels. The SmartWay rules are thus a mix of science and bureaucracy to achieve a manageable process.

7 EPA SmartWay

The establishment of an official national categorization system for aerodynamic device configurations is a significant accomplishment of the EPA SmartWay program. While accuracy and precision are likely to continue to be debated and improved upon, the SmartWay program provides a common mechanism for cataloging performance of commercial aero device configurations. Having a standardized evaluation system is the start of any improvement process. The SmartWay system promotes further substantive discussions on improving both the devices and subjecting the measurement tolerances and methodologies to greater scrutiny. The SmartWay system also subjects itself to the relentless forces of continuous improvement. [7]

Where in the 1980s fleets could experiment with a single change, like adding a roof fairing, now nearly every model year has a multitude of changes affecting fuel economy. Deconstructing a truck's performance gains and losses from each new technology has become increasingly more challenging given all these vehicle changes and since many diverse systems are concurrently changing.

Measurements of fuel economy capture the overall performance of the truck and will be the net result of all the changes to the vehicle. The performance of individual systems can and does interact with the performance of other systems. For example, reducing the aerodynamic drag on a tractor-trailer rig reduces the load on the engine, which in turn reduces the demands on the cooling systems and thus reduces accessory loads for fan engagement. On the other hand, vehicles with more aerodynamic devices installed may be demanding more from their braking systems as such vehicles will have less drag to help slow a truck, and will accelerate faster on downhill grades, both requiring more from the braking system. Trucks with both adaptive cruise control systems and substantial aerodynamic devices installed will require less fuel to maintain speeds but possibly also more brake use to avoid excessive speeds or to maintain separation distances with other vehicles.

7.1 Evolution of SmartWay Designations

Estimating specific performance gains for each vehicle in every operational environment is extremely difficult, likely impossible. The SmartWay program originally settled on estimating performance of packages of devices in what constitutes, for all practical purposes, a good, better, best ranking system that bases its test and analysis on one specific highway cruise speed steady state condition, effectively 60 mph operation on a dry track at least 1.5 miles in circumference, in temperatures between 41°F and 95°F, with average crosswinds below 12 mph, gusts below 15 mph, and a 53' dry van trailer and payload at 46,000 lbs. This track testing method means testing was without traffic, and that roadside infrastructure and vegetation was unique to the test facilities.

To demonstrate that a tractor met SmartWay's original fuel efficiency requirement, it had to be tested using the Joint *TMC/SAE J1321 Fuel Consumption Test Procedure Type II RP J1321*, [20] as modified by the EPA. Even though the EPA documentation and their published statements indicated that testing was to follow J1321, the agency accepted data that did not meet J1321 criteria; this failure may have resulted in low-performing technology being SmartWay verified.

The OEMs initially identified a limited number of specific best-performing aerodynamic tractor models as SmartWay tractors when that designation system launch. These included the International Prostar, Mack Pinnacle, Freightliner Columbia, Volvo VN 780, Peterbilt 387 and the Kenworth T2000. Any new models designed after that point had to be EPA-approved by meeting or exceeding the fuel efficiency performance of at least one current SmartWay-certified sleeper cab tractor model, of any make from any manufacturer. In sum, the initial SmartWay designation system offered a simple, binary, "this is better than that" definition for the public, by identifying performance as either being SmartWay designated or not.

For example, the SmartWay's aerodynamic designation system, recognizing the complexity of estimating solely the aerodynamic performance of a vehicle, defines aerodynamic vehicles in terms of their physical attributes, seen in Figure 81, rather than by specific performance gains. Under SmartWay definition, an aerodynamic vehicle has a roof fairing, rounded crown and grille, sloping hood, aerodynamic bumper, aerodynamic mirrors, tractor and trailer skirts, cab extenders, trailer gap reducers and trailer boat tails. The SmartWay designation also includes non-aerodynamic requirements, such as Model Year 2007 or later engines, low rolling resistance tires and idle reduction technologies.

Figure 81: SmartWay Program Establishes National Aerodynamic Benchmarking System

The challenge with both this attribute-based definition and the use of a single testing protocol is that each fleet's results will differ some around those findings, based on a host of factors. For example, tractor-trailer highway speed limits in California are set to a maximum of 55 mph, whereas in Texas it can be 75 mph and even as high as 80 mph. Data compiled by the Insurance Institute for Highway Safety shows a wide range of posted highway speeds in Figure 82. There is also much variability in secondary roads.

	Max Truck Speed Limits						
	55	60	65	70	75	80	85
Number of States	2	1	9	22	10	4	1

Figure 82: Variation in Posted Truck Highway Speed Limits

Regional ambient conditions vary considerably between, say, Gulf Coast states and the northern Rocky Mountain States; harsh winter conditions have significant effects on vehicle fuel economy performance. The interaction of traffic also has a significant effect on the performance of aerodynamic technologies, both because it will determine average route speeds and because air flow from the other vehicles directly impacts the performance of a truck. A vehicle may be in traffic 50% or more of the time — the controlled testing does not account for these and many other variables, because in order to get consistent, repeatable results in controlled tests, real world variables must be minimized. The more reality added to the testing conditions, the greater the inconsistency of the results.

Feedback from fleets contacted by NACFE showed that actual performance gains from SmartWay configured vehicles could be as little as one-half to one-third of SmartWay's published estimates. But they were still MPG gains, and the initial SmartWay configuration designation has largely been substantiated as an improvement over non-SmartWay vehicle. In the years since launching the designation, EPA clarified that approved vehicles were SmartWay Designated, and discouraged use of the term "certified".

However, though recent years have seen advances in standardized, controlled test approaches, work remains to be done to help fleets bridge the knowledge gap between tests and in-fleet performance. Many fleets still employ simple rules-of-thumb and may be dismayed when they adopt a technology that does not perform the way they expect. The EPA has also established and maintained an official categorizing system for aerodynamic devices and created an EPA SmartWay Technology Package Savings Calculator. [48] The system recognized that meeting the minimum SmartWay requirements could be done with a combination of technology choices and recognized that fleets could go well beyond the minimum by adopting all of the technologies. The tool provides a savings estimate for a collection of technology choices and could be used to prioritize whether one configuration was better than another. Beyond that, the estimations are based on the original single operating point testing and therefore remain subject to real world variability.

Along with recognizing the fact that fleets need more information to extrapolate controlled testing data to their real world operations, the EPA and the trucking industry both recognized that performance-based definitions were required to improve SmartWay, and EPA has worked with the industry and research groups to develop improved methodology and rules. In parallel with this, the SAE initiated multiple Task Forces working on revisions to industry-approved fuel economy and aerodynamics testing standards to improve data quality and precision. TMC also worked to improve performance evaluation methods. EPA issued new SmartWay performance-based definitions and rules in 2015.

7.2 Current Designations

The SmartWay program defines commercial aerodynamic devices and categorized them in terms of performance contributions used on 53' van and refrigerated trailers. [7]

For trailers, the new EPA definitions in 2015 expanded on prior ones, including refrigerated 53' van trailers along with the 53' dry vans originally included. They finalized expanded testing-verification methods to include an enhanced track test, wind tunnel testing, coastdown testing, and computational fluid dynamics (CFD). Trailer aerodynamic devices that demonstrate fuel savings in SmartWay testing are identified as SmartWay-verified and are listed, along with SmartWay-verified low-rolling resistance tires, on EPA's SmartWay website's technology verification page. [48]

The published data now segments aerodynamic devices into performance thresholds approved by EPA from supplier-submitted information to achieve fuel savings of 1%, 4%, 5% and 9% or more in the context of EPA's approval processes. The EPA clarifies though that these fuel economy improvement estimates are ranges, listed below, and not specific numbers, and that they should be taken in the context of the specific test method, reinforcing the variability that can be expected in the real world.

