Reducing Aerodynamic Drag & Rolling Resistance from Heavy-Duty Trucks:

Summary of Available Technologies

&

Applicability to Chinese Trucks

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The ICCT promotes best practices and comprehensive solutions to improve vehicle emissions and efficiency, increase fuel quality and sustainability of alternative fuels, reduce pollution from the in-use fleet, and curtail emissions from international goods movement.

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Executive Summary

This report summarizes the commercial technologies available in the U.S. and Europe that can be used to improve the fuel efficiency of heavy freight trucks by reducing aerodynamic drag and rolling resistance, and evaluates their applicability to Chinese heavy trucks. These technologies are most effective when applied to the largest, combination trucks (truck plus trailer) that spend significant time traveling at highway speeds, which are responsible for a large share of fuel consumption. There are numerous commercially-available devices designed for retrofit onto both trucks and trailers.

There are at least twenty companies that sell aerodynamic aids for U.S. heavy trucks and trailers. For trucks, these aids include: roof and side fairings, vortex generators and air dams. For trailers, these aids include: gap reducers, nose cones, side skirts, under body fairings, and boat tails/end fairings. Some US suppliers and domestic manufacturers are selling roof fairings and side fairings for use on new tractors and for retrofits on in-use fleet in China. Virtually all tire companies that supply the U.S. heavy truck market sell low rolling resistance tires and several also sell single-wide tires. Additional companies sell automatic tire monitoring or inflation systems to maintain proper tire pressure, also to reduce rolling resistance.

Wind tunnel and in-use testing on test tracks indicates that individual aerodynamic aids can reduce distance-specific fuel use (l/100km) from U.S. trucks by 1% to 15%; packages of several different types of devices together can reduce fuel use by 25% or more. Testing has also demonstrated that low rolling resistance tires can reduce fuel use from U.S. trucks by approximately 3% while the use of single-wide tires in lieu of traditional dual tire sets on truck rear axles and trailer axles can reduce fuel use by up to 9%. Automatic tire inflation systems have been shown to reduce fuel use by 0.5% to 1.2%.

The fuel efficiency benefit of aerodynamic aids is sensitive to truck speed – the faster a truck typically travels, the greater the reduction in fuel use. Rolling resistance is insensitive to speed, but is proportional to truck weight; low rolling resistance tires therefore provide greater benefits on heavier trucks than on lighter trucks. In comparison to U.S. trucks, Chinese freight trucks typically travel at lower speeds (70 km/hr compared to 105 km/hr), but operate at significantly higher gross weight (49,000 kg or more compared to 36,000 kg). As such, the expected benefits of aerodynamic aids will be smaller for Chinese trucks than for U.S. trucks, but the expected benefits of reduced rolling resistance will be greater.

For Chinese trucks typically traveling at 70 km/hr, a full package of retrofit aerodynamic aids applied to both the truck and the trailer might be expected to reduce fuel use by 11% or more. This would provide an annual fuel savings of 6,500 liters or more for a typical Chinese heavy combination truck. If combined with low rolling resistance tires and automatic tire inflation systems for both the truck and trailer, fuel use might be reduced by up to 20% - saving up to 11,800 liters of fuel per truck annually.

This report does not review the costs and economic benefits of aerodynamic or low rolling resistance technologies nor does it provide a detailed review of availability in China. These are areas of potential future research.

1. Background

Typical diesel engines used in heavy-duty combination trucks in the U.S. have an average thermal efficiency of approximately 33%; i.e. approximately 33% of the energy contained in the fuel is converted to useful energy as measured at the engine output shaft. The remaining 67% of energy is lost to friction in the engine and as heat that is released through the exhaust system or through the engine's cooling system. A small fraction of the useful energy produced by the engine is used by the drive train and transmission, and the remainder is used to propel the vehicle forward and run auxiliary loads such as the alternator, the air compressor, and hydraulic fans. To propel the vehicle forward the engine must provide enough power after losses and other loads to overcome inertia, gravity, aerodynamic drag, and rolling resistance [1].

Once a truck is moving on a level road, the use of energy is different than average conditions. As an example, Figure 1 shows the percentage contribution of various energy uses for a typical combination truck in the United States operating at highway speeds on a level road. In this case, 40% of the energy contained in the fuel burned by the engine is turned into useful work as measured at the engine output shaft (i.e., the thermal efficiency of the engine is greater than the average condition). Additionally, 85% of the useful energy produced by the engine is used to overcome aerodynamic losses and rolling resistance, with negligible losses to inertia and gravity [2].

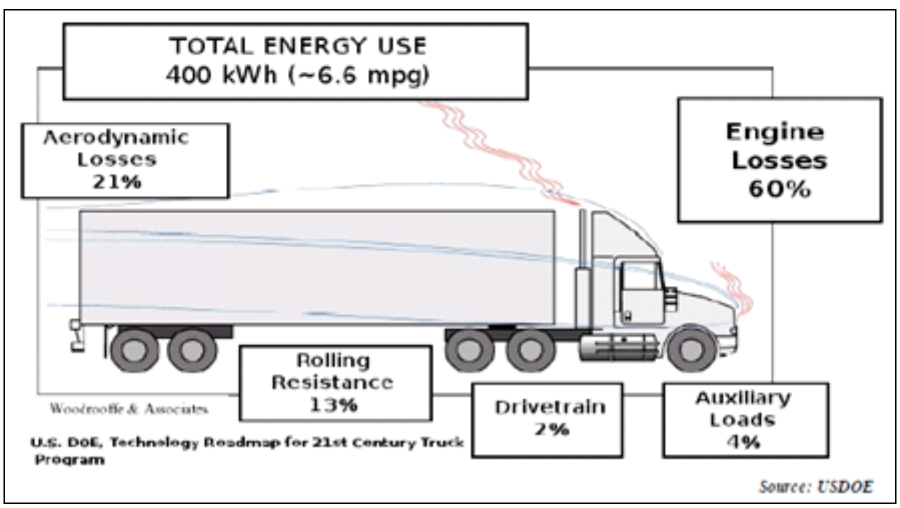

Figure 1. Components of Energy Use on a Long-Haul Combination Truck Traveling on a Flat Road at 65 Miles per Hour. [2]

The counter example to Figure 1 is a vehicle accelerating from a stopped position. At the moment it starts moving, the vehicle's thermal efficiency would be less that the average condition and more than half of the useful energy would be used to overcome inertia and gravity, with a much smaller fraction being used to overcome aerodynamic drag and rolling resistance [1].

Since long-haul combination trucks spend the majority of time operating at high, relatively constant speed (i.e. highway driving), strategies to improve their energy efficiency should focus on reducing rolling resistance and reducing aerodynamic losses, two areas that account for about 85% of energy use in a moving vehicle. These two areas are particularly attractive because a number of relevant technologies are commercially available and most of these technologies can be used to retrofit existing vehicles.

2. Reducing Aerodynamic Drag

Aerodynamic drag, also called wind resistance, is a retarding force exerted on a vehicle by the air through which it moves. As a truck travels forward, it breaks up the flow of air, creating an area of low air pressure behind the body or trailer (the wake). The high pressure air surrounding the wake then moves into the low-pressure area, exerting a force that pulls the vehicle backwards. Low pressure areas created in the gap between the tractor and the trailer, and underneath the truck, similarly contribute to aerodynamic drag.

