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Size or Mass?

The Technical Rationale for Selecting Size as an Attribute for Vehicle Efficiency Standards

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Introduction

Governments in some of the world's major automotive markets, which combined account for about 70% of total sales worldwide, have adopted varying forms of light-duty vehicle efficiency standards—that is, regulations requiring reduced CO_2 emissions, reduced fuel consumption rates, or increased fuel economy (table 1). All existing versions of such standards are indexed to either size or weight, setting less stringent targets for larger or heavier vehicles so as to reduce competitive impacts and promote efficiency improvements across an entire vehicle fleet. While the choice of which of these two attributes to use has important consequences, both attempt to accommodate differences among vehicles, balancing efficiency goals with consumer demand and manufacturers' needs to remain competitive. Three of the four largest markets (the European Union, China, and Japan) index standards to vehicle mass. The U.S. and Canada, in contrast, index standards to vehicle size.

Ideally, efficiency standards are technology neutral; they do not require manufacturers to use specific technologies. The intent is to promote the full range of approaches to making vehicles more efficient—improved engine combustion, increased transmission efficiency, lightweighting, advanced drivetrains, etc.—and, indeed, to create incentives to come up with new solutions. But size-based and mass-based efficiency standards create significantly different technology incentives, and in the end mass-based standards actually decrease the options available to improve efficiency.

This white paper summarizes the differences between size-based and mass-based efficiency standards, discusses their relative advantages and disadvantages, and provides guidance on the development of future standards. Specifically, the paper argues that size-indexed standards are more effective in promoting efficient technologies, and more neutral with respect to technology. They also escape the problem of rewarding larger engines and diesels with artificially less-stringent standards and are less subject to gaming. These advantages argue for a fundamental reconsideration of the mass-based regulatory framework where it is in use and against its extension into as-yet-unregulated light-duty vehicle markets.

Such a reconsideration is an urgent priority, as mass-based standards inherently discourage the deployment of vehicle lightweighting and lightweight

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materials. The development of lightweight materials, such as ultra-high-strength steel, aluminum, plastics, magnesium, and carbon fiber, is progressing rapidly. Continued use of mass-based standards will discourage the deployment of these lightweight materials, resulting in a missed opportunity to reduce fuel consumption and carbon emissions. Lightweight materials are also a critical area of technical development for advanced electric-drive vehicles, in which reduced vehicle weight increases vehicle range irrespective of the powertrain

Table 1. Worldwide mandatory automobile efficiency and GHG standards

Country/region	*2009 auto sales in millions (world market share)*	*Regulatory metric*	*Standard design elements*
European Union	14 (24%)	CO_2 (grams CO_2/kilometer)	Mass-indexed, continuous
United States	10 (18%)	FE (miles/gallon); GHG (grams CO_2e/mile)	Size-indexed, continuous, two vehicle-type classes
China	8 (14%)	FC (liters/100 kilometers)	Mass-indexed, discrete ranges, two transmission classes
Japan	5 (8%)	FE (kilometers/liter)	Mass-indexed, discrete ranges
Canada	1.5 (3%)	GHG (grams CO_2e/mile)	Size-indexed, continuous, two vehicle-type classes
South Korea	1.1 (2%)	FE (kilometers/liter): CO_2 (grams CO_2e/kilometer)	Mass-indexed

Sources: JD Power, Automotive News. Data are approximate, some countries use different vehicle category definitions.
Abbreviations: CO_2e = carbon dioxide equivalent; FE = fuel economy; FC = fuel consumption; GHG = greenhouse gas.

The problems with mass-based standards summarized here were raised in detail in comments to U.S. National Highway Transportation and Safety Administration (NHTSA) by American Honda Motor Company (American Honda Motor 2004, American Honda Motor 2005). In establishing footprint as the attribute in 2006, NHTSA stated: “By using vehicle footprint in lieu of a weight-based metric, we are facilitating the use of promising lightweight materials that, although perhaps not cost-effective in mass production today, may ultimately achieve wider use in the fleet, become less expensive, and enhance both vehicle safety and fuel economy.” (NHTSA 2006). Three major research institutes in the EU, which supported the European Commission in developing the vehicle CO_2 proposal, also recommended that “footprint should be substituted for the weight parameter in the Commission proposal.” (Fergusson et al, 2008).

Vehicle Efficiency

Vehicle efficiency can be increased by improving the efficiency of the power train or reducing the loads on the vehicle. Sources of power train efficiency gains include variable valve timing, direct injection, turbocharging, friction reduction, improved transmissions, and hybrid systems. These power train efficiency gains are equally incentivized under either size- or mass-based standards. But size and mass relate differently to the loads on the engine:

- Inertia losses. The energy required to accelerate the vehicle is proportional to the vehicle mass.
- Aerodynamic losses imposed by expending energy to push air aside as the vehicle moves; proportional to the vehicle frontal area, the coefficient of drag, and the square of the vehicle speed.
- Tire rolling resistance losses, proportional to vehicle mass and speed.
- Accessory loads, such as air conditioning and vehicle lights.