- 1% (1%-3.9% fuel savings)
- 4% (4%-4.9% fuel savings)

- 5% (5%-8.9% fuel savings)
- 9% (9% and higher fuel savings)

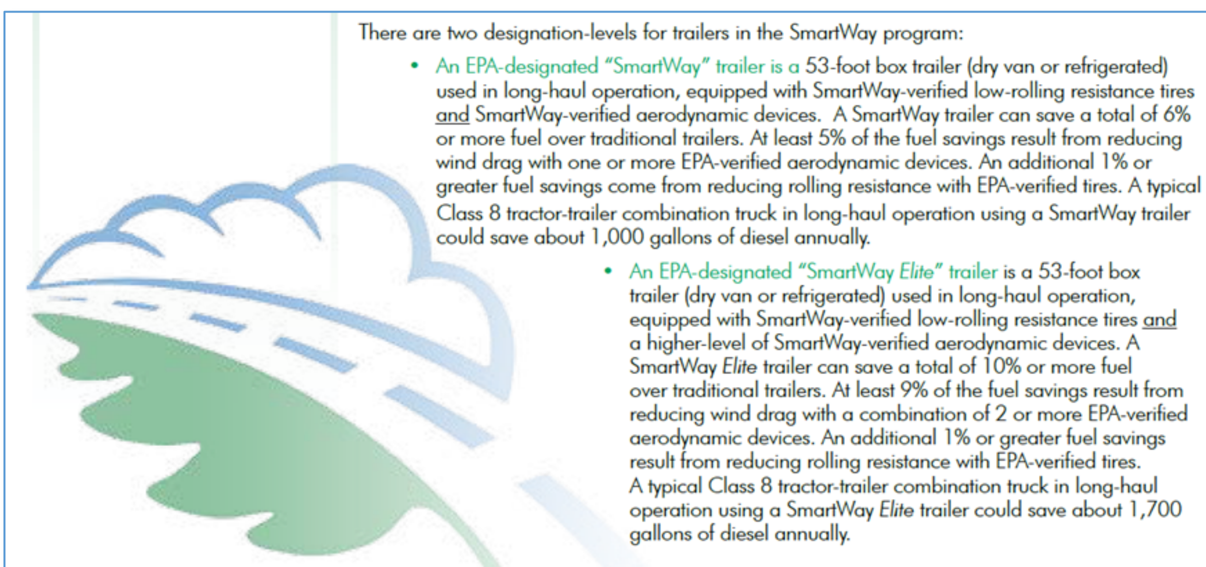
In order to receive SmartWay designation, technology manufacturers must supply the EPA with supporting testing/verification methodology to document their performance as either tested pre-2014 (grandfathered in), post 2014 Wind Tunnel, Coastdown or SAE J1321 Track testing. Complete details of the latest requirements can be found on the *Testing for SmartWay Verification of Aerodynamic Devices* page of the EPA SmartWay program website. [7]

Specific to trailer aerodynamic devices, the EPA states that:

> "Front fairings and gap reducers provide the smallest benefit of the aerodynamic technologies considered. Skirts and boat tails come in ranges of sizes and vary in effectiveness. For the purpose of this analysis, the agencies grouped these two technologies into "basic" and "advanced." Basic boat tails and skirts achieve SmartWay's verification threshold of four percent at cruise speeds. Advanced tails and skirts achieve SmartWay's five percent verification. These technologies can be used individually, or in combination. The overall performance of a combination of devices could be nearly additive in terms of the effectiveness of its individual devices. Some devices may work synergistically to achieve greater reductions or counteract and provide less reduction."

Two important qualifiers on these EPA comments are needed. First, in some cases, combining different devices could result in worse performance. Also, these SmartWay conclusions are in the context of past national average wind conditions, which might vary as future weather patterns evolve.

Additionally, EPA increased its "complete trailer" (including tires, aero, etc.) designations to two, with the minimum EPA-designated "SmartWay" trailer offering 6% or better net fuel savings and a higher-performing "Smart-Way Elite" designation offering 10% or greater fuel savings, described by EPA in Figures 83 and 84. [7]


There are two designation-levels for trailers in the SmartWay program:

- An EPA-designated "SmartWay" trailer is a 53-foot box trailer (dry van or refrigerated) used in long-haul operation, equipped with SmartWay-verified low-rolling resistance tires and SmartWay-verified aerodynamic devices. A SmartWay trailer can save a total of 6% or more fuel over traditional trailers. At least 5% of the fuel savings result from reducing wind drag with one or more EPA-verified aerodynamic devices. An additional 1% or greater fuel savings come from reducing rolling resistance with EPA-verified tires. A typical Class 8 tractor-trailer combination truck in long-haul operation using a SmartWay trailer could save about 1,000 gallons of diesel annually.
- An EPA-designated "SmartWay *Elite*" trailer is a 53-foot box trailer (dry van or refrigerated) used in long-haul operation, equipped with SmartWay-verified low-rolling resistance tires and a higher-level of SmartWay-verified aerodynamic devices. A SmartWay *Elite* trailer can save a total of 10% or more fuel over traditional trailers. At least 9% of the fuel savings result from reducing wind drag with a combination of 2 or more EPA-verified aerodynamic devices. An additional 1% or greater fuel savings result from reducing rolling resistance with EPA-verified tires. A typical Class 8 tractor-trailer combination truck in long-haul operation using a SmartWay *Elite* trailer could save about 1,700 gallons of diesel annually.

Figure 83: SmartWay Trailer & Elite Trailer Definitions

Summary of EPA-designated SmartWay Trailer Configurations

	SmartWay Trailers	**SmartWay *Elite* tTrailers**
Trailer Types	53-foot box trailers (either dry vans or refrigerated trailers) used for long haul operations	53-foot box trailers (either dry vans or refrigerated trailers) used for long haul operations
Aerodynamic Devices	One or more SmartWay-verified aerodynamic devices totaling at least 5% fuel savings	Combination of two or more SmartWay-verified aerodynamic devices totaling at least 9% fuel savings
Low Rolling-resistance Tires	SmartWay-verified low-rolling resistance tires totaling at least 1% fuel savings	SmartWay-verified low-rolling resistance tires totaling at least 1% fuel savings
Total Fuel Savings	**6% or greater**	**10% or greater**
Per Trailer Annual Fuel Savings	Approximately 1,000 gallons of diesel per year	Approximately 1,700 gallons of diesel per year

For more information: www.epa.gov/smartway/forpartners/technology.htm or Tech_Center@epa.gov

Figure 84: SmartWay Trailer Configurations

7.3 SmartWay for Tractors

Aerodynamics is a tractor and trailer system level performance factor. The performance of the trailer is impacted by the aerodynamic effectiveness of the tractor pulling it, and conversely, the tractor's performance is directly impacted by the aerodynamics of the trailer. This is a situation where the "whole is not equal to the sum of its parts." EPA SmartWay recognizes this systemic relationship by having requirements for both tractors and the trailers. For tractors, EPA's most recent updates have maintained the original system for designating SmartWay tractors. Engine Model Year 2010 or later are fully compliant in meeting emissions standards. Some 2007-2009 Model Year engines may be compliant until January 2023. Engines older that Model Year 2007 are not allowed. The base aerodynamic tractor must be specified at a minimum with the following requirements:

Component	**Specifications**
Engine	Current model year engine designated to meet U.S.EPA NOx/PM/GHG emission requirements (meaning that the engine's model year should match the vehicle's model year. So a 2019 tractor should have a 2019 engine.)
Aerodynamics	• Aerodynamically integrated high-roof fairing or cab compartment • Aerodynamic mirrors • Aerodynamic bumper • Tractor side extending fairings (also called tractor gap reducers)

Component	Specifications
	• Fuel tank fairings (also called chassis fairings)
Tires	• SmartWay verified low-rolling resistance steer and drive tires (duals or singles) (aluminum wheels optional)
Idle Reduction	Sleeper and day cabs must have automatic engine shut-off (AES) capability. For sleeper cabs, manufacturer availability of at least one option providing eight hours or more of engine idle-free auxiliary power, heat, and/or air conditioning using: • Auxiliary power unit or generator set • Fuel operated heater • Battery air conditioning system • Thermal Storage System For day cabs, manufacturers are encouraged to provide additional idle reduction options that meet regional-haul needs.

