Automotive Weight and Drag Reduction

HIGHLIGHTS

■ **TECHNOLOGY STATUS –** Weight and drag reduction are widely recognised as cost effective ways of reducing automotive energy consumption, however they have not always been given as high priority as other vehicle characteristics. The introduction of CO_2 emissions legislation for passenger cars in Europe has started to reverse this trend with several recent models being lighter than their predecessors and manufacturers increasingly striving to achieve low aerodynamic drag coefficients. However improvements in drag coefficients of passenger cars over the years have largely been offset by increasing frontal areas. Europe has also introduced legislation to mandate the reduction of rolling resistance through the use of low rolling resistance tyres for all vehicle types and tyre pressure monitoring systems on passenger cars. Typically over half of the energy used by large goods vehicles is to overcome rolling resistance and a further third is aerodynamic drag on higher speed roads so they too can benefit from these technologies.

■ **PERFORMANCE AND COSTS –** While more expensive materials such as magnesium and carbon fibre can be used to reduce weight, many reductions can be achieved through optimising design without increased cost. It is also important to realise the secondary weight reduction in components such as the powertrain, braking system and suspension system which can be achieved as a result of an overall reduction in vehicle weight. Fitment of low rolling resistance tyres and tyre pressure monitoring systems to passenger cars can each offer 2-3% reductions in CO_2. Aerodynamic drag reduction can be achieved through detailed wind tunnel design work and does not necessarily require an increase in vehicle production costs. For heavy goods vehicles, low rolling resistance tyres could reduce CO_2 by 5% at no additional cost. Tyre pressure monitoring systems could achieve 7-8% CO_2 reductions but systems cost around €11,500. However they can be removed and refitted to successive vehicles. There is also strong potential for drag reduction of long haul large goods vehicles, with CO_2 savings of 0.1-6.5% and costs of €290-1950.

■ **POTENTIAL AND BARRIERS –** There is potential for further weight and drag reduction in passenger cars and it is not unreasonable to expect that average passenger car weights could be reduced by as much as 40%. Primary barriers include concerns regarding the safety of very light vehicles particularly when in collision with heavier traditional designs, although there is no fundamental reason why very light vehicles cannot also be very safe. Public acceptance of ultra-low drag styling and the different 'feel' of lightweight vehicles may also need to be overcome. Drag and weight reduction for vans and heavy duty vehicles also have strong potential for energy and cost savings yet the technologies are not yet widely applied.

TECHNOLOGY STATUS – Weight and drag reduction are two important ways of reducing automotive energy consumption. The introduction of CO_2 emissions legislation for European passenger cars and rising oil prices has seen an increasing focus on improving efficiency through weight and drag reduction. For commercial and heavy duty vehicle operators, fuel costs are a major consideration and CO_2 emissions legislation in Europe is being extended to include light vans. This brief covers, passenger cars, light trucks and vans and heavy duty vehicles (heavy trucks, buses and coaches).

■ **Weight Reduction:** There are two commonly used ways of expressing vehicle weight. **Kerb weight** refers to the total weight of a vehicle with standard equipment, all the consumables required for operation (typically oil, lubricants and coolants) and a full tank of fuel, but no passengers or cargo. Many European manufacturers also include 75kg to represent the driver as specified by European Directive 95/48/EC [1].

Gross vehicle weight (GVW, sometimes described as Maximum Authorised Mass, MAM) is the maximum allowable weight of a vehicle including passengers and cargo. Heavy duty vehicles can be defined as those with a GVW greater than 3.5 tonnes.

In order for a vehicle to accelerate, it must overcome inertial forces. The 'inertial power' required is linearly proportional to vehicle weight, so for a given speed and acceleration rate, if vehicle weight is halved, the inertial power required will be halved.

Importantly, for almost all vehicles it is the required aceleration rate rather than the top speed that governs the required engine power. Thus reducing vehicle weight will reduce the engine power requirement and in turn the likely fuel consumption.