Of these loads, inertia is the largest under most conditions, especially at lower vehicle speeds. Vehicle mass also affects tire rolling resistance losses. Thus, vehicle mass has a direct and strong relationship with vehicle efficiency. Vehicle size has an indirect effect with aerodynamic losses, as the width of the vehicle has some effect on the frontal area, but the relationship is much weaker and, overall, aerodynamic losses are much smaller than inertia and tire rolling resistance losses.

Vehicle fuel economy can also be traded off with acceleration. Reducing the performance of the vehicle will improve the fuel economy, although the overall technical efficiency is not affected.

Relationships of vehicle attributes to CO_2

The primary goal of standards is to provide an inducement to make more efficient vehicles. The primary reason for indexing standards to a vehicle attribute is to allow a fleet to remain diverse in terms of vehicle shape, size, and functionality. Ideally, attribute-based standards maximize the range of strategies available to automakers for deploying more efficient vehicles while indexing efficiency requirements to characteristics that best reflect the range of vehicle features —passenger capacity, cargo capability, etc.—a vehicle is designed for. As the functional size or “utility” of a vehicle class increases, the emissions or fuel economy requirements decrease. The goal is to improve efficiency without compromising vehicle functionality.

Many different attributes could serve as the basis for standards.[1] The selection

1 In regulatory deliberations that led to the mass- and size-based standards of today, alternative attributes were considered and dismissed. For example, engine size is not a

of any one represents a decision to partially or entirely discount improvements in that attribute as a way to comply with the standards. An attribute-based standard neutralizes (or discounts) the use of design changes affecting that attribute as a compliance strategy, instead allowing it to vary according to market demand. That always entails some trade-off.

Advantages of using either vehicle mass or vehicle size as the indexing attribute are that both are easily measured and both correlate substantially with CO_2 emissions and fuel consumption. Substantially, but not equally. As Figure 1 illustrates, CO_2 is better correlated with mass (defined here as curb mass) than size (defined as a vehicle's "footprint," calculated by multiplying the wheelbase by the track width). This is one of the primary justifications used by governments that have adopted mass-based standards. The high correlation between mass

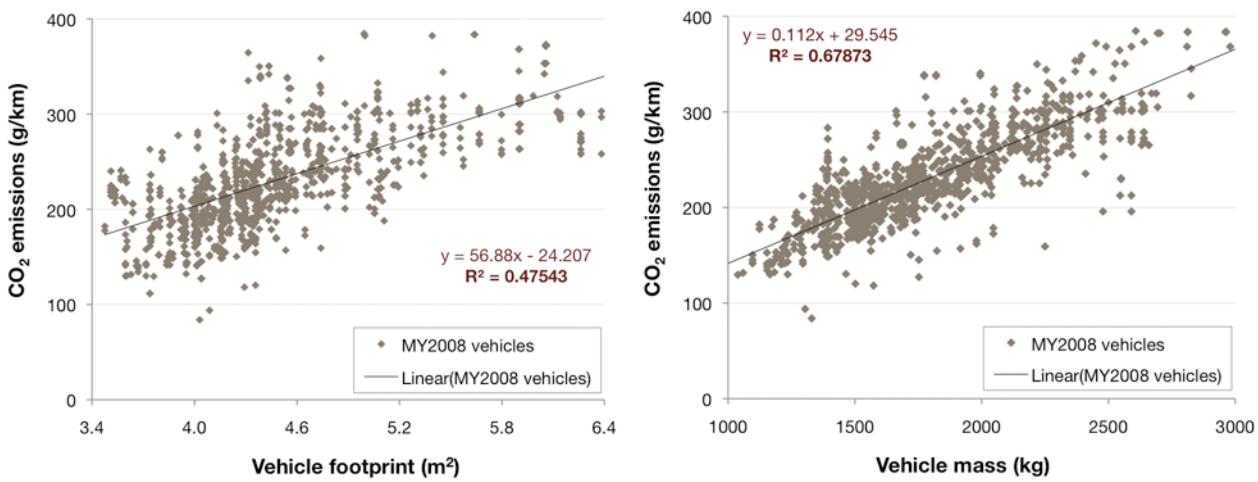

Figure 1. Relationship between vehicle attributes (size and mass) and CO_2 emissions

and efficiency follows from the direct physical relationship between the inertial mass of the vehicle and the energy required to accelerate the vehicle and overcome tire rolling resistance loads. Size is less strongly correlated to CO_2 because it has only an indirect physical relationship with energy requirements and therefore vehicle efficiency: vehicles can be lighter or heavier at a given size, even as functional vehicle size remains constant.