The EPA tractor SmartWay designation system requires the OEMs to provide test and analysis of new proposed SmartWay tractors that support that the new model is as good as or better than an existing SmartWay designated model. EPA maintains a list of the OEM models (tractor and trailers) that have been approved for this designation on the EPA website. [7]

However, the open road sees much more than the subset of OEM models listed by the EPA. And even within these models, it is possible to specify optional changes to design such that a tractor is no longer SmartWay compliant. While California mandates SmartWay tractors for pulling 53' dry van and refrigerated trailers (which must also be SmartWay-designated configurations), in other states SmartWay is voluntary. Even within California's rules, there are a number of exceptions which include container trailers, agricultural trailers like cattle haulers, drayage carriers who stay within designated operating distances, oversize loads, etc. The SmartWay tractor may not offer its advertised benefit when applied to other types of trailers. However even these vehicles experience aerodynamic loads whether on urban or highway travel. CARB has done testing on vocational trailers and tractors, and in October 2015 submitted requests to EPA through their response to the Proposed Phase II GHG Rule Making to include aerodynamic requirements for these other types. The effectivity was highly dependent on unique duty cycles and difficult to predict benefits. The California request migrated into the rules as CARB describes "in the final federal Phase 2 GHG regulation for medium- and heavy-duty vehicles, the U.S. EPA and the National Highway Traffic Safety Administration allow optional emission credits for installing aerodynamic devices on regional vocational vehicles, depending on eligibility criteria."

It should be noted that some of the fleets with these other trailer types have experimented themselves with improving aerodynamics, and in some cases have found promise enough to outfit equipment in the field. Examples of some these are shown in Figure 85, such as where front corners show rounding and streamlining, vertical side structural ribs have been reoriented inboard, rear ends boat tail designs, and skirts have been applied to tank units. The desire to improve operating margins by reducing fuel use has been driving these early adopters, as there are yet no regulations requiring these improvements.

Figure 85: Aerodynamic Improvements To Non-Van Trailers

7.4 EPA SmartWay SmartWay and SmartWay *Elite* Trailers

There are two levels of designation for trailers:

- SmartWay
- SmartWay *Elite*

Both trailers use verified low rolling resistance tires — the difference is the level of aerodynamics and the resulting total fuel savings. The specifications are summarized in Figure 86. [7]

	SmartWay Trailer	**SmartWay *Elite* Trailer**
Tires	Verified Low Rolling Resistance Tires (1% fuel savings)	
Aerodynamic Devices	One or more devices (at least 5% fuel savings)	Combination of two or more devices (at least 9% fuel savings)
Total Fuel Savings	6% or more	10% or more

Figure 86: Specifications For SmartWay and SmartWay Elite Trailers

As noted, mixing and matching component technologies can have unpredictable impacts. The performance of the individual devices is not additive, and so the sum of parts rarely equals the total performance of the combination. Fleets adopting a mix of devices from different manufacturers should do so with caution if the mix they are pursuing has not been tested as a set by reputable methods. This

EPA Elite list of technology packages is expected to grow, but is largely constrained by business forces, as packages are generally created by the suppliers of those devices. Competing companies may not wish to package sets with technologies from other suppliers.

Therefore, the EPA will need to evaluate mechanisms for approving “home grown” fleet trailer aerodynamic device combinations, so that the fleets can be credited at the SmartWay Elite level even where no supplier or group of suppliers has offered and tested that same package of technologies. For administrative simplicity the current rules allow fleets to select from listed devices and simply add their performance gains to achieve an Elite configuration if one is not listed. This is for administrative simplicity. As stated, not all combinations actually add in this simple manner and some combinations may actually subtract.

It should be noted that most of the current SmartWay-listed Elite packages have been so designated based on subscale wind tunnel testing. The extrapolation of that wind tunnel data to fuel savings in the real world has yet to be validated.

In December 2015 NACFE conduced one of its signature workshops at the Automotive Research Center (ARC) in Indianapolis for a group of fleets, dealers, suppliers, and industry representatives. As part of the event, ARC conducted wind tunnel tests on a 1:8 scale aero tractor (Figure 87) and dry van trailer vehicle. Starting from a basic configuration, they added trailer skirts, a trailer tail, a trailer front gap device and finally wheel covers. This was all accomplished within one day, and results were shared with the participants of the workshop before the day was over. The exact results cannot be shared here due to agreements with the component suppliers, but the study team can report that the results were directionally correct with expectations. The tested component combination represented four different suppliers, so is not an identified SmartWay combination. The skirts were found to be the most beneficial aerodynamic addition, followed by the rear tail device, the front gap reducing device, and lastly the wheel covers.

Figure 87: ARC Wind Tunnel

7.5 Non-SmartWay Verified Devices

The trailer aerodynamic device industry consistently produces new ideas and repurposes old ones depending on the market sensitivity to fuel economy and other regulatory factors. This inventiveness has been somewhat cyclical since the oil crisis of the 1970s. What is different today is that federal and state regulations are creating categories of approved devices versus all others. This does not mean that new non-SmartWay-verified technologies are unacceptable for use — they may simply be in the process of being tested to be added to lists, or their contributions may be individually too small to be measured by current test methods. Such devices may need to be combined with other systems to create approved sets of devices, and perhaps are just waiting for some group to take on the work of getting them approved. Certainly, there will also be some non-SmartWay-verified technologies that have poor performance or otherwise are not worth investing in.

With California, Oregon and other states mandating or looking to mandate the adoption of trailer aerodynamic devices based on SmartWay designations, and with the U.S. EPA and NHTSA likewise looking to mandate SmartWay trailer aerodynamic devices as part of Phase II GHG emission reduction regulations, combined with the fact that trailers tend to have long lives of up to 25 years, the business question for fleets is whether it is worth investing in a non-SmartWay device for its possible efficiency gain, but risking that it may not be an approved device, or only choosing SmartWay approved devices and risking that the performance for their specific operations is less than expected.

Based on interviews with industry leaders, NACFE found that some form of SmartWay compliance will be expected on new trailers, and existing rules in California already mandate retrofitting of compliant devices to older trailers, so fleets should focus their technology choices on SmartWay approved systems. This insight should, in turn, incentivize manufacturers of non-approved devices to pursue SmartWay designation. Barring that, there is the opportunity for fleets to package their own combinations of devices and pursue SmartWay designation for them on their own or through third-party groups. Many trailer manufacturers already support multiple trailer aerodynamic device options at their customers' behest, sometimes offering devices that compete with their own in-house designs. These vested parties may also be potential advocates for new SmartWay designations of non-approved sets of devices as fleets' requests.

8 Fleet & Operator Comments on Trailer Aerodynamic Devices

NACFE surveyed fleets about their experiences with tractor and trailer aerodynamic devices for its two Confidence Reports on aerodynamics. Even with fuel prices at unpredictable lows this year, NACFE found that fleets are continuing to invest in aerodynamic devices for their trailers.

The large fleets ultimately each do their own testing before investing in large orders, because the reported testing by vendors and other agencies are conducted under controlled "perfect conditions" not representative of real world. Fleets do see benefits in the controlled tests, as they let them compare devices for relative performance, but they discount the findings by as much as 50%. One fleet stated, "If the EPA estimate is 6% then the actual real-world numbers would be 3%." Another stated, "Easily 50% less" in real world.

One of the fleets interviewed has migrated from robust undertrays that are low maintenance, (described as hard to damage "anvils" where the goal was primarily to be compliant with California trailer rules), to now specifying the best-performing skirt packages as determined by their own rigid evaluations including CFD analysis, wind tunnel tests and their own version of SAE J3015 Type II on-road testing on representative routes.

No matter the testing methods chosen, the overall perception of the savings offered by trailer aerodynamics is positive. As one fleet shared, they are "really effective devices now." This can even be seen in driver behavior in the trailer yard. One contract driver said that when he is picking up a trailer, "he always grab a skirted trailer" when given the choice.

Fleets contacted stated that aero device construction, designs, and materials had all vastly improved in the past five to seven years, mainly to become both lighter and more robust. The fleets NACFE contacted stated they expect aerodynamic device purchases to last for the life of the trailer, which varies based on each company's trade-in polices, but can be seven to more than 10 years. Some fleets felt that drivers have also become more accustomed to having aerodynamic devices, and when combined with fuel economy incentive programs, actually really appreciate having them.

But fleets also pointed out that the conditions that can cause damage have not changed, many of the docks and aprons are of older configurations that are more challenging on devices, and visibility on tail devices is a consistent challenge.