Over the years passenger car weights have increased as vehicles in a given segment have got larger, and have had additional safety and comfort features added. For example each successive new version of the Volkswagen Golf hatchback has increased in weight until in 2003 the Mk5 version weighed 67% more than the 1974 original. Recently this trend has started to change and the Mk6 version introduced in 2009 is lighter than the Mk5, despite being physically larger.

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Since many small vans such as the Volkswagen Caddy and the Opel/Vauxhall Combo are based on passenger car platforms, they too have grown larger and heavier over the years. Larger panel vans such as the Ford Transit have followed the same pattern. The current production Transit panel van now weighs 25-40% more than it did 30 years ago [2].

Analysis by the Japanese Automotive Manufacturers Association suggests that since 1990 weight and fuel economy trends have varied in different markets (see Figure 1).

In the US there has been a strong trend towards larger Sport Utility Vehicles with resulting increases in average mass and fuel consumption. Sales weighted average new light duty vehicle weight in the US has been reported as increasing by 1% a year since the early 1980s [4]. In Europe which has until recently had voluntary targets, manufacturers have managed to achieve around a 10% improvement in specific fuel efficiency despite a 20% increase in mass since 1990. However in Japan, which has had mandatory fuel efficiency targets since 1998, average mass increase has been just 10% while specific fuel efficiency has increased by 20%.

There are several potential advantages to reducing vehicle weight:

- Reduced fuel use and/or improved performance;
- Reduced material use and cost – both directly and through secondary effects, sometimes called “mass decompounding” e.g. lighter vehicle weight allowing reduced engine, braking and suspension system sizes and weights;
- Improved handling.

■ **Drag Reduction:** The drag which a vehicle must overcome is made up of three factors: climbing resistance; rolling resistance; and aerodynamic drag. The **Climbing or gradient resistance** is due to the effect of gradients in the road and is linearly related to mass. Thus halving mass will halve climbing resistance. The **Rolling resistance** is caused primarily by deformation of a vehicle’s tyres as they roll over the road surface. It is calculated by multiplying the vehicle’s weight by the coefficient of rolling resistance. Thus reducing vehicle weight directly reduces rolling resistance. The coefficient of rolling resistance is dependent on the design, materials and inflation pressure of the tyre, the tyre diameter, vehicle speed and the nature of the road surface itself. Rolling resistance is also greater when cornering due to cornering resistance, which is itself a function of vehicle speed, curve radius, axle kinematics, tyres and the coefficient of lateral friction [5]. Typical coefficients of rolling resistance (C_{rr}) for pneumatic tyres are 0.01-0.05, depending on the road surface. By comparison, a steel wheel on rails has a coefficient of rolling resistance of 0.001-0.002 [5]. The **aerodynamic drag** force (F_L) which a vehicle must overcome is calculated as follows:

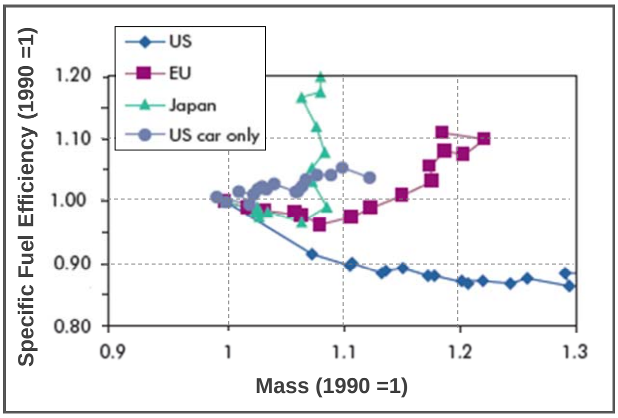

Figure 1 - Specific fuel efficiency versus mass (1990-2006) [3]

$F_L = 0.5 \bullet \rho \bullet C_d A \bullet (\text{road speed + head wind velocity})^2$

Where ρ is air density, C_d. is the **coefficient of drag,** and A is the **frontal area.** The coefficient of drag (C_d) and frontal area (A) can be influenced through vehicle design. They are sometimes multiplied together to give the **drag area** (C_dA). In common with weight, the frontal area of passenger cars has generally increased overtime, with increasing car dimensions. Figure 2 illustrates this trend, showing average frontal areas of selected vehicles over the last 15 years. Manufacturers have however paid increasing attention to reducing the **coefficient of drag**. While there are several notable examples of early vehicles with low drag coefficients, in general, average passenger car drag coefficients have reduced over time. Since aerodynamic drag increases as a square of vehicle speed, reducing it is particularly important for vehicles with primarily higher speed usage patterns. Reducing drag can also have additional benefits in terms of wind noise reduction.