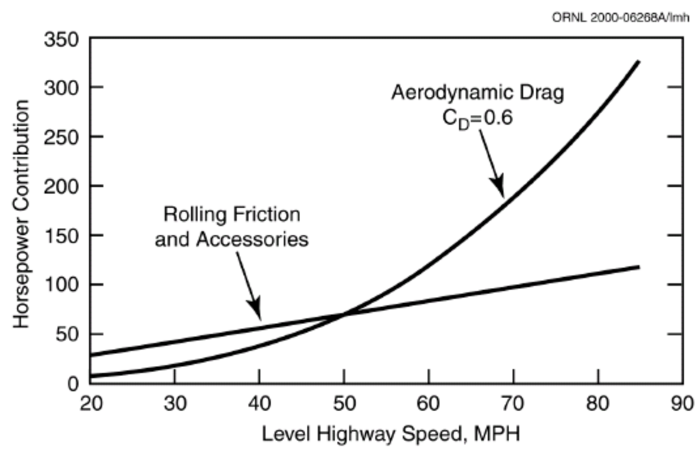

Figure 2. Horsepower required to overcome aerodynamic drag and rolling friction/accessories as a function of travel speed for a typical Class 8 tractor-trailer. [2]

The amount of energy required to overcome aerodynamic drag is affected by three factors: 1) the effective frontal surface area of the vehicle, 2) the shape of the vehicle, and 3) the speed at which the vehicle is traveling. A vehicle with less frontal surface area will have lower drag. A vehicle with a rounded or stream-lined shape will also have lower aerodynamic drag since air flow separation will be less dramatic (i.e. reduced wake). As shown in Figure 2, the power required to overcome aerodynamic drag increases as a function of the cube of vehicle speed. Distance-specific fuel consumption (liter per 100 kilometers, l/100km) required to overcome aerodynamic drag increases as a square of vehicle speed[1].

Aerodynamic drag on a tractor-trailer is affected by: 1) the shape of the tractor cab, the transition between the back of the cab and the front of the trailer, 2) the gap distance between the tractor and the trailer, 3) the underbody of the truck, and 4) the rear edge of the trailer [3]. These areas are highlighted in Figure 3. Efforts to reduce aerodynamic drag are based on the following principles:

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[1] Fuel consumption (energy per unit distance) is equal to Power (energy per unit time) divided by speed (distance per unit time).

1.) The cab should be shaped as aerodynamically as possible, and there should be a smooth transition between the top of the cab and the top of the trailer (either through height matching or connections that create a smooth line between the two) [2]
2.) The gap distance between the tractor and the trailer should be minimized, by positioning the two as close together as possible or blocking the air flow into the gap [2]
3.) Air should be blocked from traveling under the truck, or the underbody of the truck should be made as aerodynamic (smooth) as possible [2]
4.) The rear end of the trailer should be rounded or extended in a way that creates a more aerodynamic shape [4]

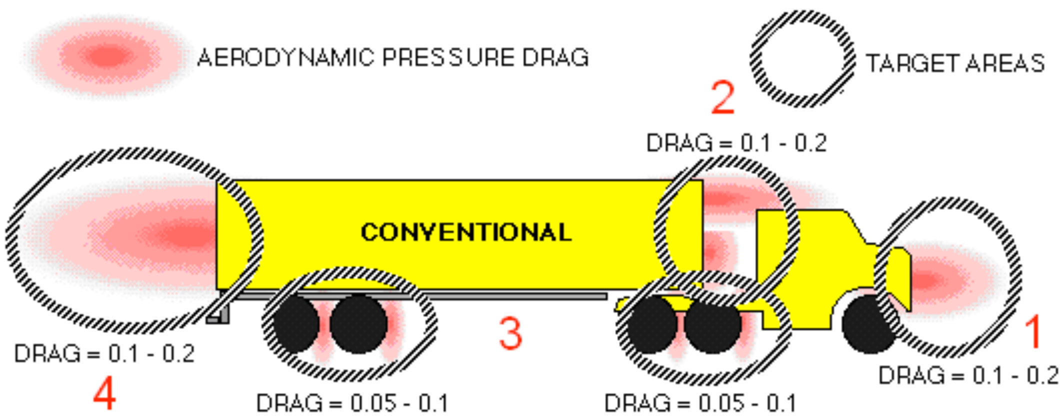

Figure 3. Drag contributions of areas on a conventional truck-trailer. [5]

Improvements in these areas offer potential for significant fuel savings, especially when applied to vehicles that operate at high speed. The U.S. Environmental Protection Agency estimates that improving the aerodynamics of typical U.S. combination trucks can improve fuel economy by up to 15%, reduce annual fuel use by up to 8,860 liters and save up to US$3,644 in annual fuel costs per truck [6].

2.1 Commercial Devices Available

Aerodynamic improvements can be incorporated into the design and manufacture of new trucks and trailers. Devices or components which will improve their aerodynamic performance can also be retrofit onto existing trucks and trailers. Both the U.S. Department of Energy [2] and the Platform for Aerodynamic Road Transport, based in the European Union [7] have conducted extensive research into available technologies/devices.

The specific devices highlighted below are commercially available in the United States and/or in the European Union. These same devices, or similar devices constructed based on the same design principles, could be adapted for use on Chinese trucks.

Truck Technologies

Many newer U.S. and European truck models are designed specifically with aerodynamics in mind; these trucks have an overall smoother shape than a “traditional” truck, with a sloped windshield, a smooth transition between truck cab and body, and headlights recessed out of the airflow [3]. The images below (Figure 4 and Figure 5) depict how aerodynamically shaped cabs compare to traditional models for both conventional U.S. and cab-over (EU) engine tractors.

Figure 4. Conventional Cab – Peterbilt Model 389 (left), Peterbilt Model 587 (right). [8]

Figure 5. Cab-Over Engine – 1982 DAF 3300 DKX Series (left), DAF XF105 Series (right). [9]

To a limited extent, older in-use trucks can also be modified to improve aerodynamics. Most strategies have the greatest utility when applied to combination trucks (trucks pulling a trailer), but some of them will also be applicable to single unit trucks. The strategies available to modify older trucks include:

- *Roof fairings or air deflectors*: these components change the shape of the cab roof and direct air flow smoothly over the top of the truck cab and the truck body or trailer.
- *Side fairings and side extenders*: these modify the shape of the sides of the cab to make it more aerodynamic, or extend past the rear edge of the cab to keep airflow from entering the gap between the truck and trailer as much as possible.
- *Aerodynamic side mirrors, or replacing mirrors with cameras*: these reduce the drag caused by rear-view mirrors that stick out from the cab.
- *Vortex generators*: these are plates attached to the rear edge of the truck cab, which are specially shaped to create vortices that keep air flow from entering the truck-trailer gap.

- *Air dam*: this is a downward extension of the truck's front bumper that blocks air from traveling under the truck and instead redirects it upward, over the more aerodynamic front and top of the cab.

Commercial examples of these approaches are shown in Table 1.

Trailer Technologies

While aerodynamic truck technologies have been widely adopted in the U.S., trailer add-ons are less common. Truck modifications are easier and less expensive to implement throughout a fleet in the U.S. because owners of fleets typically have only one tractor for every three trailers [3]. However, aerodynamic drag is shared roughly equally between trucks and trailers [3] so trailer modifications are important to consider as well. Strategies include:

- *Front fairings and nose cones*: these are modifications to the front of the trailer, above the tractor cab, that direct airflow more smoothly over the trailer. They are generally curved, convex structures.
- *Side skirts*: like air dams on the tractor, these attach to the bottoms of the sides of the trailer and block airflow underneath the trailer, particularly in crosswinds.
- *Aerodynamic underbody*: the underbody of the trailer can be made more aerodynamic by adding fairings that redirect air around underbody components, such as wheels and axles.
- *Boat tails*: these are tapering extensions to the trailer that reduce the amount of wake at the rear of the vehicle. They are often inflatable, flexible, or retractable to make unloading easier.
- *Vortex generators*: the vortex generators mentioned in the truck section can also be installed on the back of the trailer, performing the same function by keeping high-pressure air from entering the low-pressure wake and causing drag.
- *Pneumatic blowing*: this technology is not yet commercially available, but has performed well in tests [10]. Air is blown from slits at the rear of the trailer, which causes the flow around the vehicle to be drawn in, diminishing the size of the wake.