The distinction between casual (size) and causal (mass) connections to vehicle efficiency is crucial. Efficiency is dependent on powertrain technology and

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good indicator of vehicle utility and engine size standards encourage the use of larger naturally aspirated engines instead of smaller, more efficient turbocharged engines with the same performance.

vehicle losses. Size is effectively disconnected from these: losses correlate with size to some degree, but it is possible to improve technology and reduce losses—inertial losses, as well as losses due to other factors—without changing vehicle footprint. A size-based standard rewards manufacturers that accomplish that. But mass cannot be disconnected from vehicle losses, and especially from the most important, inertial losses. Efficiency is causally dependent on mass, and a mass-based standard rests on the error of confusing a vehicle efficiency factor with a vehicle attribute. It is logically no different than indexing standards to engine thermal efficiency or tire rolling resistance and has the perverse effect of imposing tougher CO_2 standards on improved-efficiency vehicles. As a result, mass-reduction technology receives full credit for its resulting CO_2 emission reduction under a size-indexed CO_2 standard but little to no credit under a

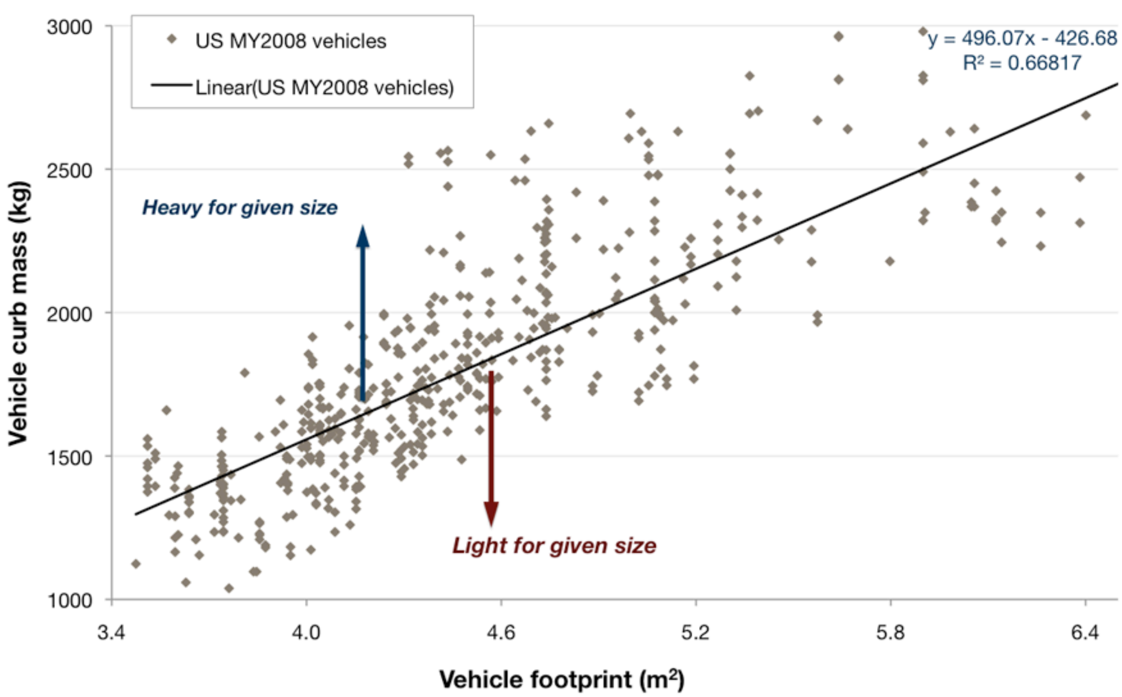

Figure 2. Model year 2008 U.S. light duty vehicle curb mass and size.

mass-indexed standard. The ideal for efficiency standards is technological neutrality; size-based standards approach that ideal much more closely than mass-based standards.

It is also important to understand how size and mass are linked, because that connection is important in understanding the advantage of using size over mass as a standard-indexing attribute—as are the factors that can break it. Figure

2 illustrates the vehicle size-to-mass relationship in the 2008 model year U.S. light-duty vehicle fleet. [2] Note that for any given vehicle size there is a reasonable correlation between size and mass across the different car and light truck classes. An important feature for setting regulatory standards is the vertical spread of the vehicle models' mass for any given size. It is possible to pick out vehicles are that are relatively heavy for a given size (furthest above the regression line), and vehicles that are relatively light (below the line). It is clear there is a large discrepancy in the mass characteristics of similarly sized vehicles. Comparatively light vehicle models, for which automakers have optimized mass to help improve efficiency, can be as low as 25% below the line. On the other hand, comparatively heavy vehicle designs with the same size and functionality can be as high as 40% above the average vehicle size-to-mass line, due at least in part to underutilization of mass-reduction technology.