Fleets were uniform in stating that drivers need devices that "require no driver interaction," as in their experience, if the driver has to do something, then it will not work 100% of the time. One fleet declared that "Any statement that starts with 'All the driver has to do is…' should be questioned." Fleets were particularly critical of tail devices that required driver interaction to open or close, stating that it was common to see such devices not deployed on highway, or easily suffering damage in truck stop parking lots. One fleet stated that "tails are amazingly strong" and can cause damage to light poles and garage doors. It is clear that tails need to be passive devices that deploy and stow automatically with no driver involvement. One fleet, when asked what the industry could do better stated, "trailer tails will be much more important in EPA GHG Phase II — they need to be better designed, lighter, more effective and automated."

Fleets with driver fuel economy tracking and incentive programs were generally more positive about low aerodynamic device maintenance costs — drivers were more likely to care for the aerodynamic devices if they saw their benefit in accessing fuel efficiency incentives but methods for fuel economy tracking vary across the industry. Some fleets use ECM data and others use pumped fuel vs. miles driven, still another used "dispatched miles." Fleets stated that ECM data is good for driver training and feedback, but care must be taken as ECM data can vary in its precision. One fleet stated, "ECM data is not necessarily correct. There are errors when comparing across the board," so they use fuel pumped and miles driven as the official data for MPG calculations.

Anecdotal feedback from drivers suggests that aerodynamic-equipped trailers are generally less taxing and maintain their lane with less frequent steering correction by the driver. Several drivers contacted by NACFE confirmed that aerodynamic-equipped trailers were more stable in most situations, and one fleet volunteered, "some of their drivers prefer the stability of the trailers with aero devices."

Another contributor to driver fatigue is ambient noise level; anecdotal feedback is that the more aerodynamic tractors tend to have lower interior noise levels. Driver fatigue with respect to aerodynamics is a future opportunity for more definitive study by TMC, SAE and other industry affiliated research groups.

Regarding the impact of trailer aerodynamics on resale values, feedback from one major trailer manufacturer was that currently the addition of such devices is "not a factor" with respect to whether resale values of trailers see any premium or loss associated with installed aerodynamic devices.

Regarding the weight of devices versus the fuel economy gains from aerodynamics, one fleet stated that when they started using them in 2009-2010, skirts weighed 250 lbs. per set and are now just 130 lbs. per set, while simultaneously have become better designed to be more robust. In that fleet's view, the "aero benefit clearly outweighs weight increase."

Across the board, interviewed fleets have been investing in trailer skirts as their first choice for aerodynamic improvements. But now having done that, they are looking at next steps, and are debating the merits of tails versus other options, even perhaps some on the tractors. Fleets are sensitive that trailer investments depend on trailer mileage. One fleet estimated that their average on-highway annual trailer mileage was 24,000 miles while their tractors would see 125,000 to 135,000 miles per year. For most fleets, trailer investments can have much longer payback periods, leading one fleet to measure trailer payback not in terms of time but in terms of miles, using the expression “miles to payback” as a better metric.

Fleets are sensitive to managing the trailer gaps, and some have moved to fix fifth wheels to standardize trailer gaps. Fleets told NACFE that the gap treatments on the front of trailers pulled by newer sleeper tractors with minimal gaps do not pay for themselves. But where a larger gap is needed for maneuverability with many day cabs or due to axle loading needs, these devices are more commonly used.

Finally, fleet fuel economy data mining is an area that can be challenging, particularly with respect to trailer devices. The nature of trailer use generally prohibits controlled testing over long periods on dedicated routes. As one fleet stated, occasionally they can find a dedicated point A to point B then back to point A shipping lane, but more often they see “A-to-B-to-C-to-D-to-Z” trailer routing, which precludes collecting uniform data.

9 Perspectives for Future Systems

One thing that became very clear to the study team while compiling this Confidence Report is that trailer aerodynamic technologies and strategies are constantly and rapidly evolving. The options discussed previously are all currently available on the market today, and most are mature with a good track record of functionality though they may be more or less economical depending on the specifics of a fleet’s operations. The following sections capture some likely future developments in technologies for improving freight efficiency through trailer aerodynamics.

Active Flow Control Systems

The current trailer aerodynamic device market is dominated by add-on fairings. These tend to be passive, robust devices that alter the trailer shape to reduce drag. As these devices saturate the market, the next phase of aerodynamic refinement will include active systems which can adapt and respond to conditions to better optimize performance. For example, fairings may reposition themselves automatically, based on the local ambient wind conditions, vehicle speeds and/or traffic. More sophisticated solutions might inject or remove air to manipulate flow for better performance.

The Cummins/Peterbilt SuperTruck II vehicle is designed now with two active flow control systems. One is tied to the air suspension and vehicle speed sensors so that the entire truck lowers at various highway speeds. The other is an innovative new system that uses pneumatic pressure tied to wind sensors to deform the rubber sleeper extenders to better control the air flow across the side of the tractor-trailer gap. The concept has been demonstrated as reported at the June 2020 DOE Annual Merit Review and should be on the prototype truck in 2021.

On-Board Aerodynamic Sensing

Obtaining accurate current conditions for a vehicle has been primarily limited to 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 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. The ability for the tractor-trailer to be more self-aware is fundamental to this and other future improvements.

Aero Adaptive Cruise Control and Routing Systems

Cruise controls are becoming more sophisticated, with the ability to maintain set distances to other vehicles using a variety of sensing technologies and real time data. These systems will eventually mature to include aerodynamic factors to optimize fuel efficiency. Enabling this will be innovations in on-board vehicle aerodynamic instrumentation as well as cloud-based real-time local environment and traffic data 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 crosswind conditions, vehicle aerodynamics, terrain, traffic and desired time of travel, rather than just the information available today about traffic or roadwork.

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. These current systems include efforts to optimize for fuel efficiency. They generally do not yet address including aerodynamic factors. Simplistic platooning concepts improve aerodynamics by maintaining two vehicles at a prescribed separation distance, but 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 the way some cars can have multiple suspension settings or performance settings depending on driver selection.

Trailer Geometry Morphing

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 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.

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 one-quarter of the annual mileage, hence only one-quarter of the possible aerodynamic efficiency gain from any investment in new technologies. But the core issues of the tractor-trailer ratio is 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 result in fuel savings thanks to aerodynamics.

Dedicated Truck Highways and Lanes

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

Electric and 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. Examples of what may be possible can be found in the Peterbilt/Walmart, Volvo, Tesla, Xos and Nikola concepts shown in Figure 88.

Figure 88: Battery Electric and Fuel Cell Electric Vehicles Offer The Possibility To Change The Shape Of The Vehicle (Peterbilt/Walmart, Volvo, Tesla, Xos, Nikola)

Combining Technologies

Taking the automation of vehicles forward to one conclusion, the future may see the driver operating a drone terminal similar to the driving simulators currently in use shown in Figure 89. This may 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 90.

Figure 89: Driving Simulator Could Be Drone Controller (TranSim)

Figure 90: 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 91 Taking it further, road trains are possible with independent units connecting and disconnecting in transit as conceived in this Volvo slipstream concept in Figure 92.

Figure 91: Possible 70 Foot Aero Trailer with Drone? (Renault)