To encourage the use of more fuel efficient equipment in the U.S. freight transport system the U.S. Environmental Protection Agency's SmartWay Transport program "certifies" new trucks and trailers, and verifies trailer aerodynamic add-on equipment, as being more fuel efficient than non-certified vehicles and non-verified equipment. SmartWay partners, both transport companies and their customers, are required to demonstrate that they are continually reducing the energy intensity of their freight operations; one way that they can demonstrate this is by increasing use of SmartWay-certified trucks and trailers and SmartWay-verified equipment.

To be SmartWay certified, trucks may be 2007 or newer Class 8[2] models and must have an aerodynamic profile and certain aerodynamic components, such as roof and side fairings,

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[2] In the US Class 8 trucks are the largest on the road, with gross vehicle weight rating greater than 15,000 kg. Virtually all combination truck/trailers are Class 8.

integral to the cab design. Additionally, the trucks must prove through a standardized test procedure (SAE J1321) that they meet or exceed the fuel efficiency of a model that is already SmartWay-certified [11].

For new trailers to be SmartWay-certified, they must be equipped with the following SmartWay-verified aerodynamic add-ons: side skirts; weight-saving technologies; gap reducer on the front or trailer tails (either extenders or boat tails); and options for low-rolling resistance tires (single wide or dual). Aluminum wheels are encouraged, but optional.

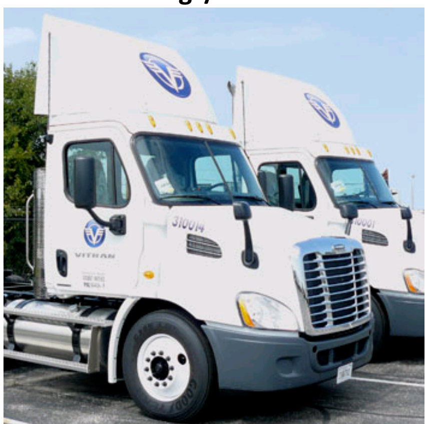
Trailer add-ons can be SmartWay-verified technologies in the following categories if standardized testing (SAE J1321) shows that they increase fuel economy (kilometers per liter) by 5% or more: trailer gap reducer and trailer side skirts (used in combination with one another); trailer boat tail and trailer side skirts (used in combination with one another); advanced trailer end fairing; and advanced trailer skirt.

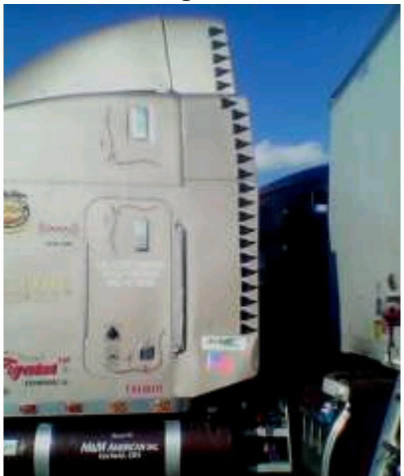
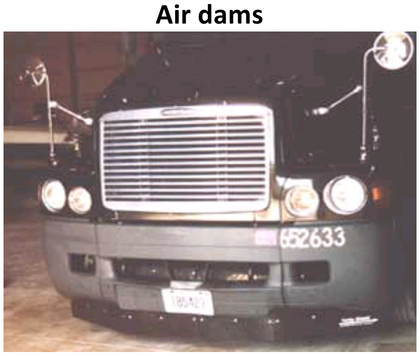
The SAE J1321 test procedure used for SmartWay certification is a paired-truck test conducted on a test track at a constant speed of 97 km/hr. The target truck or device is tested against a baseline truck, and fuel efficiency results are reported as a percent difference compared to the baseline. Multiple runs are conducted to ensure data repeatability.

Table 1 provides a summary of commercially available add-on aerodynamic devices for both tractors and trailers; this list is not comprehensive, but gives an idea of the wide availability of these technologies. SmartWay-verified technologies are highlighted in green. [3]

[3] EPA maintains a list of SmartWay-verified technologies at http://www.epa.gov/smartway/transport/what-smartway/verified-technologies.htm.

Table 1. Examples of commercially available aerodynamic technologies (SmartWay-verified technologies highlighted in green).

AERODYNAMIC TECHNOLOGY	MANUFACTURER:MODEL(S)
Roof fairings/air deflectors   	**Airodyne:** Multiple models, some collapsible, for Freightliner (pictured, top [12]) , Kenworth, Mack, Peterbilt, Sterling, Volvo and International tractors **Laydon Composites Ltd**: Collapsible air fairings and universal deflectors **DongGuan CAIJI:** Roof fairing (pictured, bottom [13])
Side fairings/cab extenders   	**Airodyne:** Multiple models, generally combined with roof fairings (pictured [12]) **DongGuan CAIJI:** Side fairing (pictured, bottom [13])

AERODYNAMIC TECHNOLOGY	MANUFACTURER:MODEL(S)
Vortex generators  	**Airtabs:** Back of cab (pictured, top [14]), back of trailer (pictured, bottom [14])
Air dams  	**Turbo Shield:** Model 3000 R and Model 8600 (pictured [15])

AERODYNAMIC TECHNOLOGY	MANUFACTURER:MODEL(S)
Trailer gap reducer 	**Carrier Transicold:** Gap Fairing (pictured [16]) **FreightWing**: Gap reducer **Laydon Composites:** Gap reducer **NoseCone:** "Nose 3-D" Gap reducer
Nose cones/trailer front fairings  	**NoseCone:** Frontal mount models (pictured, top [17]; Custom mount models; EyeBrow™ model **FreightWing:** NXT Leading Edge Fairing **DongGuan CAIJI:** Nose cone (pictured, bottom [13])
Trailer side skirts 	**Carrier Transicold:** Belly Fairing **Fleet Engineers:** Extended Air Slipper **Freight Wing:** Belly Fairing Trailer Skirts (pictured, prototype used in China GreenTrucks Pilot project [18]) **Laydon Composites**: Trailer Skirts (6 or 7 panel) **Ridge Corp.:** GreenWing RAC0002 **Silver Eagle**: Mid-length Skirt; Mini-skirt **Transtex**: Trailer Skirts **Utility Trailer**: Utility Side Skirt 120

AERODYNAMIC TECHNOLOGY	MANUFACTURER:MODEL(S)
Advanced trailer skirt 	**Aerofficient:** Aero-slide side fairing system (Model ASFS), Fixed side fairings (models FFGW and FFTI) **Airflow Deflector:** Deflector **ATDynamics-Transtex**: Trailer Side Skirts **Atlantic Great Dane**: AeroGuard Side Skirt (AGD400-43) **Carrier Transicold**: Aeroflex Fairing **FreightWing: Aeroflex** Trailer Skirt (pictured [19]) **Laydon Composites**: 8-Panel Trailer Skirt; Classic 7-Panel Trailerskirt, Hybrid 24 ft. Trailerskirt **Ridge Corp**.: GreenWing RAC0003 **Silver Eagle**: Aero Saber **Strehl:** Windblade (Model 715) **Sweet Bottom Trailer Skirt:** Trailer Skirt **Transtex:** MFS Trailer Side Skirts **Utility Trailer**: Utility Side Skirt 160 **Wabash National**: Advanced Trailer Side Skirt, DuraPlate AeroSkirt – Standard, DuraPlate AeroSkirt – Angled **Windyne**: Flex-Fairing **Ephicas**: Sidewing
Underbody fairings 	**SmartTruck:** UnderTray system (UT-5 or UT-6 base configuration) (pictured [20])