A number of factors help explain this distribution: the use or non-use of lighter-weight materials and designs, powertrain size, and number and type of features and amenities (e.g., power electronics, sun roofs). As will be examined further below, standards indexed to vehicle mass do not acknowledge differences between light and heavy vehicles for a given size, and therefore fail to provide automakers with an incentive to produce vehicle models that use mass-efficient designs.

Disincentive for lightweight materials under mass-based standards

Any efficiency standard, whether indexed to vehicle size or mass, directly promotes increased powertrain efficiency, because the indexing attribute is irrelevant to the technical options for improving the powertrain. However, only size-based standards also fully encourage and capture lightweight technology deployment. Deploying technologies such as component-level lightweight material substitution (high-strength steel, aluminum, and composites) and using more comprehensive mass-optimized vehicle structural designs that integrate parts and employ more advanced lightweight bonding and forming techniques can reduce vehicle mass by up to 30% without any compromise in vehicle size or function (Geck et al, 2007; Goede et al, 2009; Lotus Engineering, 2010). Various engineering studies estimate that mass reductions on this scale would reduce CO_2 emissions by approximately 20% (Casadei and Broda, 2008; Bandivadekar

2 U.S. data are used here simply for illustration purposes; these mass and size relationships hold for every automobile market. For data from EU, China, India and Mexico, please refer to the appendix.

et al, 2008; FKA, 2007; Pagerit et al, 2006). But mass-based regulations take away (or discount) the incentive for automakers to use vehicle lightweighting: if an automaker deployed these lightweighting technologies in a market with mass-indexed standards, they would simply become subject to increasingly tougher standards. As a result, a mass-indexed standard actually discourages vehicle efficiency.

To demonstrate the difference in the treatment of lightweighting technology in the two regulatory structures, consider an identical vehicle powertrain-

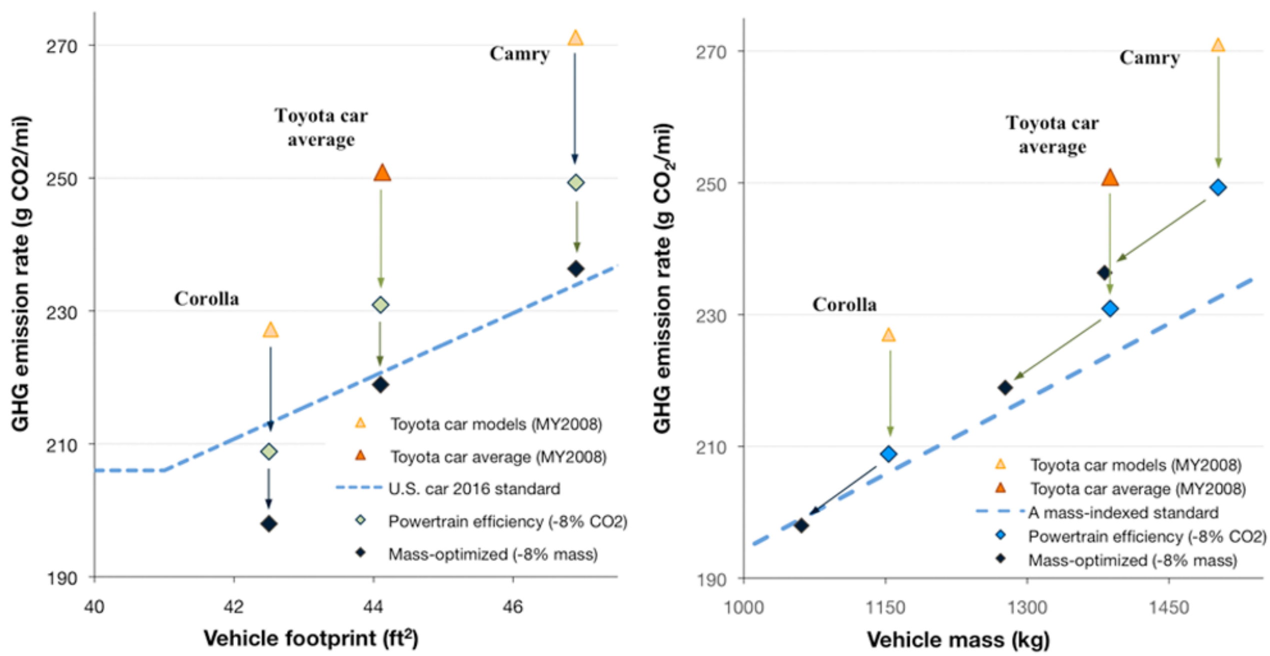

Figure 3. Impact of an identical efficiency-and-lightweighting technology package under size- and mass-based CO_2 emission regulations.