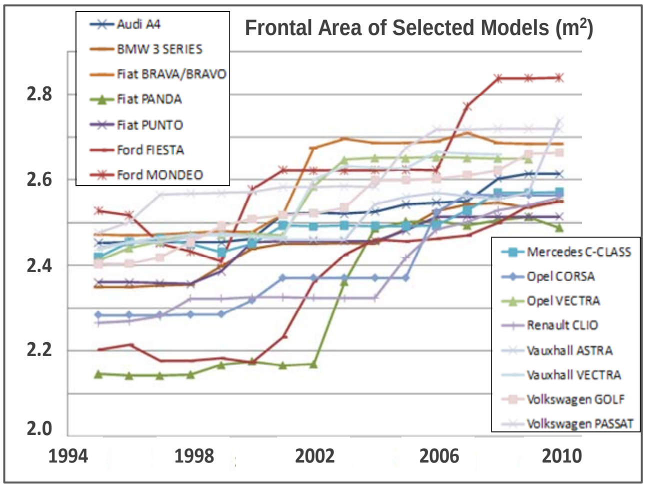

Figure 2 - Passenger Cars Frontal Area, 1995-2010, [6]

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Performance and Costs

■ **Weight Reduction:** Probably the most cost effective way of achieving low vehicle weight is by giving high priority throughout the whole vehicle concept, design and development process to minimising weight. The cumulative impact of small weight savings achieved through detailed design on all components can be substantial. For instance seats can be lightened by 11kg each through the use of innovative materials and design [7]. Lighter sound insulation material can save 8kg per vehicle [8]. The use of structural plastics and hollow rods in dampers can achieve a 4kg saving per vehicle [9] and BMW have introduced a glass fibre polypropylene dashboard carrier component in their 7-series vehicles which is 20% lighter [10]. In common with the 2009 Golf, the 2009 model Ford Fiesta was the first since the nameplate was introduced to be lighter than its predecessor. In both cases this has been achieved without the use of exotic materials and while the overall vehicle dimensions have increased. Newer technologies such as electrically assisted power steering systems replacing heavier hydraulic systems and smaller displacement downsized turbocharged engines replacing larger capacity ones can also reduce weight. A further technique is to try to minimise the number of parts used either by making one part perform multiple functions or by eliminating interfaces between components and thus reducing fastener use. This can have the additional benefit of improving reliability. Manufacturers' use of comparatively heavy materials such as mild steel and iron has declined over the last 20 years in favour of lighter alternatives. Now high strength steel may account for more than 50% of the total weight of steel in some vehicles [3]. High strength steel is stronger per unit weight than conventional steel enabling improved body structure stiffness and safety while simultaneously reducing weight. However it is more difficult to manipulate in manufacturing and material costs can be up to 50% higher for a given part [12]. Use of lighter weight materials such as aluminium, magnesium, ceramics, plastics and composites can also reduce vehicle weight, although consideration must be given to the need to maintain the appropriate strength and stiffness.

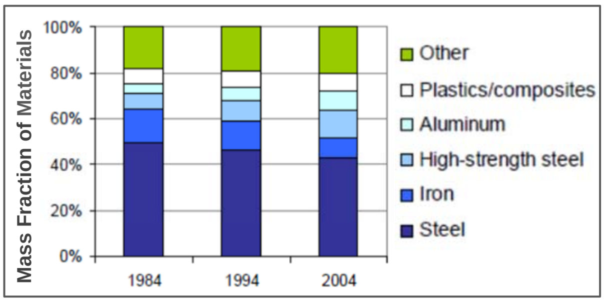

Figure 3 - Average Material Composition of Automobiles in the US [12]

Replacing mild steel with aluminium or magnesium can increase material cost by a factor of 1.3-2.5 and for composites such as carbon fibre costs can increase by a factor of 2-10 [13].