AERODYNAMIC TECHNOLOGY	MANUFACTURER:MODEL(S)
Trailer boat tail 	**Aerodynamic Trailer Systems (ATS):** Dual Lobe Boat Tail; SmartTail **AeroVolution** Inflatable Boat Tail **Transtex**: Rear Trailer Fairing (pictured [21]) **Slipstreem** Showtime 100
Advanced trailer end fairing 	**ATDynamics:** TrailerTail Rear Trailer Fairing **ATS:** Integrated Automated System (WindTamer with SmartTail) (pictured [22]) **SmartTruck** UT-6 **AFC Technologies**: Active Flow Control (pressurized air add-on device)

<table>
<tr><th>AERODYNAMIC TECHNOLOGY</th><th>MANUFACTURER:MODEL(S)</th></tr>
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Teardrop trailer

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Don-Bur: Teardrop MK2 (pictured [23])

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2.2 In-Use Experience & Test Data

Numerous studies have attempted to quantify the potential fuel savings from implementing aerodynamic improvements to combination trucks and trailers. Some of these studies are based on model results in wind tunnels and use reductions in measured drag coefficient to extrapolate expected fuel savings. Others studies are based on actual measured fuel use from trucks driving on a test track or on the highway.

See Table 2, which provides a summary of some of these studies. The fuel efficiency benefits of aerodynamic technologies are highly sensitive to vehicle speed; because the energy required to overcome aerodynamic drag is a function of the square of vehicle speed, all aerodynamic aids provide greater percent reduction in relative fuel use at higher speeds. All of the tests summarized in Table 2 were conducted at average speeds between 97 and 105 km/hr, reflective of U.S. highway operations. Table 2 includes the estimated benefit (% reduction in fuel use) of each tested device at the actual test speed, but also provides an estimate of the benefit that would accrue at 70 km/hr, which is assumed to better represent typical conditions for Chinese freight trucks.

Also note that the tests summarized in Table 2 were conducted with U.S. trucks with a maximum gross vehicle test weight of 36,000 kg. Chinese trucks have a legal gross vehicle weight of 49,000 kg, and are reportedly routinely overloaded. As such, Chinese trucks likely expend a greater percentage of total fuel use overcoming inertia and rolling resistance than U.S. trucks, and consequently, a lesser percentage of total fuel use to overcome aerodynamic drag. Given this, the potential benefits of aerodynamic technologies shown in Table 2 (percent reduction in fuel use) may be somewhat over-stated for Chinese trucks.

Table 2 also provides an estimate of the amount of fuel (liters) that could be saved per truck if these technologies were applied to Chinese freight trucks. This calculation is based on the following assumptions:

- Annual mileage accumulation: 120,000 km
- Average in-use speed: 70 km/hr
- Baseline fuel use from current trucks: 47.6 l/100km

The assumption of 47.6 l/100 km average fuel use is consistent with modeling of economy-wide Chinese vehicle fuel use conducted by the International Energy Agency, and reflects the assumption that Chinese trucks are routinely overloaded. The assumption of 70 km/hr average speed of freight trucks is based on a few data points collected from studies on in-use truck fuel use and emissions and is consistent with the average freight trucks speed data collected from the Jingjintang Expressway, a key highway corridor in China [24].

As shown in Table 2, individual aerodynamic devices can reduce fuel use (at 70 km/hr) by 0.5% to 6.6%, resulting in annual fuel savings of 297 to 3,752 liters per truck. Several approaches combined might produce fuel savings of 11% or more, resulting in an annual reduction in fuel use of 6,500 or more liters per truck.

Table 2. Estimated fuel savings from aerodynamic technologies

TECHNOLOGY	FUEL SAVINGS: % Reduction (Liters/100 km) Original Estimate	FUEL SAVINGS: % Reduction (Liters/100 km) Adjusted to 70 kph [1]	FUEL SAVINGS: Annual Savings [2] (Liters)	Source
Single Technology Aerodynamic Improvements				
Front Trailer Skirt	10.9% at 105 kph	4.9%	2,797	Cooper 2003[3] [25]
Front/Back Trailer Skirt	14.7% at 105 kph	6.6%	3,752	Cooper 2003[3] [25]
Side Skirt	4.8% at 105 kph	2.1%	1,219	EPA 2004 [26]
Gap Seal	4.0% at 105 kph	1.8%	1,027	Cooper 2003[3] [25]
Underbody Fairings (Aerodynamic Underbody)	6.4% at 100 kph	3.1%	1,791	SmartTruck Products 2010 [27]
	3.2% at 97 kph	1.7%	959	RMI 2005 [28]
Boat Tail	4.8% at 97 kph	2.5%	1,430	RMI 2005 [28]
	5.7% at 103 kph	2.6%	1,494	Slipstreem 2007
	6.1% at 105 kph	2.7%	1,557	Cooper 2003[3] [25]
Pneumatic Blower Device	7.4 - 8.3% at 105 kph	3.3% - 3.7%	1,895 – 2,113	Englar 2005 [10]
	1.2% at 97 kph	0.6%	356	RMI 2005 [28]
Cross Vortex Trap Device	4.8% at 97 kph	2.5%	1,430	RMI 2005 [28]
Electronic Vision System (No Mirrors)	1.0% at 97 kph	0.5%	297	RMI 2005 [28]
Multiple Technology Aerodynamic Improvements				
Cab Deflectors, Sloping Hood, Cab Side Flares	2.0% at 97 kph	1.0%	589	RMI 2005 [28]
Tractor-Trailer Gap, Wheel Wells, Baffles, Bumper	0.5% at 97 kph	0.3%	149	RMI 2005 [28]
Leading/Trailing Edge, Vortex Strake Device	2.0% at 97 kph	1.0%	589	RMI 2005 [28]
Aerodynamic Underbody + Nose/Side Fairings	9.9% at 100 kph	4.9%	2,787	SmartTruck Products 2010 [27]
Aerodynamic Tractor	13% at 105 kph	5.8%	3,338	EPA 2004 [26]

Design				
Front/Rear Trailer Skirts, Gap Seal, Boat Tail	25.4% at 105 kph	11.4%	6,493	Cooper 2003[3] [25]

[1] *% Reduction$_{V=70kph}$ = % Reduction$_{VT}$ * ($70^2 \div VT^2$); VT = average velocity of actual test (kph)*

[2] *Based on: 120,000 km annually, average speed 70 kph; baseline fuel consumption 47.6 Liters per 100 km. Baseline fuel consumption assumes regularly overloaded trucks. Based on the difference in weight between U.S. and Chinese trucks, the improvements from Aerodynamic technologies may be slightly overstated because % improvement is based on U.S. tests at a lower truck weight.*

[3] *Cooper 2003: Wind tunnel model results; % reduction relative to truck with a standard aerodynamic package including: cab shaping, cab-mounted deflectors, trailer front-end fairings, cab side extenders, body front-edge rounding, tractor-trailer gap seals, trailer side skirts, and rear boat tailings. Wind tunnel models tend to overestimate the actual savings from some aerodynamic improvement, but are effective in determining the appropriate design of equipment.*

2.3 Safety Issues and Concerns

While any modification to a vehicle can raise questions about safety, some aerodynamic improvements can enhance truck safety and stability. For example, pneumatic blowing systems can reduce drag at high speeds to increase fuel economy, and rapidly increase drag when necessary to allow rapid-response braking for improved operational safety [10]. Improved aerodynamics can also lead to better stability and performance in crosswinds, and reduced water spray in rainy weather.