efficiency-plus-lightweighting technology package within the U.S. size-based standards and hypothetical mass-based standards of similar stringency. Figure 3 illustrates the potential for efficiency improvements and vehicle mass reduction to contribute toward compliance with size-based and mass-based regulatory standards, using 2008 Toyota Corolla, Toyota Camry, and average U.S. car values. These 2008 models are modified to reflect realistic near-term technology improvements that are being developed and deployed by automakers in the next several years. The two illustrative improvements are an 8% CO_2 reduction from improved powertrain efficiency (e.g., an improved engine and transmission) and an 8% mass reduction, which in turn reduces CO_2 emissions by 5%.

The left side of the figure shows the outcome under the U.S. footprint-based car standard. Under size-based standards, options such as material substitution and optimizing vehicle design to reduce overall vehicle mass are fully valued toward automaker compliance. Taken together, the efficiency and lightweighting steps result in vertical drops in the vehicle models' GHG emissions, bringing the models approximately to the diagonal standard line and resulting in compliance with the standards.

The right side shows results for a mass-based standard that is comparable in stringency to the U.S. footprint-based standard. The powertrain improvements produce a vertical improvement in CO_2 emissions, but mass-reduction is not a successful strategy because the models would become subject to a more stringent mass-indexed standard. Automakers that elect to deploy lightweighting technology that reduces CO_2 emissions and increases fuel economy will not be rewarded in mass-indexed regulatory schemes.

Mass-based standards can attempt to mitigate their relative disincentive for lightweighting technology by reducing the slope of the mass-to-CO_2 emission standard-setting curve. Shifting this slope to be more gradual than the natural regression of existing baseline vehicle models in the fleet would effectively shift the mass-based standard toward a flat standard. The EU scheme does intentionally set the standard target line at a slope that is lower than the actual fleet of vehicles, in an attempt to minimize future shifts toward a heavier fleet (EP, 2009; CEC, 2007). However, as long as there is any slope in a mass-indexed standard target line, such an approach will always provide less inducement for automakers to deploy lightweighting technology than flat or size-indexed standards, because lighter vehicles would be subject to more stringent standards.

The relative advantage of size-based standards in promoting more efficient technologies is even more critical in the long-term. While the lightweighting technologies are fundamental for the efficiency of all vehicles, they are especially critical for advanced electric-drive technologies, as lighter materials will increase the range of battery-electric vehicles and reduce costs.

Other deficiencies of mass-based standards

Mass-based standards have the side effect of encouraging heavier engines. Higher performance engines are usually larger and heavier and a mass-based standard gives them a less stringent efficiency standard to meet. Diesel engines are also heavier and receive a similar incentive, which can worsen air quality by promoting dieselization.[3] This is especially a problem in countries that have not adopted the latest diesel emission control requirements, or where criteria pollutant emission standards (e.g., for particulate matter) treat diesel vehicles more favorably than petrol vehicles (Rutherford 2008).

Another problem is that mass is much easier to game than size. Mass is invisible to the customer, who generally does not know or care about it, while size is obvious. For example, since 1983 the average weight of all cars in the U.S. increased from 1415 kg in 1983 to 1605 kg in 2008, or more than 13 percent. During the same period, the average interior volume of cars increased from 3.08 cubic meters to 3.14 cubic meters, or by less than two percent (U.S. EPA 2009). The increase in vehicle weight was not of concern to customers as long as vehicle performance and interior space was maintained. Increasing vehicle size impacts the market segment in which the vehicle competes, which increases customer expectations for the vehicle. Thus, while there may be some upsizing under a size-based scheme, the net negative impact should be far lower than a mass-based scheme.

NHTSA's concerns about gaming of mass-based standards was one of the reasons it selected footprint instead. "We noted that vehicle weight and shadow were discussed in the ANPRM, but along with commenters to the ANPRM, we had concerns that weight and shadow could more easily be tailored for the sole purpose of subjecting a vehicle to a less stringent target" (NHTSA 2006).

There is also evidence that size-based standards may reduce vehicle and pedestrian crash fatalities compared to mass-based standards (Gordon et al. 2007, Van Auken and Zellner 2005, Evans 2004). This is a highly technical and detailed area of analysis that is beyond the scope of this white paper. The ICCT plans to issue another white paper in the future on the safety issues.