Regression analysis of production vehicles from 1996-2002 performed for the European Commission concluded that from the eight factors examined, kerb weight had the greatest impact on CO_2 emissions (Figure 4). A 10% reduction in kerb weight would lead to an 8.5-10% in reduction in CO_2. Computer simulation results published in 2010 and run using data from a Toyota Camray and a Ford F-150 pick-up truck indicated that a 10% weight reduction from the average new car or light truck would reduce fuel consumption by 6.9% and 7.6% respectively [4]. A further study published in 2010 looked at the potential for lightweight 'eco' cars to reduce CO_2 emissions. Computer modelling of NEDC drive cycles was undertaken with an 'eco' car (defined as 40% lighter than the comparator vehicle and being specified to achieve a 0-60mph acceleration time of 20 seconds). Frontal area, coefficient of drag and rolling resistance were all left unchanged. The study predicted 29-35% CO_2 reductions over the test cycle [15] depending on vehicle size. A study commissioned by the International Aluminium Institute shows how weight saving is particularly important for vehicles with a primarily stop/start duty cycle and a long lifetime. The study estimated that lifetime primary energy savings per 100kg reduction in weight for a city bus would be more than double those for cars. Long distance buses and articulated trucks offer similar potential energy savings to passenger cars (Figure 5).

The overall costs associated with weight reductions are very difficult to assess. They range from a potential reduction in cost in cases in which a new design results in reduced material use or where new lighter materials are also cheaper, to a significant increase if expensive materials which are often unsuitable for mass production such as carbon fibre are introduced.

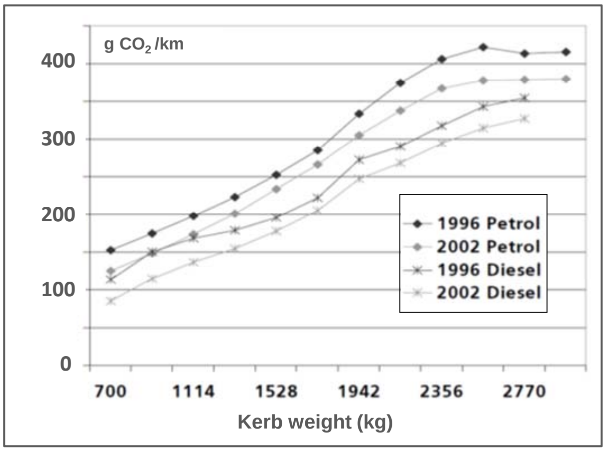

Figure 4 - Predicted CO_2 emissions vs. kerb weight [14]

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■ **Drag Reduction**

Rolling Resistance - Reducing rolling resistance can also provide a cost effective way of reducing energy use. In Europe, this has been recognised by the European Commission which introduced regulation 661/2009 mandating the fitment of **tyre pressure monitoring systems** on the sale of all new passenger cars in 2014 and the use of **low rolling resistance tyres** for passenger cars, light and heavy duty vehicles being phased in between 2013 to 2017 [16]. **Tyre pressure monitoring systems**, which alert the driver if the pressure falls below 20% of the normal value are expected to achieve a 2.5% reduction in carbon emissions while for passenger cars, **low rolling resistance tyres** are expected to achieve a further 3%. The cost effectiveness of these measures are estimated to be 84€/tonne for low rolling resistance tyres and minus 64€/tonne for tyre pressure monitoring systems (the minus indicating that the savings would outweigh the costs) [17]. Similar benefits would be expected for smaller car-based vans. The Econetic version of Ford's Fiesta van and the Bluemotion version of VW's Caddy van are both fitted with low rolling resistance tyres. In 2010, Continental launched a range of low rolling resistance tyres specifically for vans, claiming up to 30% lower roling resistance [18].