However, there is some speculation that modifications that reduce aerodynamic drag overall – without the adaptability given by a pneumatic blowing system – could increase stress on braking systems by reducing the contribution of drag to slowing down the vehicle, which could have safety implications [2]. There are also concerns associated with certain aerodynamic improvements that increase the length of the trailer, such as boat-tails. These extensions at the rear of the vehicle can endanger other vehicles in the case of rear-end collision or if they swing into other lanes of traffic [4]. To promote highway safety, when evaluating technologies for the SmartWay Program, the U.S. Environmental Protection Agency requires tractors and trailers meet all applicable U.S. Department of Transportation safety requirements [29].

2.4 Operational Issues and Concerns

One operational difficulty in implementing aerodynamic improvements is maintaining the correct interplay between truck and trailer. Since trailers are interchangeable, it's important to coordinate within the fleet so that trucks and trailers are matched up in the optimal aerodynamic configuration [4]. Some aerodynamic technologies can also be damaged during normal operations. For example, cab side extenders, or other devices designed to reduce the gap between the tractor and trailer, can be crushed or distorted if the tractor turns at too sharp an angle in relation to the trailer. This typically occurs during loading or unloading operations [30]. Additionally, trailer side skirts can be damaged when driving in situations where there is little ground clearance, such as driving over railroad tracks [31].

There are also potential regulatory issues with aerodynamic modifications: some may make the truck too tall, wide or long to comply with size limits in certain jurisdictions. A report by the European Federation for Transport and Environment argues that aerodynamic trailer extensions should be exempt from length restrictions under European Union guidelines [4]. Where such legislative exemptions do not exist, care must be taken that aerodynamic modifications stay within size limits.

3. Reducing Rolling Resistance

The rolling resistance created by truck and trailer tires in contact with the roadway surface accounts for almost 13% of truck energy use for typical U.S. freight trucks [1]. Given their greater weight, Chinese freight trucks likely use an even greater percentage of total energy to overcome rolling resistance. Most of this energy is lost as heat created in the side wall of the tire as it deforms and recovers while rolling under the weight of the vehicle [33].

Various modifications to tires are available that can reduce their rolling resistance, including:

- use of different materials;
- use of tread patterns and geometries that reduce the deformation of the tire;
- use of wider single tires instead of dual-tire assemblies; and
- keeping tires inflated to the proper pressure, as defined by the tire manufacturer (manually or through automated means).

The engine power required to overcome rolling resistance is directly proportional to the speed and mass of the vehicle, while distance-specific fuel consumption (l/100km) required to overcome rolling resistance is proportional to the vehicle mass only, and is independent of speed.[4] The more heavily loaded a truck is, the greater the potential benefits of reducing rolling resistance, and these benefits can accrue even in relatively low speed duty cycles. Under certain circumstances, reducing rolling resistance by 15% can result in fuel savings of up to 5% [33].

3.1 Commercial Devices Available

Specially designed low-rolling resistance tires are available from a number of manufacturers in the U.S. and Europe. These include low-rolling resistance tires for traditional dual-tire assemblies (used on truck rear axle and trailer axles), as well as single wide-based tires (Figure 6), which are designed to replace traditional dual tire assemblies but are significantly lighter and also have lower rolling resistance. Low-rolling resistance tires are normally more expensive than traditional tires but are expected to be more durable. A large contributor to rolling resistance is the deformation and recovery of tire sidewalls, and a single wide-based tire has

[4] Fuel consumption (energy per unit distance) is equal to Power (energy per unit time) divided by speed (distance per unit time).

half as many sidewalls as a dual tire assembly. Efficiency standards also often recommend the use of aluminum wheels, which do not specifically reduce rolling resistance, but are lighter than steel wheels and improve fuel economy via reduction of both vehicle weight and rotational inertia of the tire assemblies. Aluminum wheels also dissipate heat far better than steel (saving tire life), which could be important if the truck is outfitted with more expensive low-rolling resistant tires. High-strength, low alloy wheels are a potential alternative to aluminum wheels with similar benefits at a lower cost.

Figure 6. Michelin® X One® wide-base tire, left, next to traditional dual-assembly tires. [34]

In the United States, the EPA SmartWay Transport program verifies tires that offer estimated fuel savings of at least 3% compared to the best-selling tires[5]. Table 3 lists the SmartWay-verified tires by manufacturer; some are single wide-base tires, and others are low rolling-resistance tires designed for dual assemblies. Virtually all manufacturers selling into the U.S. heavy truck market offer SmartWay-verified models.

Table 3. SmartWay-verified low rolling-resistance tires.

MANUFACTURER	TYPE	MODEL NUMBER(S)
BF Goodrich	Steer	ST244
	Drive	DR 444
	Trailer	TR144
Bridgestone	Steer	R250F, R260F, R280, R287, R287A
	Drive	M720, Greatec
	Trailer	Greatec Trailer, Greatec R125, R195, R197, S197
Continental	Steer	HSL2 (replaces HSL), HSL2 ECO Plus, HSR, HSR1, HSR1 ECO Plus, HSR2, HSR2 ECO Plus, HSR2 SA
	Drive	HDL ECO Plus, HDL2 ECO Plus, HDL2 DL ECO Plus, HDR1 ECO Plus, HSR, HSR1, HSR1 ECO Plus, HSR2, HSR2 ECO Plus, HSR2 SA
	Trailer	HTL ECO Plus, HTL1
Double Coin	Steer	FR605

[5] EPA maintains a list of SmartWay-verified technologies at http://www.epa.gov/smartway/transport/what-smartway/verified-technologies.htm.

MANUFACTURER	TYPE	MODEL NUMBER(S)
	Drive	FD405
	Trailer	FT105
Dunlop Tire	Steer	SP384 FM
	Drive	SP456 FM
	Trailer	SP193 FM
Falken	Steer	RI109 Ecorun
	Drive	BI887 Ecorun
	Trailer	RI119 Ecorun
Firestone	Steer	FS590 PLUS, FS507
	Drive	FD662
	Trailer	FT455 PLUS
General	Steer	S371, S580, S581
	Drive	D660, S371, S580, S581
	Trailer	ST250
Goodyear	Steer	G395 LHS Fuel Max, G399 Fuel Max, G662 Fuel Max
	Drive	G305 LHD Fuel Max, G392 SSD, G305 Fuel Max AT
	Trailer	G316 LHT Fuel Max, G316 Fuel Max DuraSeal
Hankook	Steer	AL07+, AL11, ST244
	Drive	DL11, DR444, Z35A
	Trailer	TL01, TR144
Michelin	Steer	XZA3, XZA2, XZA1+, XZE, XZE2, XZA2 Energy,
	Drive	XDA2+ Energy, XDA Energy, XDA3, X-One XDA, X-One XDN2, X-One XDA Energy, XDE2+, XDN2, XDE M/S
	Trailer	XTA Energy, XT1, X-One XTA, X-ONE XTE, XTE
Toyo Tires	Steer	M137, M154
	Drive	M657
	Trailer	M127
Yokohama	Steer	RY617, 103ZR, 101ZL
	Drive	703ZL, TY517mc2, TY577
	Trailer	RY587mc2, RY587

Keeping tires properly inflated is a simple and inexpensive way to reduce rolling resistance, but manually checking tire pressure on a regular basis can be time-consuming and is routinely ignored by many fleets and drivers. A U.S. survey of combination truck tire pressures showed that less than half of the tires tested were within 5% of the recommended inflation pressure; another survey of drivers showed that only 8% of them check their truck's tire pressure with a gauge before every trip [35].