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3 Some argue that diesels are needed to help achieve CO_2 reductions and that size-based standards disadvantage diesels. But weight-based standards give diesels an artificial advantage by reducing the stringency of the standard corresponding to the increased weight. This reduction in stringency is not associated with any real-world reduction in CO_2. Size-based standards properly represent the actual CO_2 reductions from diesels in use.

Summary

Table 2 summarizes the advantages and disadvantages of mass-indexed, size-indexed, and flat (i.e., non-attribute-indexed) vehicle-efficiency standards. As can be seen, mass-based standards have considerable disadvantages compared to size-based standards. Most important, mass-based approaches provide little or no incentive for lightweighting. Mass-based standards are also susceptible to backsliding in per-vehicle mass increases and engine size increases. The consistent upward weight creep that is commonplace when vehicles are redesigned is unchecked in mass-based standards, and thus backsliding in CO_2 emissions is inevitable unless other policy mechanisms prevent it. Another way in which overall public benefits are diminished is that vehicles with larger engine sizes (and increased CO_2 emissions) are granted more lax emission standards in a mass-based regime. Size-based standards offer the broadest incentives for automakers to improve vehicle efficiency, while avoiding critical disadvantages of the mass-based approach.

Table 2. Pros and cons of mass-indexed, size-indexed, and flat efficiency standards

		Design of Standard		
		Mass	*Size*	*Flat*
The potential for compliance benefits from given strategies	Power train efficiency	+	+	+
	Engine downsizing	+	+	+
	Per-vehicle mass reduction (lightweighting)		+	+
	Downsizing sales-shift			+
Potential disadvantages in loss of intended benefits	Backsliding due to vehicle fleet sales shift	–	–	
	Backsliding due to per-vehicle mass creep	–		
	Backsliding due to increased engine size	–		
Equitable technology-based improvement across vehicle types		+	+	–
Simplicity, transparency of standards; outcome certainty		–	–	+

"+" denotes an advantage of the given efficiency design approach;" –" denotes a disadvantage or limitation

Conclusions

The ultimate objective of this report is to argue that regulators should reconsider the use of the mass-based regulatory framework where it is already in use (the European Union, China, and Japan), and not extend it to as-yet-unregulated markets. Due to the inherent disadvantages of the mass-based framework, it should be supplanted by size-based standards.

Of the two vehicle attributes currently used in attribute-based standards, vehicle mass has a closer statistical correlation with vehicle efficiency precisely because it is one of the basic factors directly influencing vehicle efficiency. As a result, the use of mass-based standards negates the lightweighting designs that automakers have recently begun to use and discourages further developments along those lines. Vehicle size is a more legitimate proxy of a vehicle's usefulness to consumers (passenger and cargo capacity) and it is largely disconnected from vehicle losses. Thus, it does not eliminate the benefits of mass reduction and is a much more reasonable factor for attribute-indexed efficiency standards. Lightweight materials have the potential to reduce fuel consumption and greenhouse gas emissions by 20%, if not more, and it is extremely important to encourage their future development and implementation. Size-based standards also avoid rewarding heavier engines, including diesels, with artificially less stringent standards and are less subject to gaming.

The best practices for establishing automobile efficiency standards involve maximizing the amount of efficiency strategies than can be utilized for standard compliance and minimizing the potential for consumer or industry trends that can erode a program's benefits. Size-indexed standards outperform mass-indexed standards in promoting more efficiency technology options and preventing deleterious trends.