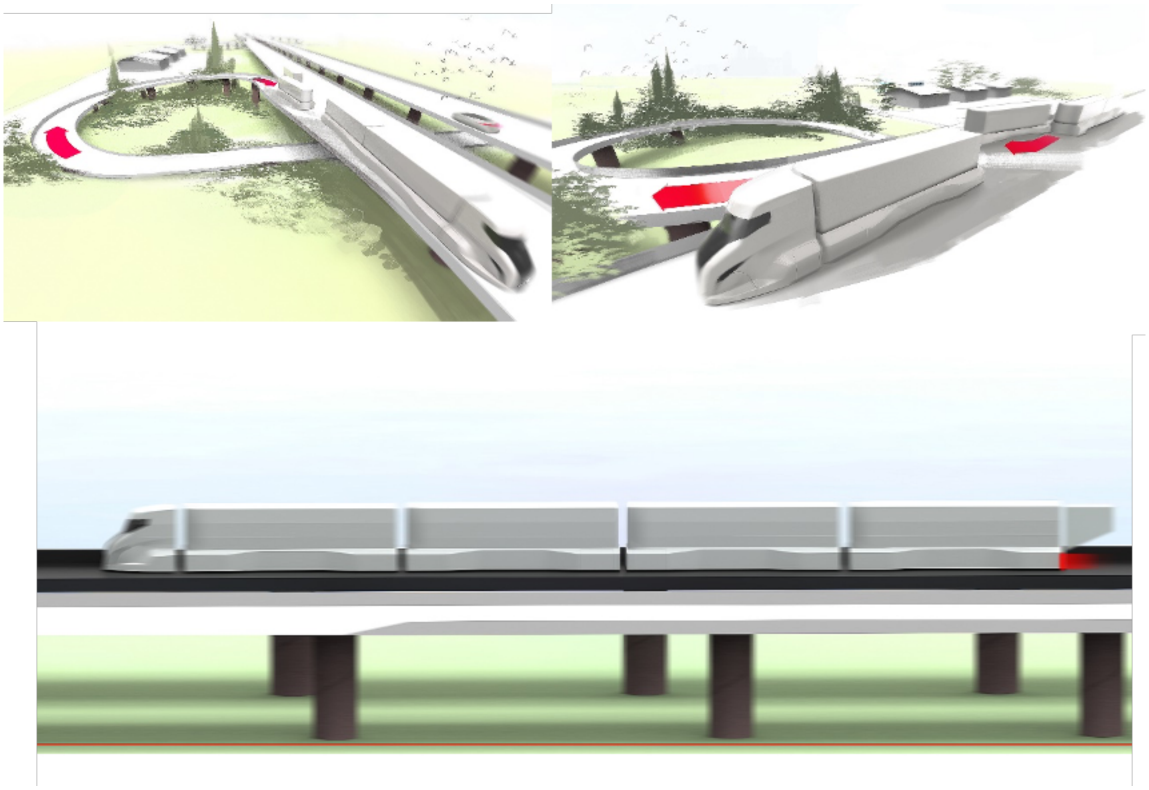


Figure 92: Volvo Slipstream Road Train

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

A report on how to improve trailer fuel efficiency 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, platooning and proposed autonomous vehicle technologies all can improve safe vehicle operations while offering other benefits to a fleet's bottom line.

Improving the ratio of tractors to freight hauled will eventually require allowing growth in use 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. These advances will need to be tied to changes in highway policies on size and weight. They will need to mitigate public safety concerns through innovations inherent in the automation technology development.

Due to such concerns, the one area that government, industry, and public groups have made little progress on since the Surface Transportation Assistance Act (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.

What are the differences between an operation with two tractors each pulling one 53' van trailer, or an operation with one tractor pulling two 53' van trailers in a Long Combination Vehicle (LCV) configuration? An 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 93, including for safety. [45]

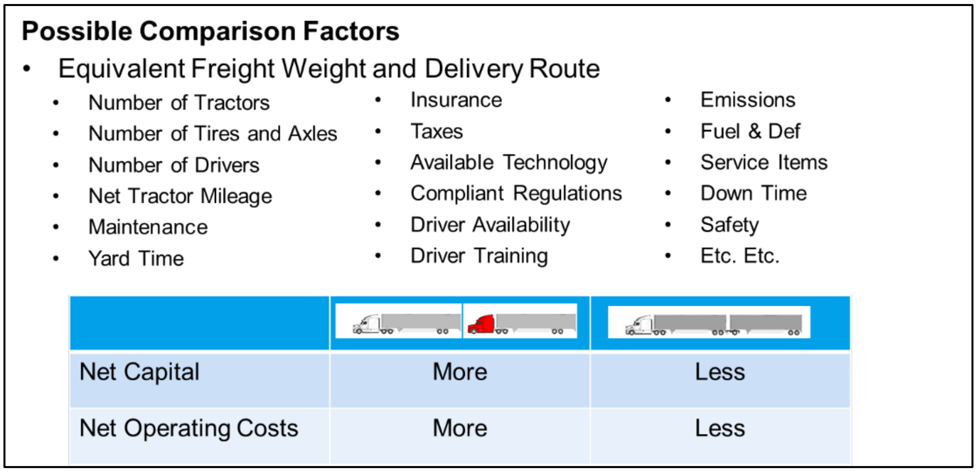


Figure 93: Comparison Factors (Mihelic)

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. Canadian, Oregon and Idaho operations with LCVs have documented that accident rates for LCVs are not significantly different than those of singles, so reducing the 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 on actual LCV operations in Canada, Oregon, and Idaho showed there was no significant difference in infrastructure maintenance costs while documenting significant reductions in cost of operations, fuel used, and corresponding reductions in emissions.

The discussion 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 lbs. 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 lbs. of freight to the same tractor.

10 Estimating Payback

It is critical to evaluate the total cost of ownership of adopting a particular technology. Most fleets estimate the payback using various financial models. A simple payback calculator is included with this Confidence Report publication package and can be downloaded as a spreadsheet here. This tool can be used to understand the payback on an investment in any aerodynamic device or combination of aerodynamic devices. The study team suggests monetizing all benefits and consequences of adoption in order to be as comprehensive as possible with this financial impact of adoption.

A screenshot of the output of the Calculator is shown below.

NACFE Study Payback Calculator: Trailer Aerodynamics Devices				
Yellow boxes are for user inputs				
Device(s) Name				**Notes:**
				Can be used per tractor or for all in the fleet
Number of Tractors	1	1	1	
Number of Trailers	3	5	3	
Miles per year per tractor	100,000	100,000	100,000	
Miles per year per trailer	33,333	20,000	33,333	
Benefits				
Fuel Economy				
Current fuel economy	6.0	6.0	6.0	
Gallons consumed per mile per trailer	5,556	3,333	5,556	
Fuel mpg improvement for device(s)	3%	3%	3%	
Gallons fuel saved per trailer with device	$ 166.67	$ 100.00	$ 166.67	
Cost of fuel per gallon over time	$ 3.00	$ 3.00	$ 4.00	
Fuel dollars saved per year per trailer	$ 500.00	$ 300.00	$ 666.67	
Other specific benefits	$ -	$ -	$ -	Includes any other benefits. E.g. Operating equipment in California,
Total benefits per trailer	**$ 500.00**	**$ 300.00**	**$ 666.67**	
Costs				
Upfront Costs				
Cost of Aero Device(s)	$ 700.00	$ 700.00	$ 700.00	
Installation Labor (when not factory install	$ 50.00	$ 50.00	$ 50.00	
Total Installed Cost	**$ 750.00**	**$ 750.00**	**$ 750.00**	
Annual Costs				
Mainenance costs with device	$ 25.00	$ 25.00	$ 25.00	
Other specific costs				Includes any other costs E.g. Driver retention or attraction issues
Total annual costs per trailer	**$ 25.00**	**$ 25.00**	**$ 25.00**	
Payback in months	**18.9**	**32.7**	**14.0**	
Payback in trailer miles	**52,632**	**54,545**	**38,961**	

As stated earlier, it is important to estimate the fuel efficiency performance that a fleet believes it will experience given their specific duty cycle of speed, routes, etc. TMC has developed and excellent tool to help with this challenge of determining the payback of trailer aerodynamic devices, specifically using time at various speeds for a fleet's duty cycle to predict the payback of such devices. RP 1118 provides equipment operators with a supplemental, interactive mathematical tool to evaluate the potential fuel and economic savings of an aerodynamic device that has been tested using one of TMC's fuel economy testing procedures.

11 Summary, Conclusions and Recommendations

11.1 Summary

Extensive insights into fleet decision making on trailer technologies were recently assembled in another report, a fleet survey by Ben Sharpe of ICCT and Mike Roeth of NACFE in the February 2014 ICCT/NACFE white paper *Costs and Adoption Rates of Fuel-Saving Technologies for Trailers in the North American On-Road Freight Sector*. [48] That report provided a table (Figure 94) summarizing cost and adoption rates.