Maintenance of proper tire pressure can be ensured with an automatic tire monitoring system, or an automatic tire inflation (ATI) system. ATI systems (like the one in Figure 7) maintain optimal tire pressure, even while driving, by monitoring and automatically adjusting the air pressure in the tires. These systems may use the air-brake compressor to supply air to the tires, or compressors powered by the rolling motion of the wheels [35].

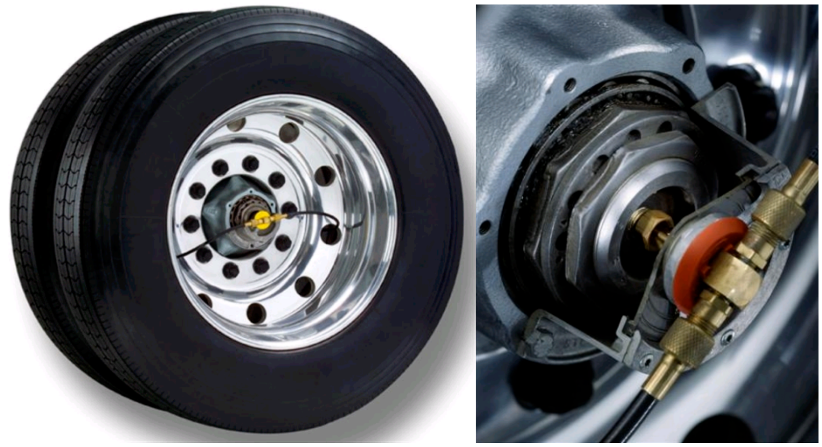

Figure 7. Two views of the Meritor Tire Inflation System. [36]

Table 4 lists some examples of commercially available automatic tire inflation or tire pressure monitoring systems.

Table 4. Examples of commercially available automatic tire inflation and tire pressure monitors.

TECHNOLOGY	MANUFACTURER AND MODEL
Automatic tire inflation systems	AIRGO® System P.S.I.™ Meritor Tire Inflation System PressureGuard Tire Inflation System Hendrickson TIREMAAX PRO (launching 2011)
Automatic tire pressure monitors	PressurePro wireless tire pressure monitor Doran tire pressure monitor Bartec tire pressure monitoring systems

3.2 In-use Experience

Experimental and road tests have demonstrated the ability of advanced tires, wide-based tire assemblies, and automatic tire inflation systems to achieve significant fuel savings. Table 5 summarizes the results of recent tests.

As shown in Table 5, low rolling resistance tires applied in a traditional dual-assembly configuration can reduce distance-specific fuel use by almost 3%, while single wide-based tires can reduce fuel use by up to 5%. Advanced single wide technologies, such as Michelin's New Generation Single Wide-Based Tire (NGSWBT), have been shown to reduce fuel use by 9% [37]. Automatic tire pressure control can add an additional 0.5% - 1.2% in fuel savings. Implementation of these technologies have the potential to reduce annual fuel use per truck by more than 5,000 liters.

Table 5. Estimated fuel savings from rolling resistance reduction technologies.

TECHNOLOGY	FUEL SAVINGS		Source
	% Reduction (l/100 km)	Annual Savings[1] (liters)	
Single Wide-Based Tires ("Super Singles")	3.8%	2,308	RMI 2005 [28]
	2% - 5%	1,176 – 2,857	EPA 2004 [35]
Michelin New Generation Single Wide-Based Tire (NGSWBT)	9%	5,117	ORNL 2008 [37]
Low Rolling Resistance Tires	2.9%	1,748	RMI 2005 [28]
Automatic Tire Pressure Control	1.2%	711	RMI 2005 [28]
	0.5% - 1.0%	299 – 594	EPA 2004 [35]

[1] Based on: 120,000 km annually and baseline fuel consumption of 47.6 Liters per 100 km. Baseline fuel consumption assumes regularly overloaded trucks

Note: Driving speed does not significantly affect rolling resistance, but rolling resistance is proportional to truck weight. These fuel savings estimates (% reduction) are based on the average weight of trucks in the U.S., and may understate the benefits of these technologies to Chinese trucks which typically operate at significantly higher weight.

3.3 Safety Issues and Concerns

In the U.S. there has been some resistance to adoption of single wide-based tires due to perceived safety and operational issues. Most of these issues have been resolved with time and newer tire technology. For instance, the perception that a blowout of a wide-base tire would be more dangerous than that of a regular dual tire has been shown to be false. In a series of tests, Michelin blew out steer, drive, and trailer tires and found no difference in loss of control or stability between trucks with dual versus wide-base tire assemblies [3].

Earlier generations of wide-based tires ("super singles") caused more damage to pavement than dual tires, leading many jurisdictions to discourage their use; however, newer wide-base tires do not damage roads any more than regular tires. Regulations may not have been updated everywhere to reflect these changes [38]. Wide-based tires are prohibited in China due to regulations that prohibit making changes to the truck structure [18].

Drivers and fleet managers have also expressed concern about reduced traction during rain or snow events when using low-rolling resistance tires. Although it is true that, in the past, there was generally a trade-off between low rolling resistance and wet traction, newer technologies have allowed for a balance between these characteristics [39]. Newer tires, such as Goodyear's LHT II, use silica compounds and advanced design to optimize rolling resistance without sacrificing performance in wet weather conditions [40].

3.4 Operational Issues and Concerns

Some U.S. drivers have expressed concern about the availability of wide-base tires at repair facilities if a tire blows out on the road. The growing use of wide-based tires in the U.S. has alleviated this concern somewhat [41], but in countries where wide-based tires assemblies are rare this may be an issue. Additionally, if one tire on a traditional dual tire assembly blows out, the truck can continue driving for a short distance; if a single-wide tire blows out, the truck must be stopped immediately and the tire replaced.

Single wide-base tires wear at a similar rate to other tire types, and can be retreaded. It may be slightly more difficult to maintain a fleet while transitioning to the use of wide-based tires, because maintenance procedures for both types of assemblies must be in place [41].

4. Applicability to China

SmartWay technologies and other energy saving devices are not necessarily universal in application and their results may vary considerably from one operation to another and one country to another. Additional research will be needed on what technologies provide the most appropriate results for their market, but the aero and rolling resistance technologies highlighted in this document have the potential to markedly improve the efficiency of the Chinese truck fleet – and all the technologies have been successfully deployed elsewhere, if not in China.

The use of some aerodynamic technologies, such as roof fairings and, to a lesser extent, side fairings, is increasingly common in China, particularly for new freight trucks. These technologies are being adopted by customers for their fuel savings and low costs (e.g., cost of steel glass roof fairing is reportedly at ~500-600 yuan) [42]. The World Bank Green Truck project in China has piloted the use of various aerodynamic and rolling resistance technologies (discussed in more detail below). However, there is not much information available at this time on the on-road experiences of applying other aerodynamic and rolling resistance technologies for freight trucks in China. One aero technology that may not be applicable in China is the option of replacing rear mirrors with cameras. China's safety regulations require medium- and heavy-duty trucks to have rear mirrors.