Typically large goods vehicle energy consumption, as measured over a long distance route [19] is split as follows: 52% rolling resistance; 35% aerodynamic drag; and 13% climbing [20]. At motorway speeds it is estimated that aerodynamic drag accounts for 40% of HGV fuel consumption [21]. Figure 6 illustrates how aerodynamic drag and rolling resistance vary with vehicle speed for a typical medium duty truck. Note that for urban usage patterns, aerodynamic drag would have minimal effects.

Tests of **low rolling resistance tyres** indicate up to a 20% reduction in the coefficient of rolling resistance, and fuel economy and CO_2 reductions averaging 5% for large goods vehicles, 3% for intercity coaches and 1% for other applications [22]. **Low rolling resistance tyres** for heavy duty vehicles are available on the market now and average costs are no different from standard tyres [20]. The savings in fuel costs would be expected to be more than double the tyre costs. Their use would therefore result in substantial energy and cost savings despite the fact they are reported to have a 100,000km lifespan as opposed to 120,000km for conventional tyres [20]. Further heavy duty vehicle energy reductions could be achieved through the use of **single wide tyres** to replace dual tyres. A CO_2 reduction of 2% would be expected for their use on a single tractor axle, rising to 6-10% for fitment to the whole vehicle [22]. The tyres offer a weight and rolling resistance reduction in comparison to dual tyres, while offering a similar lifespan.

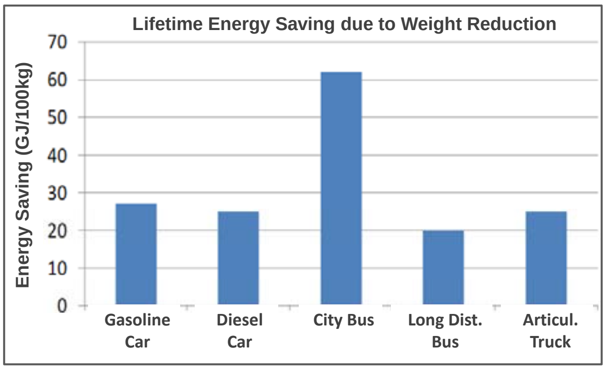

Figure 5 - Lifetime primary energy savings from weight reduction [11]

A further benefit is their reduced diameter which allows a lower trailer deck height and hence increased load volumes to be carried within the maximum 4m trailer height, potentially allowing further energy savings where loads are limited by volume rather than weight. Single wide tyres could also reduce energy consumption associated with manufacture and disposal since they use 25% less rubber and only one wheel instead of two, however their use is currently limited by legislation which dictates that twin wheels must be used on the drive axle of vehicles over 40 tonnes [20].

The estimated benefits of **tyre pressure monitoring systems** are again higher for heavy duty vehicles than for passenger cars. Systems are available that can automatically use the vehicle's air compressor to ensure correct tyre pressures are maintained. CO_2 and energy reductions of 7-8% are estimated based on the numbers of heavy duty vehicles currently running with under inflated tyres [20]. The system costs about €11,500 but can be removed and re-fitted to successive vehicles. Prices have already reduced with increasing sales volumes. Further manufacturing and disposal energy savings would be expected from the reduction in tyre replacement due to reduced wear [20]. Rolling resistance can also be reduced by reducing driveline drag. Some manufacturers have introduced 'eco-roll' freewheel systems which automatically disengage the driveline when it is not needed. Mercedes-Benz have claimed a 1% CO_2 reduction [22], while Volvo claim up to 2% savings in fuel when utilised [23].

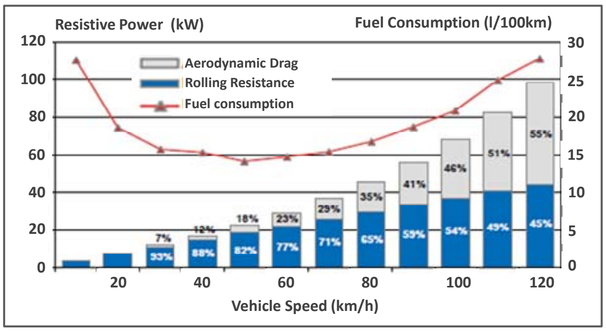

Figure 6 - Variation in fuel consumption with vehicle speed for medium duty truck [22]