Appendix

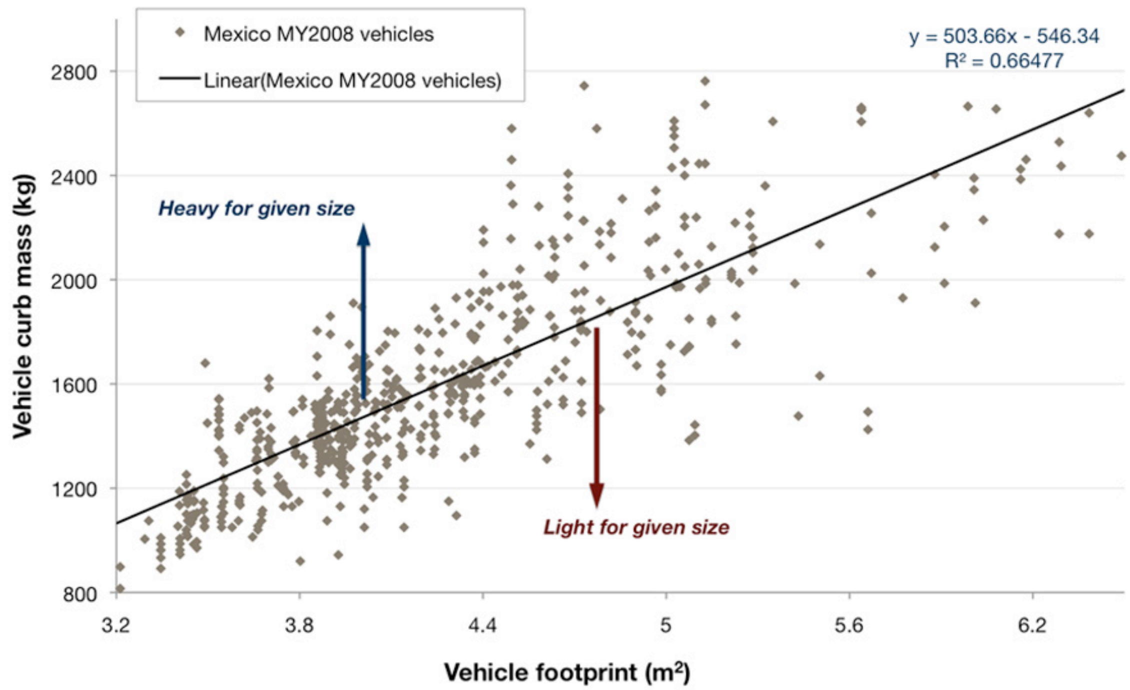

Figure 4. Model year 2008 Mexican light duty vehicle curb mass and size

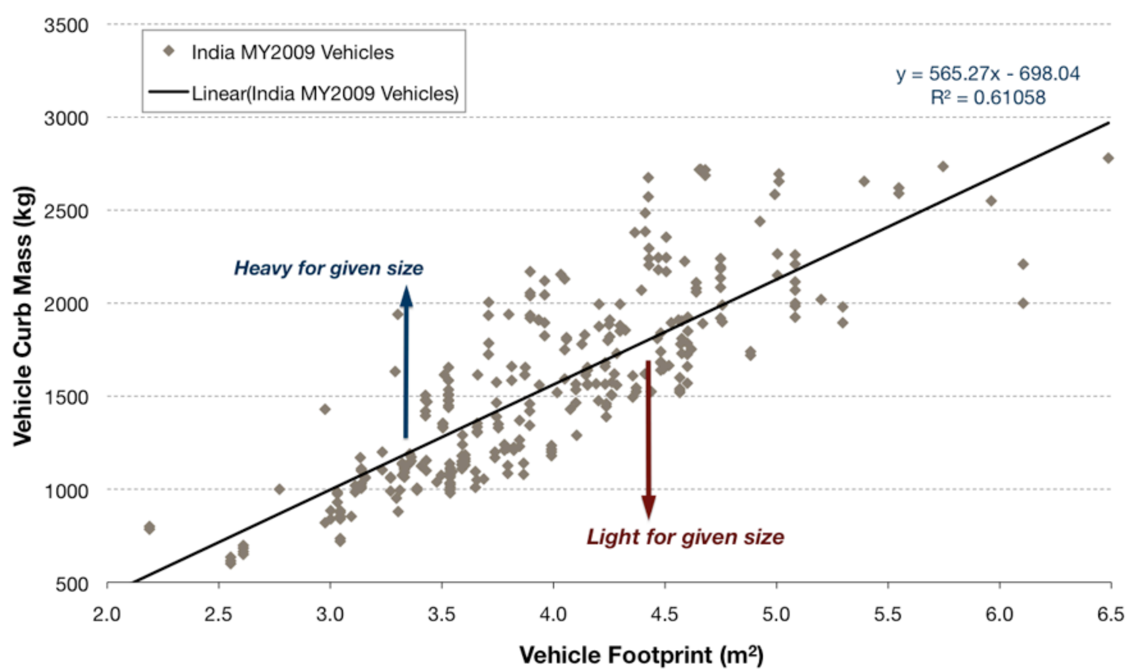

Figure 5. Model year 2009 Indian light duty vehicle curb mass and size.