Table 6: Summary of interview responses on trailer technology costs and level of adoption

Technology	Fuel Savings	Cost to End User		Typical Payback Time	Adoption In New Trailer Sales
		High	Low		
Side skirts – average	3%	$1,100	$700	1–2 years	40%
Side skirts – best	7%			< 1 year	
Boat tails – average	3%	$1,600	$1,000	2–3 years	3%
Boat tails – best	5%			1–2 years	
Gap reducers	1%–2%	$1,000	$700	2–5 years	Minimal
Underbody devices	2%–5%	$2,200	$1,500	2–5 years	3%
Low rolling resistance dual-sized tires	1%–3%	Data on costs and payback time inconclusive			50%
Wide base single tires	2%–4%	Data on costs and payback time inconclusive			10%
Tire pressure monitoring systems	1%	$1,000	$750	1-2 years	10%
Automatic tire inflation systems	1%	$1,000	$700	1-2 years	30%

Figure 94: Cost & Adoption Rates (ICCT/NACFE)

The ICCT white paper also presented these key findings with respect to trailer aerodynamic devices:

- The cost of trailer side skirts has decreased substantially over the past three to five years. Current costs for trailer aerodynamic technologies — particularly side skirts — have decreased significantly in recent years, due to far more market entrants driving cost competition and much higher deployment volumes reducing cost per unit. From the interview responses, it is estimated that costs for side skirts have dropped roughly 70% compared to cost estimates that were compiled as part of the 2010 National Academy of Sciences study that investigated fuel efficiency technologies for commercial vehicles. [6] A consensus position from the interviewees was that California's tractor-trailer GHG regulation has been the primary driver for the rapid uptake and cost reductions of technologies but that an increasing number of fleets are adopting these aerodynamic devices because of attractive economics as well as improvements in the reliability and durability of products.

- Among aerodynamic technologies, side skirts have had the largest rate of adoption, while the uptake of underbody, rear-end, and gap reduction devices has been more limited. Interview responses and sales data show that side skirts are the dominant trailer aerodynamic technology, with boat tails and underbody devices making up a much smaller percentage of the market. The study team estimates that approximately 40% of new box trailers are sold with side skirts. Uptake of both underbody and rear-end devices is estimated to be roughly 3% of new box trailer sales, while sales of gap reducers have been fairly negligible and primarily limited to fleets that pair their trailers with day cabs.

- Roughly one-quarter of all trailers on the road in the U.S. have at least one aerodynamic technology (e.g., side skirts, underbody device, or boat tail). Feedback from trailer and component manufacturers gives evidence of a robust market for aerodynamic technologies for both new and used trailers. The responses from these industry experts suggest that about one-quarter of all trailers operating in the U.S. have at least one aerodynamic enhancement.

11.2 Study Conclusions

This report focuses primarily on sleeper tractors pulling van trailers on-highway in North America. It describes both individual and combinations of technologies and practices available to fleets in pursuit of fuel economy improvement, operating cost reduction, and greenhouse gas emissions decrease through the use of trailer aerodynamic devices. The study team found the following conclusions with respect to fleets, truck and trailer OEMs, manufacturers and others concerning the adoption of trailer aerodynamic devices.

- **Trailer aerodynamic devices save fuel**. There is significant data showing fuel savings for the various technologies. The priority for device adoption by fleets is side, underbody and gap and then other devices. Operators look to large fleets and mimic their technology decisions where these fleets have done sufficient testing before making the investments. In other cases, operators look to various research groups, laboratories, and independent evaluators to get aerodynamics guidance. Many other sources exist for aerodynamic device performance data: device manufacturers, tractor and trailer OEM's, EPA SmartWay, test organizations, government agencies, NGO's and professional organizations like SAE and TMC. The EPA SmartWay program has made noteworthy progress since its inception in 2004, providing the industry with a structure for cataloging and ranking trailer aerodynamic devices. It should be considered a foundation for further improvement in performance evaluation.

- **Devices have matured and will continue to improve.** Skirts have become lighter, less expensive and more robust improving their payback. Other devices are maturing but need continued development to improve their total cost of ownership. There is a widespread recognition of the further improvements and efficiency gains that stand to be achieved in trailer aerodynamics and tire technologies. In the interviews conducted for the ICCT report, all the component suppliers of aerodynamic technologies spoke of their technology development activities and next-generation products that will offer enhanced quality and fuel savings. [6] One of the aerodynamic device manufacturers asserted that its third-generation product would offer roughly an additional 40% reduction in aerodynamic drag over its second-generation product, and nearly a 100% improvement over its first-generation product. This and other anecdotes provide evidence that important innovations continue to materialize in trailer efficiency technology.

- **Unique challenges exist**. These include trailer-to-tractor ratio which limit the miles per trailer, some cases of the trailer aerodynamics purchaser not buying the fuel and lastly, devices should be driver passive: no driver interaction is required to deploy or stow. Solutions to these three challenges may include:
    - Limiting the trailer-to-tractor ratio, using trailer tracking and other tools will help increase the miles per trailer to improve payback
    - Creative incentives for tractor owners to share savings of pulling aerodynamic trailers is an attempt to limit the issue of the split incentive on purchasing devices

  - Devices that must be manually deployed/stowed have inherent procedural failure points, as drivers may not activate/retract the devices when/as needed.

- **Performance for each fleet is difficult to determine.** Performance of any device is subject to many variables and each operator will likely have their own experiences. But the standardized test methods are directionally useful in evaluating different devices and combinations of devices. Trailer aerodynamics and freight efficiency improvement have advanced significantly since the 1970s oil crisis first brought them to the industry. A range of products are now readily available that offer proven savings. As these products have matured, so has the industry's understanding of the need for improvements in the way fuel efficiency performance is measured and allocated. Advances in test and analysis continue to be made, but the tools available today tend to report performance judged under controlled, focused, operating conditions rather than representing the full range of operations possible in industry. These standardized methods are important and relevant, but end users of the data still need to adapt those results to their own specific operations. The greater a fleet operation varies from the controlled test conditions, the less beneficial the tests and analyses will be for them to make investment decisions and performance predictions. Although most fleets can measure tractor efficiency very closely, they do not have the tools to monitor the trailer efficiency at all.

- **Regulations will drive greater adoption.** GHG Phase II and CARB rules will drive much greater adoption of trailer aero devices in the near future, taking them from being add-on options to being standard equipment. [9, 10, 11, 32] The Greenhouse Gas Phase II emissions rules are likely to significantly influence trailer aerodynamic technology adoption. The rules have been released but await litigation proceedings before they can be implemented at this time. California's existing CARB rules, which are linked to EPA SmartWay designated technologies, are already influencing some investment decisions. However, the primary motivation for aerodynamic technology investment remains a business one, with fleets demanding a two year or less payback for technologies.

- **Aerodynamic devices must work without driver intervention.** History has shown that devices that need driver intervention — such as first generation trailer tails — are not effective solutions as drivers do not deploy them 100% of the time. When a device that needs to be deployed is not being used, the fleet will not reap the fuel economy benefits it had hoped for. Second generation rear devices are addressing some of the challenges of the earlier versions of those devices. Future aerodynamic devices must work without needing driver involvement in their operation.

11.3 Recommendations

The study team has the following recommendations for those engaged in adopting or providing aerodynamic devices.

- Both aerodynamic device suppliers and fleets need to have better communication concerning performance. Fleets should ask more questions to clarify how performance claims will apply to their specific operations, while device suppliers need to provide better clarity on how device testing was completed.

- Manufacturers and trailer integrators should increase development efforts to improve the total cost of ownership/payback of the devices — lower upfront costs, better performance, lighter weight, less maintenance and driver interaction, better reliability and durability, etc. Creating driver passive devices is also critical.

- Research into advanced aerodynamic technologies should continue, so that these devices can better meet end-users payback expectations.
- Organizations like SAE, TMC, EPA, CARB need to push for improved aerodynamic assessment and correlation to real world conditions, including having official reference vehicles and improved on-board non-obtrusive methods for assessing aerodynamics of test vehicles so accuracy can be determined, not just precision.

12 Prioritizing Actions

Fleets make technology investments by prioritizing the best returns on investment, but once that investment is made, the priority list inherently must be shuffled as the best has been removed (implemented). This continuous reevaluation of technology alternatives highlights a critical fact about aerodynamic devices, namely, the fact that the aerodynamic technologies a vehicle already has installed will largely determine the next ones to consider for making trailer performance improvements. Figure 95 outlines NACFE's recommendations for how fleets should prioritize investment in a suite of trailer aerodynamic devices, depending on their own starting point.

If you are currently running this trailer configuration:	**This might be your next best step for better trailer aerodynamics:**
Aero tractor with typical dry van trailer	Add trailer skirts
Trailer with side skirts	Add trailer rear device
Trailer with side skirts and manually deploying rear boat tail	Convert to the second generation trailer rear devices
Trailer with side skirts and rear boat tail	Add trailer front nose fairing
Trailer side skirts, rear boat tail and nose fairing	Start investigating other minor areas such as wheel covers, license plate position, and vented mud flaps.
Day cab tractor with larger tractor-trailer gap	Add trailer-mounted gap device

Figure 95: NACFE Trailer Technology Recommendations

13 Confidence Rating

For each of the Confidence Reports completed by NACFE, 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 NACFE 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 there is high confidence in those short payback times, usually because the technology is more mature or otherwise has a more substantial track record of results.