Aerodynamic drag - Many modern production cars are now being designed to achieve very low coefficients of aerodynamic drag. The most aerodynamic variant of the 2009 Mercedes E220 Coupé achieves a figure of 0.24 – the lowest of any series production vehicle [24]. The 2010 Toyota Prius achieves 0.25 [25] and the 2001 Audi A2 1.2TDi also achieved 0.25 [26] which is particularly noteworthy as it is harder to achieve a low figure for a shorter vehicle. While achieving these figures can require expensive detailed windtunnel test work, it is unlikely to mean a significant increase in vehicle retail prices. Relatively low cost measures to reduce drag include reducing the ride height, smoothing the underbody, and fitting smooth wheel covers. More expensive measures such as active grille shutters which close at higher speeds have been introduced on Opel/Vauxhall [27] and Ford models resulting in a claimed 2% reduction in CO_2 [28]. However average passenger car frontal areas have increased approximately 10% between 1995-2010 [29], which may have offset reductions in drag coefficient.

Measures to reduce aerodynamic drag apply equally to vans. Low emissions models such as the Ford Fiesta Econetic Van and the VW Caddy Bluemotion have lowered ride height and aerodynamic devices to reduce drag from the wheels [30][31]. Opel/Vauxhall claim to be the first in the industry to offer an 'Ecoflex' version of all of their van models [32]. Overall, reductions in drag for light vehicles are generally less effective at reducing fuel consumption than weight reduction. A study based on the EPA fuel economy test found a 10% reduction in weight resulted in 6-7% fuel economy improvement, whereas a 10% reduction in rolling resistance or aerodynamic drag resulted in a 2% improvement [33] although this is dependent on duty cycles.

There are a number of ways of reducing drag on large goods vehicles too. One of the most cost effective measures is the fitment of cab roof fairings. When combined with a 'cab collar' (partially filling the gap between cab and trailer) CO_2 reductions of 3.5-6.2% can be achieved. Various other drag reduction measures are available with CO_2 reductions ranging from 0.1-4.8% and costs of €290-1750 (see Table 2). Teardrop shaped box van trailers are claimed to achieve CO_2 reductions on average of about 10%, but up to 24% on constant speed testing [22]. The use of lighter aluminium roof rails to achieve the roof profile also allows an 8.5% increase in load capacity for curtain side and box van trailers, giving further energy savings. However for double decks and lifting decks, height increases are not practical, and available load space is reduced due to the curve of the roof at the front [20].

POTENTIAL AND BARRIERS – There is further potential for significant weight and drag reduction in passenger cars. The ultimate potential for lightweight and low drag has been demonstrated by entrants to the Automotive X-prize such as the Aptera 2e and the winning Edison 2 design [34].

Vehicle	Kerb Weight	Drag	Source
Aptera 2e	816 kg	0.15	www.Aptera.com
Edison 2	<363kg	0.15	www.edison2.com

These vehicles use wheels which are completely contained in their own fairings as well as small built-in cameras instead of rear view mirrors in order to minimize drag. The Aptera seats only two people, but despite its ultra low weight the Edison is a full four seater. The X-prize rules require that vehicles should be 'production capable' meaning that they would need to be able to be compliant to Federal Motor Vehicle Safety Standards, although they are not formally tested. As a result of the Edison's extreme lightweight, it needs only a 250cc diesel engine and achieves over 100mpg in the EPA cycle [35]. These designs illustrate the benefits of low weight and drag, however they are very far removed from current passenger car designs. The Volkswagen XL1 concept car illustrates the direction that mainstream designs may evolve towards. The vehicle weighs 795kg and has a drag coefficient of 0.186 and with a hybrid powertrain featuring a 800cc 48PS diesel engine and a 27PS electric motor, it is claimed to achieve 313mpg and 24g/km CO_2 [36]. It features extensive use of lightweight materials with only 23% of the vehicle being iron or steel. The wheels are magnesium with ceramic brake discs and aluminium is used for dampers, steering system and brake callipers [36]. Developing the model has led VW to patent a new process to produce carbon fibre reinforced polymers.