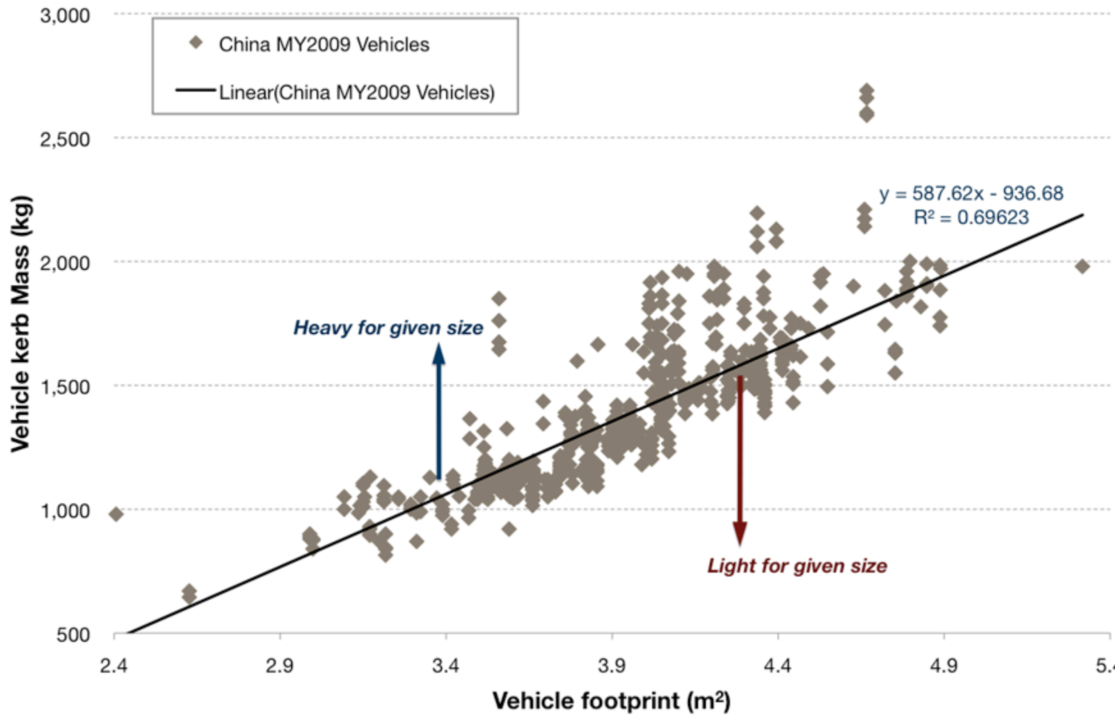

Figure 6. Model year 2009 Chinese light duty vehicle curb mass and size.

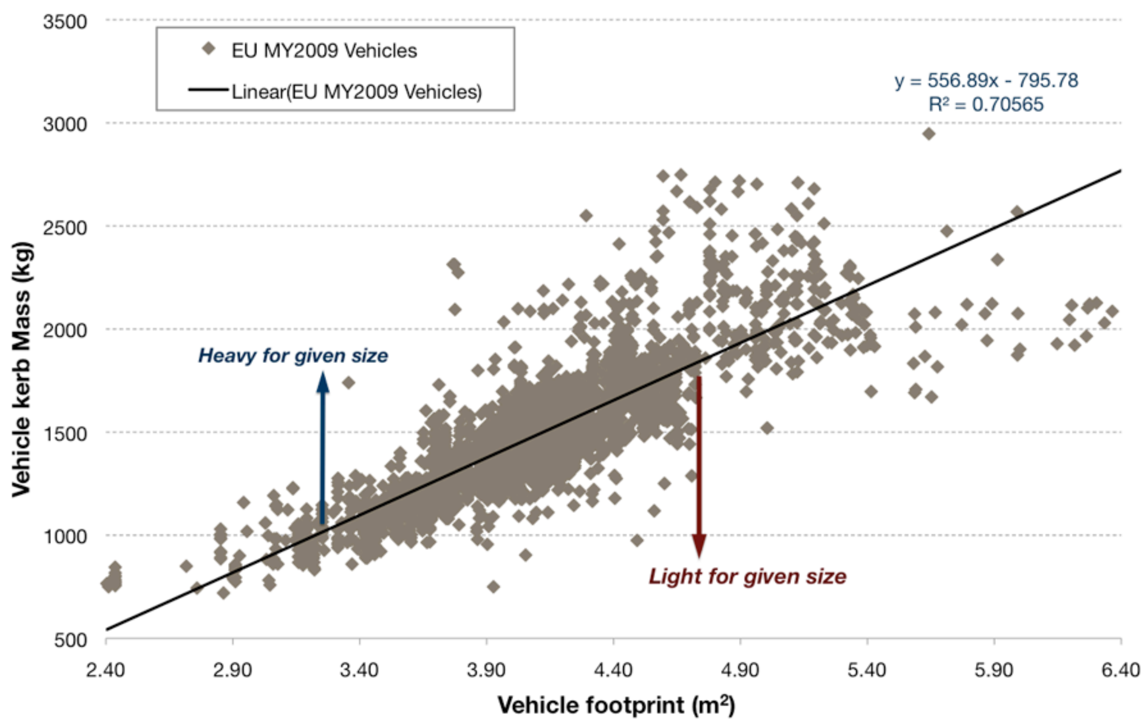

Figure 7. Model year 2009 EU light duty vehicle curb mass and size.

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