The existing heavy-duty vehicle market can also impact the successful deployment of technologies. Heavy-duty vehicles in China are largely manufactured based on general specifications and are not customized before purchase. Additionally, the truck market is highly price sensitive, and the lifetime operation costs of trucks are not typically apparent to truck buyers. This suggests that, absent regulatory interventions to require vehicle labeling that shows efficiency benefits, the purchase price of trucks is a determining factor affecting purchase decisions, and buyers will be reluctant to purchase trucks with better aerodynamics and lower rolling resistance if they are more expensive.

Logistic companies that pay attention to both initial capital and operating and maintenance costs typically look for a short payback period, about 2-3 years, for capital investments to improve truck performance. This suggests that costs could be a deciding factor for the adoption of aero and rolling resistance technologies with relatively high initial costs. As an example, while bias tires are less durable and increase rolling resistance, they still account for a large share (over half) of the Chinese commercial truck market because they are cheaper to purchase than the more durable and fuel efficient tires.

There is additional tension between energy efficient technologies and the pressures of shipping in China. It is believed that the common practice of overloading have induced truck manufacturers to use heavier parts, like steel wheels, that can withstand heavy loads, even though heavier wheels add weight and hurt fuel efficiency.

4.1 Infrastructure Design/Compatibility

To date, neither the World Bank China Green Truck project nor other experiences in China have indicated any serious compatibility issues regarding the use of aero and rolling resistance technologies. However, further research is needed to determine if infrastructure design changes (e.g., loading dock modifications) are needed to accommodate the adoption of some of the aero and rolling resistance technologies.

4.2 Safety & Operational Issues

There are concerns that low resistance tires having less traction might compromise safety in inclement weather. However, current generation low rolling resistance tires as sold in the U.S. balance these concerns. In addition, radial tires that have low rolling resistance offer better stability, and hence both improve vehicle safety and reduce fuel use when compared to bias tires commonly used in China.

Some truck companies in China have established a standard practice of over inflating tires to compensate for overweight loads. This practice compromises vehicle handling. The installation of tire pressure monitors, together with better education and enhanced enforcement of overloading, could help discourage the practice of over inflating tires and improve vehicle handling and safety.

4.3 World Bank Green Truck Pilot Project in China

In 2009, the World Bank funded a pilot “Green Truck” project in Guangzhou, China. In preparation for the 2010 Asian Games, which will take place in Guangzhou, the project was intended to contribute to improvements in local air quality by improving the fuel efficiency of trucks while reducing their exhaust emissions, which contribute heavily to pollution in Guangzhou and the Guangdong province.

The project was implemented by the Clean Air Initiative for Asian Cities Center (CAI-Asia Center), in cooperation with Cascade Sierra Solutions, U.S. EPA and World Bank, and with support from Guangzhou Environmental Protection Bureau (GEPB), Guangzhou Transport Committee (GTC), and Guangzhou Project Management Office (PMO) for the World Bank. The project received financial support from the Australian Government (AusAid) and the Energy Sector Management Assurance Program (ESMAP). [18].

Three Guangzhou companies – a long-haul fleet, a short-haul fleet, and a garbage truck fleet – participated in the project. Participation entailed upgrading pilot trucks with selected technologies to improve fuel economy, and training drivers to drive more efficiently. The technologies installed on the trucks (some of which are shown in Figure 8) were [43]:

- Lightweight aluminum wheels (Alcoa model 886523)
- Low rolling resistance tires (Michelin XZA2 Energy LRR Tires; Chinese legislation currently does not support wide-base tires from being installed unless exceptional endorsement obtained.)
- Tire pressure monitoring system (Doran brand)
- Cab roof fairing (DongGuan CAIJI brand)
- Nose cone (DongGuan CAIJI brand)
- Trailer skirts (FreightWing Inc)

Figure 8. Clockwise from top left: Doran tire pressure monitoring system; Alcoa aluminum wheels; Freight Wing trailer skirts; DongGuan CAIJI nose cones. [18]

Overall, results from the technology improvements were good. Due to problems with data collection the fuel savings for the short-haul trucks could not be evaluated, but the long-haul trucks achieved an average fuel savings of 6.6%, and the garbage trucks achieved even better fuel savings – an average of 18.1%. (More detailed results can be seen in Table 6.)

Fuel savings for the long haul trucks were lower than initially expected; due to driving conditions, the trucks traveled at an average speed of only 50-60 kilometer per hour. Savings from aerodynamic improvements are greater at higher speeds; at lower speeds, the added mass of improvements like trailer skirts can outweigh aerodynamic benefits. Nose cones and cab roof fairings, on the other hand, provided good results even at lower speeds, and at a low cost. This project demonstrated that actual driving conditions should determine which truck improvements should be implemented.

The project also highlighted the importance of good driver training in achieving emissions reductions; it found that the overall effectiveness of driver training could be 8-12% better fuel economy.

Table 6. Summary results of Guangzhou Green Truck pilot project

	SOCL LONG-HAUL PILOT TRUCKS	**Baiyun District Garbage Pilot Trucks**
Technologies installed	Aluminum wheels, low rolling-resistance tires, tire pressure monitoring system, cabin fairing, nose cone, trailer skirts	Low rolling-resistance tires, tire pressure monitoring system
Investment cost (USD)	$ 16,333	$ 6,325
Average fuel savings	6.64% (36.16 liters per 100 km compared to 38.73 for control truck)	18.14% (32.25 liters per 100 km versus 39.39 for control truck)
Fuel savings per year	3,557 liters	2,520 liters
Payback period	5.1 years	3.09 years (adjusted for LRR tire life compared to existing tire life: 1.49 years)
CO_2 reductions	9.18 metric tons per year	6.71 metric tons per year
NO_x reductions	33.21 kg per year	23.53 kg per year
PM_{10} reductions	1.41 kg per year	1.00 kg per year
Note: Please see full technology pilot report [18] for assumptions and calculations.		

The final project report used results from the study and the existing literature to project the benefits of applying rolling resistance and aerodynamic improvements to all 826,520 heavy-duty trucks in Guangdong province. The report concludes that annual fuel savings could reach

US$2.74 billion, with emissions reductions of 7.9 million tons of carbon dioxide, 28,435 tons of nitrogen oxides, and 1,218 tons of particulate matter.

The report highly recommends efficiency improvements as a way to reduce pollution in China. However, it notes that the regulatory environment and infrastructure of the trucking industry are significantly different in China as compared with the United States or Europe, and programs need to be tailored to account for these differences. The legal restrictions on truck modifications may make it difficult to implement some types of aerodynamic and rolling resistance improvements, and the more fragmented structure of the trucking industry may present additional challenges. They concluded, however, that aerodynamic and rolling resistance improvements to trucks represent a promising strategy for reducing emissions in China.