NACFE is highly confident that all fleets should be considering the aerodynamics of their trailers, and the adoption of devices which will improve aerodynamics, as a major opportunity to save fuel. The best package of devices to adopt will depend on a fleet's unique duty cycle. But overall, available savings are likely quite high, up to 10%, for most fleets running 53' dry box trailers. (See Figure 96.)

Moreover, many regulations are likely to manage the adoption of trailer aerodynamic devices in coming years, so fleets which have not even begun to consider this opportunity will be wise to do so in anticipation of mandates.

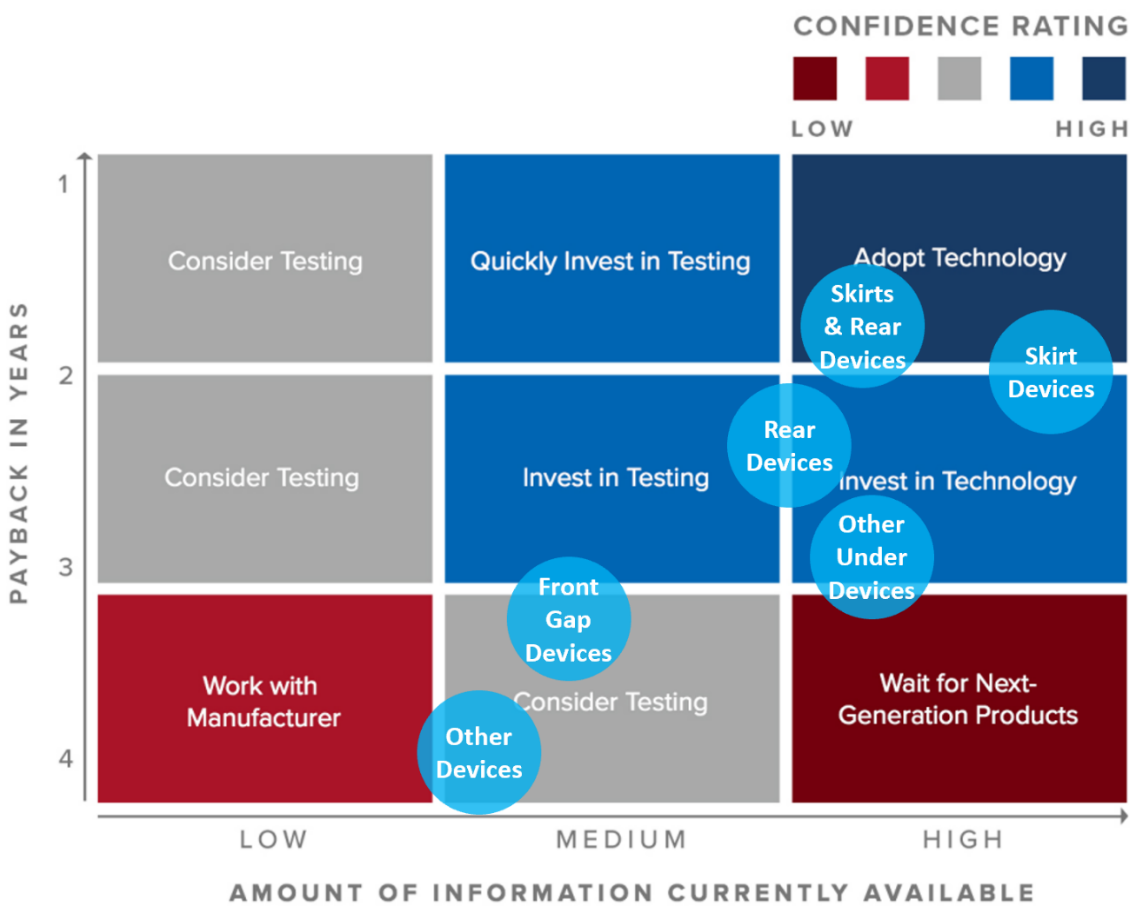


Figure 96: Confidence Matrix of Trailer Aerodynamic Device Technologies
On-Highway Van Trailer/Tractors

14 Appendix A – EPA SmartWay Verified Aerodynamic Trailer Devices

The following is a sample page of the EPA SmartWay Verified List of Aerodynamic Devices for trailers. It can be found on the EPA SmartWay website.

.

Device Name	Fuel Savings Category	Device Category	Testing Method	Test Protocol
Wabash Ventix DRS & Wabash AeroFin	9% Elite Combination	Skirt, Tail	WindTunnel (2014)	Post-2014
Wabash AeroFin XL & Ventix DRS ABC Standard	9% Elite Combination	Skirt, Tail	WindTunnel (2014)	Post-2014
Transtex E-2332TI Skirt (recessed installation) + T30 Tail	9% Elite Combination	Skirt, Tail	WindTunnel (2014)	Post-2014
Transtex E-2330T Skirt (flush installation) + E-Tail436	9% Elite Combination	Skirt, Tail	WindTunnel (2014)	Post-2014
Transtex E-1932T Skirt + T30 Tail + Dome Gap Reducer	9% Elite Combination	Skirt, Tail, Gap Reducer	WindTunnel (2014)	Post-2014
Ridge Corp. RAC0054 Skirt + Green Tail RAC0048 + Freight Wing Gap Reducer	9% Elite Combination	Skirt, Tail, Gap Reducer	WindTunnel (2014)	Post-2014
Ridge Corp. RAC0054 Skirt + Green Tail RAC0048	9% Elite Combination	Skirt, Tail	WindTunnel (2014)	Post-2014
Ridge Corp. RAC0012 Skirt + Green Tail RAC0048	9% Elite Combination	Skirt, Tail	WindTunnel (2014)	Post-2014
Laydon 514 Elite Trailer Fairing Package	9% Elite Combination	Skirt, Gap Reducer	WindTunnel (2014)	Post-2014
ATDynamics AeroTrailer™ 2 (with TrailerTail® Trident)	9% Elite Combination	Skirt, Tail	WindTunnel (2014)	Post-2014

Figure 97: Sample of EPA SmartWay Verified Aerodynamic Trailer Devices page

15 References

1. U.S. Energy Information Administration, Gasoline and Diesel Fuel Update, https://www.eia.gov/petroleum/gasdiesel/
2. American Transportation Research Institute, Operational Costs of Trucking 2019 Update, https://truckingresearch.org/2019/11/04/an-analysis-of-the-operational-costs-of-trucking-2019-update/
3. North American Council for Freight Efficiency, Annual Fleet Fuel Study, https://nacfe.org/annual-fleet-fuel-studies/
4. U.S. Department of Energy, 21st Century Truck Partnership, Roadmap and Technical White Papers, December 2006, https://www.energy.gov/sites/prod/files/2014/03/f8/21ctp_roadmap_2007.pdf
5. University of Maryland, Division of Research, Glenn L. Martin Wind Tunnel, https://research.umd.edu/glenn-l-martin-wind-tunnel
6. National Academies of Sciences, Engineering, Medicine, Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles, 2010, https://www.nap.edu/catalog/12845/technologies-and-approaches-to-reducing-the-fuel-consumption-of-medium-and-heavy-duty-vehicles
7. U.S. Environmental Protection Agency, SmartWay, https://www.epa.gov/smartway
8. Truck Manufacturers Association, Test, Evaluation and Demonstration of Practical Devices/Systems to Reduce Aerodynamic Drag of Tractor/Semitrailer Combination Unit Trucks, Final Report, April 2007, https://www.osti.gov/servlets/purl/926158
9. California Air Resources Board, ARB Adopts Landmark Rules To Clean Up Pollution From "Big Rigs", December 12, 2008, https://ww2.arb.ca.gov/news/arb-adopts-landmark-rules-clean-pollution-big-rigs
10. California Air Resources Board, Truck and Bus Regulations 2014, https://ww3.arb.ca.gov/regact/2014/truckbus14/truckbus14.htm
11. U.S. Environmental Protection Agency, Regulations for Emissions from Vehicles and Engines, Final Rule for Phase 2 Greenhouse Gas Emissions Standards and Fuel-Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles, October 25, 2016, https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-phase-2-greenhouse-gas-emissions-standards-and
12. North American Council for Freight Efficiency, Determining Efficiency, January 28, 2016, https://nacfe.org/report-library/determining-efficiency/
13. National Research Council Canada, Review of Aerodynamic Drag Reduction Devices for Heavy Trucks and Buses, May 11, 2012, https://www.airmansystems.com/ewExternalFiles/Canadian-AERODYNAMICS_REPORT-MAY_2012.pdf
14. National Research Council Canada, Improving The Aerodynamic Efficiency of Heavy-Duty Vehicles: Wind Tunnel Tests Results of Trailer-Based Drag-Reduction Technologies, https://nrc-publications.canada.ca/eng/view/ft/?id=2bb332d0-924d-445b-bf23-9658934e59e0
15. Society of Automotive Engineers, Recommended Practice for Splash and Spray Evaluation, J2245_199404, https://www.sae.org/standards/content/j2245_199404/