Lighter weight materials and reduced aerodynamic drag can be applied equally to vans and lorries. Reducing commercial vehicle weights not only directly reduces fuel consumption but can also help by increasing payloads and thus reducing the numbers of journeys made. For heavy duty vehicles, the saving can be a 1-2% reduction in greenhouse gas emissions per tonne of weight saved rising to 4% for weight limited applications where the number of journeys can be reduced [22].

There is also strong potential for energy savings from drag reduction of large goods vehicles. Although the technology is proven, application is not yet widespread. Barriers include the initial cost, the fact that fittings must be correctly adjusted to achieve savings and the fact that some devices may reduce load capacity. There may also be resistance from operators worried that aerodynamic mouldings may not be robust to daily operations requirements. Aerodynamic trailer tail extensions have potential for 3-8% fuel consumption reductions for long haul applications but are not generally used as their inclusion in current length restrictions would result in loss of load space [22].

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Barriers to low weight and drag passenger cars include public acceptance of the unusual styling required for very low drag, concerns over the safety of very light vehicles particularly when in collision with heavier traditional designs and the fact that occupants in very light vehicles can feel more exposed. In fact there is no reason why ultra-light vehicle designs cannot be made to be safe. Lightweight vehicles are by their nature more nimble and manoeuvrable meaning that their 'active safety' (their ability to avoid collisions) is very good. Light but very strong 'safety cell' structures are used in Formula 1 cars making very high speed crashes survivable. A potential barrier for low drag designs is that they can suffer from instability in cross-winds. However detailed aerodynamic design work can resolve instability issues.

Table 1 - Summary Table: Weight and drag reduction for passenger cars and light vans

Measure	% Reduction in CO_2	Cost[a] (varies with vehicle size and petrol/diesel) [37]
10% weight reduction [33] [14][38][15]	6-10%	€212-538[b]
10% aerodynamic drag reduction [33]	2.0%	€75
Tyre pressure monitoring system [17]	2.5%	€58
Low rolling resistance tyres [39]	3.0%	€25-35

Typical passenger car and van CO_2 emissions reductions through weight and drag reduction (note: actual CO_2 reductions will be dependent on duty cycle). a) Costs in euros – 2006 prices. b) Based on 9% reduction in total vehicle weight.

Table 2: Typical heavy duty vehicle CO_2 emissions reductions through weight and drag reduction

Device	% Reduction in CO_2	Cost[a]
Weight reduction [22]	1-2% per tonne (4% with weight limited loads)	€11845-31625 [39][b]
Cab roof fairing and collar [20]	3.2-6.5%	€860-1150
Cab deflector [20]]	2.3-4.8%	€460-750
Container front fairing [20]	0.7-3.6%	€340
Chassis/trailer side panels [20]	0.4-1.0%	€860-1950
Trailer roof tapering [20]]	0.1-0.5%	€290
Teardrop trailer [22]	Average 10%	€2875 [39]
Low rolling resistance tyres [22]	5% (HGV), 3% (intercity coach)	€184-575 [39]
Tyre pressure monitoring system [20]	7-8%	€11,500
Single wide tyres [20]	2% per axle (6-10% for whole vehicle)	Approximately neutral

a) Cost conversion factor from original source: £1 = €1.15. b) Figures for 'strong' weight reduction (costs: low = 3.5-7.5 tonne, high = >33 tonne vehicle)

Table 3: Typical coefficients of rolling resistance for pneumatic tyres [5]

Surface	Crr
Concrete asphalt	0.011
Rolled coarse gravel	0.020
Tarmacadam	0.025
Unpaved road	0.050

Table 4: Typical coefficients of aerodynamic drag [5]

Vehicle Body Type	Coefficient of Drag
Open convertible	0.33-0.50
Notch back sedan	0.26-0.35
Estate / station wagon	0.30-0.34
Wedge shaped body	0.30-0.40
Headlamps and all wheels enclosed within body; underbody paneled	0.25-0.30
Optimum streamlining	0.15-0.20
Large goods vehicle	0.8-1.5
Motorcycles	0.6-0.7
Buses	0.6-0.7
Streamlined buses	0.3-0.4

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