5. References

1. M.J. Bradley & Associates. 2009. "Setting the Stage for Regulation of Heavy-Duty Vehicle Fuel Economy & GHG Emissions: Issues and Opportunities." International Council on Clean Transportation Report, February.
2. U.S. Department of Energy. 2000. "Technology Roadmap for the 21st Century Truck Program, a government-industry research partnership." Technical Report 21CT-001, December.
3. Ogburn, M., L. Ramroth, and A.B. Lovins. 2008. "Transformational Trucks: Determining the Energy Efficiency Limits of a Class-8 Tractor-Trailer." Rocky Mountain Institute White Paper, July.
4. European Federation for Transport and Environment. 2010. "The case for the exemption of aerodynamic devices in future type-approval legislation for heavy goods vehicles." Transport & Environment Report, January.
5. Image courtesy of Solus Inc. "Drag Contributions." Accessed October 13, 2010. http://www.solusinc.com/transport.html
6. U.S. EPA. 2004. "A Glance at Clean Freight Strategies: Improved Aerodynamics." EPA Fact Sheet 420-F-04-012, February. http://www.epa.gov/smartwaylogistics/transport/documents/carrier-strategy-docs/aerodynamics.pdf
7. Platform for Aerodynamic Road Transport. 2010. "Applications." Accessed October 7, 2010. http://www.part20.eu/en/applications/cab/
8. Images courtesy of Peterbilt. "Model 389" and "Model 587." Accessed October 21, 2010. http://www.peterbilt.com/trad389.1.aspx
9. Images courtesy of DAF Trucks N.V. "1982 3300 DKX Series" and "XF105 Series." Accessed October 25, 2010. http://www.daf.com/SiteCollectionDocuments/Products/Edition-2009-infosheets/Modelrange/DAF-XF105-infosheet-All-EN.pdf
10. Englar, R.J. 2005. "Improved Pneumatic Aerodynamics for Drag Reduction, Fuel Economy, Safety and Stability Increase for Heavy Vehicles" SAE Technical Paper 2005-01-3627.
11. U.S. EPA. 2010. "Interim Requirements to Determine Eligibility of SmartWay Tractors." EPA Report 420-F-09-045, August. http://www.epa.gov/smartwaylogistics/transport/documents/tech/interim-tractor-rqmts.pdf
12. Images courtesy of Airodyne Industries LLC. "Truck Fairing Product Images." Accessed October 13, 2010. http://www.airodyne.com/parts_pics.asp?manuf=Freightliner#
13. Images courtesy of Tsai Kee Glass City Steel Co., Ltd.
14. Image courtesy of Airtabs. "What are they?" Accessed October 13, 2010. http://www.airtab.com/en/35
15. Image courtesy of Turbo Shield. "Model 8600 - Semi Tractors." Accessed October 13, 2010. http://www.turboshield.com/8600.asp

16. Image courtesy of Carrier Transicold Performance Parts. “Trailer Gap Fairing” brochure. http://www.transportparts.carrier.com/Files/RCG/Global/US-en/Gap_Fairing_Sell_Sheet.pdf
17. Image courtesy of NoseCone. “Semi-Trailer Models” brochure. Accessed October 13, 2010. http://www.nosecone.com/TrailerAps.pdf
18. Clean Air Initiative for Asian Cities (CAI-Asia). 2010. “Guangzhou Green Trucks Pilot Project: Technology Pilot Report for the World Bank ‘Truck GHG Emission Reduction Pilot Project.’”Final Technology Report, June.
19. Image courtesy of FreightWing. “AeroFlex.” Accessed October 13, 2010. http://www.freightwing.com/aeroflex.php
20. SmartTruck Products. 2010. “UnderTray System Overview.” Presentation for US Xpress, August 30th.
21. Image courtesy of Transtex Composite. “BoatTail.” Accessed October 13, 2010 http://www.transtexcomposite.com/products_BoatTail.html?ProduitID=3
22. Image courtesy of Aerodynamic Trailer Systems, LLC. “SmartTail and WindTamer.” Accessed October 13, 2010. http://www.ats-green.com/products.htm
23. Image courtesy of Don-Bur. “Don-Bur Free Trial Demonstrators.” Accessed December 2, 2010. http://www.donbur.co.uk/gb/demo/demonstrators.shtml
24. ICCT communication with China Research Academy of Environmental Science (November 28, 2010), the Vehicle Emissions Control Center (October 12, 2010), and data collected for the World Bank “China Green Truck” project. For more information about the data collected from the Jingjintang Expressway, see Chen et. al. 2007. *Speed Difference and Its Impact on Traffic Safety of One Freeway in China Transportation Research Record*: Journal of the Transportation Research Board, No. 2038, Transportation Research Board of the National Academies, Washington, DC., pp. 105-110.
25. Cooper, K.R. 2003. “Truck Aerodynamics Reborn – Lessons from the Past.” SAE Technical Paper 2003-01-3376.
26. U.S. EPA. 2004. “A Glance at Clean Freight Strategies: Improved Aerodynamics.” EPA Fact Sheet 420-F-04-012, February.
27. Smart Truck Products. 2010. “UnderTray System Overview.” Presentation for US Xpress, August 30th.
28. Bustnes, O.E. 2005. “Taking on the Leadership Challenge in Class 8 Trucking: How To Double Class 8 Truck Efficiency — Profitably.” Rocky Mountain Institute Presentation, February 22.
29. U.S. EPA. 2009. “SmartWay Certified Tractors and Trailers, Webinar Questions & Answers.” February 2009. Accessed October 25, 2010. http://www.epa.gov/smartwaytransport/transport/documents/webinars/tractor-trailer-webinar-q-and-a.pdf
30. Lawrence Livermore National Laboratory. “Investigation of Tractor Base Bleeding for Heavy Vehicle Aerodynamic Drag Reduction.” October 2007. https://e-reports-ext.llnl.gov/pdf/354146.pdf

31. Fleet Equipment. “Trailer skirts for improved fuel economy.” October 19, 2010. http://www.fleetequipmentmag.com/Item/80645/trailer_skirts_for_improved_fuel_economy.aspx
32. Slipstreem Aerodynamics. 2007. “SAE J1321 Type 2 Fuel Test.” April 5.
33. Transportation Research Board of the National Academies of Science. 2006. “Tires and passenger vehicle fuel economy: informing consumers, improving performance.” TRB Special Report 286.
34. Image courtesy of Cascade Sierra Solutions. “Products: Tires and Wheels: Michelin.” Accessed October 13, 2010. https://secure.cascadesierrasolutions.org/products/detail.php?prodId=0058
35. U.S. EPA. 2004. “A Glance at Clean Freight Strategies: Automatic Tire Inflation Systems” EPA Factsheet 420-F-04-010, February.
36. Image courtesy of Cascade Sierra Solutions. “Products: Automatic Tire Inflation: Meritor Tire Inflation System (MTIS).” Accessed October 14, 2010. https://secure.cascadesierrasolutions.org/products/detail.php?prodId=0031
37. Oakridge National Laboratory (ORNL). 2008. “Class-8 Heavy Truck Duty Cycle Project Final Report” ORNL/TM-2008/122. December. http://cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2008-122.pdf
38. U.S. EPA. 2004. “A Glance at Clean Freight Strategies: Single Wide-Based Tires.” EPA Factsheet 420-F-04-004, February.
39. Kojima, K., and L. Ryan. 2010. “Transport energy efficiency: Implementation of IEA Recommendations since 2009 and next steps.” Information paper, September. http://www.iea.org/papers/2010/transport_energy_efficiency.pdf
40. Goodyear. “Goodyear Marathon LHT II.” Brochure. http://www.fleetfirst.eu/ff_home_en/Images/Goodyear%20Marathon%20LHT%20II.pdf
41. American Trucking Association. 2008. “New Generation Wide Base Single Tires.” ATA White Paper, November 6.
42. National Development and Reform Commission. 2009. Energy Saving and New Energy Vehicle Technology Policy Study. June. (in Chinese). Specialized Topic 4.
43. Clean Air Initiative for Asian Cities (CAI-Asia). 2010. “Guangzhou Green Trucks Pilot Project: Final Report for the World Bank ‘Truck GHG Emission Reduction Pilot Project.’” Final Report, June.