16. Technology & Maintenance Council, Splash & Spray Suppression Guidelines, RP 759, https://tmcconnect.trucking.org/tmclibraries/newrplibrary?ssopc=1
17. Berg, T., Aerodynamic Designs Help Cut Water Spray, Heavy Duty Trucking HDT, September 2015, https://www.truckinginfo.com/156364/aerodynamic-designs-help-cut-water-spray
18. North American Council for Freight Efficiency, Confidence Report: Lightweighting, August 2015, https://nacfe.org/technology/lightweighting-2/
19. U.S. Environmental Protection Agency, Transportation, Air Pollution, And Climate Change, https://www.epa.gov/transportation-air-pollution-and-climate-change
20. Society of Automotive Engineers, Fuel Consumption Test Procedures – Type II J1321_201202, https://www.sae.org/standards/content/j1321_201202/
21. Society of Automotive Engineers, Fuel Consumption Test (Engineering Method), J1526_201509, https://www.sae.org/standards/content/j1526_201509/
22. Society of Automotive Engineers, Truck and Bus Aerodynamic Device and Concept Terminology, J2971, https://www.sae.org/standards/content/j2971_201908/
23. Society of Automotive Engineers, Road Measurement Using Coastdown Techniques, J2978, https://www.sae.org/standards/content/j2978/
24. Society of Automotive Engineers , Guidelines for Aerodynamic Assessment of Medium and Heavy Commercial Ground Vehicles Using Computational Fluid Dynamics, J2966_201704, https://www.sae.org/standards/content/j2966_201704/
25. Society of Automotive Engineers, SAE Wind Tunnel Test Procedure for Trucks and Buses, J1252_201207, https://www.sae.org/standards/content/j1252_201207/
26. Society of Automotive Engineers, Joint RCCC/SAE Fuel Consumption Test Procedure (Short Term In-Service Vehicle) Type I (Stabilized May 2011), J1264_201105, https://www.sae.org/standards/content/j1264_201105/
27. Society of Automotive Engineers, Road Load Measurement and Dynamometer Simulation Using Coastdown Techniques, J1263_201003, https://www.sae.org/standards/content/j1263_201003/
28. Society of Automotive Engineers, Road Load Measurement Using Onboard Anemometry and Coastdown Techniques, J2263_202005, https://www.sae.org/standards/content/j2263_202005/
29. Federal Register, Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles-Phase 2, October 25, 2016, https://www.federalregister.gov/documents/2016/10/25/2016-21203/greenhouse-gas-emissions-and-fuel-efficiency-standards-for-medium--and-heavy-duty-engines-and
30. U.S. National Institute of Standards and Technology, Bias and Accuracy, https://www.nist.gov/fusion-search?s=Bias+and+Accuracy
31. Society of Automotive Engineers, Reynolds Number Impact on Commercial Vehicle Aerodynamics and Performance, 2015-01-2859, https://www.sae.org/publications/technical-papers/content/2015-01-2859/
32. U.S. Environmental Protection Agency, Regulations for Emissions from Vehicles and Engines, Greenhouse Gas Emissions Model (GEM) for Medium- and Heavy-Duty Vehicle Compliance, https://www.epa.gov/regulations-emissions-vehicles-and-engines/greenhouse-gas-emissions-model-gem-medium-and-heavy-duty

33. Cooper, K., Commercial Vehicle Aerodynamic Drag Reduction: Historical Perspective as a Guide, https://link.springer.com/chapter/10.1007/978-3-540-44419-0_2
34. Society of Automotive Engineers, Truck Aerodynamics Reborn – Lessons from the Past, 2003-01-3376, https://www.sae.org/publications/technical-papers/content/2003-01-3376/
35. Society of Automotive Engineers, A Parametric Assessment of Skirt Performance on a Single Bogie Commercial Vehicle, 2013-01-2415, https://www.sae.org/publications/technical-papers/content/2013-01-2415/
36. Park, J., Aero Add-ons Put to the Test, Heavy Duty Trucking, November 8, 2013, https://www.truckinginfo.com/153351/aero-add-ons-put-to-the-test
37. Society of Automotive Engineers, EPA SmartWay Verification of Trailer Undercarriage Advanced Aerodynamic Drag Reduction Technology, 2012-01-2043, https://www.sae.org/publications/technical-papers/content/2012-01-2043/
38. Society of Automotive Engineers, Practical Devices for Heavy Truck Aerodynamic Drag Reduction, 2007-01-1781, https://www.sae.org/publications/technical-papers/content/2007-01-1781/
39. Society of Automotive Engineers, The Unsteady Wind Environment of Road Vehicles, Part One: A Review of the On-road Turbulent Win Environment, 2007-01-1236, https://www.sae.org/publications/technical-papers/content/2007-01-1236/
40. Society of Automotive Engineers, The Unsteady Wind Environment of Road Vehicles, Part Two: Effects of Vehicle Development and Simulation of Turbulence, 2007-01-1237, https://www.sae.org/publications/technical-papers/content/2007-01-1237/
41. The National Academies of Science, Engineering, Medicine, Review of the 21st Century Truck Partnership, https://www.nap.edu/catalog/21784/review-of-the-21st-century-truck-partnership-third-report
42. Society of Automotive Engineers, Understanding Practical Limits To Heavy Truck Drag Reduction, 2009-01-2890, https://www.sae.org/publications/technical-papers/content/2009-01-2890/
43. Oregon Department of Transportation/Oregon Transportation Research And Education Consortium, Freight Performance Measures: Approach Analysis, May 2010, https://www.oregon.gov/ODOT/Programs/ResearchDocuments/Freight_Performance_Measures.pdf
44. Rocky Mountain Institute, Transformational Trucks: Determining the Energy Efficiency Limits of a Class 8 Tractor Trailer, 2008, https://rmi.org/insight/transformational-trucks-determining-the-energy-efficiency-limits-of-a-class-8-tractor-trailer/
45. Society of Automotive Engineers, Aerodynamic Comparison of Tractor-Trailer Platooning and A-Train Configuration, 2015-01-2897, https://www.sae.org/publications/technical-papers/content/2015-01-2897/
46. International Council of Clean Transportations, February, 18, 2014, Costs and Adoption Rates of Fuel-Saving Trailer Technologies, https://theicct.org/publications/costs-and-adoption-rates-fuel-saving-trailer-technologies
47. North American Council for Freight Efficiency, Confidence Report: Idle-Reduction Technologies, July 30, 2019, https://nacfe.org/technology-guide/idle-reduction/
48. U.S. Environmental Protection Agency, Verified Technologies for SmartWay and Clean Diesel, https://www.epa.gov/verified-diesel-tech/smartway-verified-list-low-rolling-resistance-lrr-new-and-retread-tire

49. North American Council for Freight Efficiency, Confidence Report: Tractor Aerodynamics, May 2016, https://nacfe.org/technology-guide/tractor-aerodynamics/
50. National Highway Traffic Safety Administration, The Effect of Increased Speed Limits in the Post-NMSL Era, February 1998, https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/808637
51. United Stated Census Bureau, The Vehicle Inventory and Use Survey, https://www.census.gov/library/publications/2002/econ/census/vehicle-inventory-and-use-survey.html