

Technical Analysis of Vehicle Load-Reduction Potential for Advanced Clean Cars

- Technical Seminar -

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and the
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This research benefitted immensely from the experience and talent of Heidi Schroeder. Heidi's attention to detail and her analytical skills were key to the successful analysis of nearly 1400 vehicle models as required to support the research objectives. CONTROLTEC also appreciated the constructive input and feedback from the Air Resources Board project team.

- Research Motivation, Objective, & Scope
- Vehicle Load Primer
- Assessment of Model Year 2014 Vehicle Load Attributes
 - Aerodynamic Drag
 - Tire Rolling Resistance
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- Fuel Economy & CO₂ Emissions Projection Results
- Conclusions
- Q&A

Research Motivation, Objective, and Scope

- Reducing greenhouse gas emissions will require light-duty vehicle manufacturers to implement vehicle load reduction strategies such as aerodynamic drag improvements, reduced tire rolling resistance, and mass optimization.
- In support of the California Air Resources Board Advanced Clean Cars program, these vehicle load attributes were assessed for the potential to reduce carbon dioxide (CO₂) emissions from the future light-duty vehicle fleet.

Research Task: Assuming that all current vehicles adopt similar amounts of load reduction technologies and strategies already available in today's better performing vehicles, determine the potential reduction in tailpipe CO₂ emissions from the future California light-duty vehicle fleet.

Research Scope Is:

- Model Year (MY) 2014 light-duty vehicles.
- Aerodynamic drag, tire rolling resistance, and mass.
- EPA combined drive cycle.
- An analytical study.

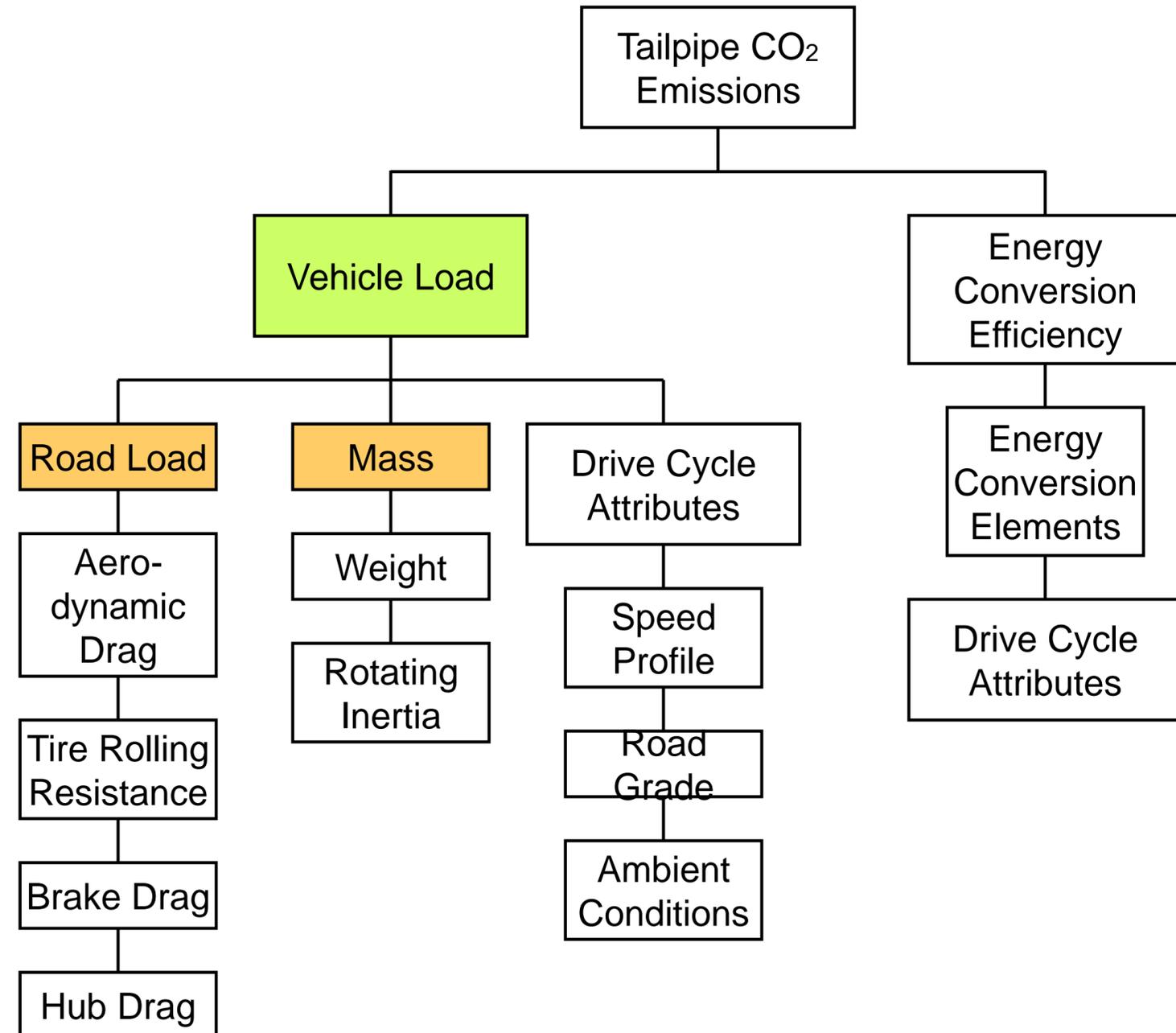
Research Scope Is Not:

- Powertrain technology.
- Alternate drive cycles (e.g., NEDC, JC08, WLTC).
- Testing.
- Design and cost assessment.

Vehicle Load Primer

Tailpipe CO₂ Emissions.

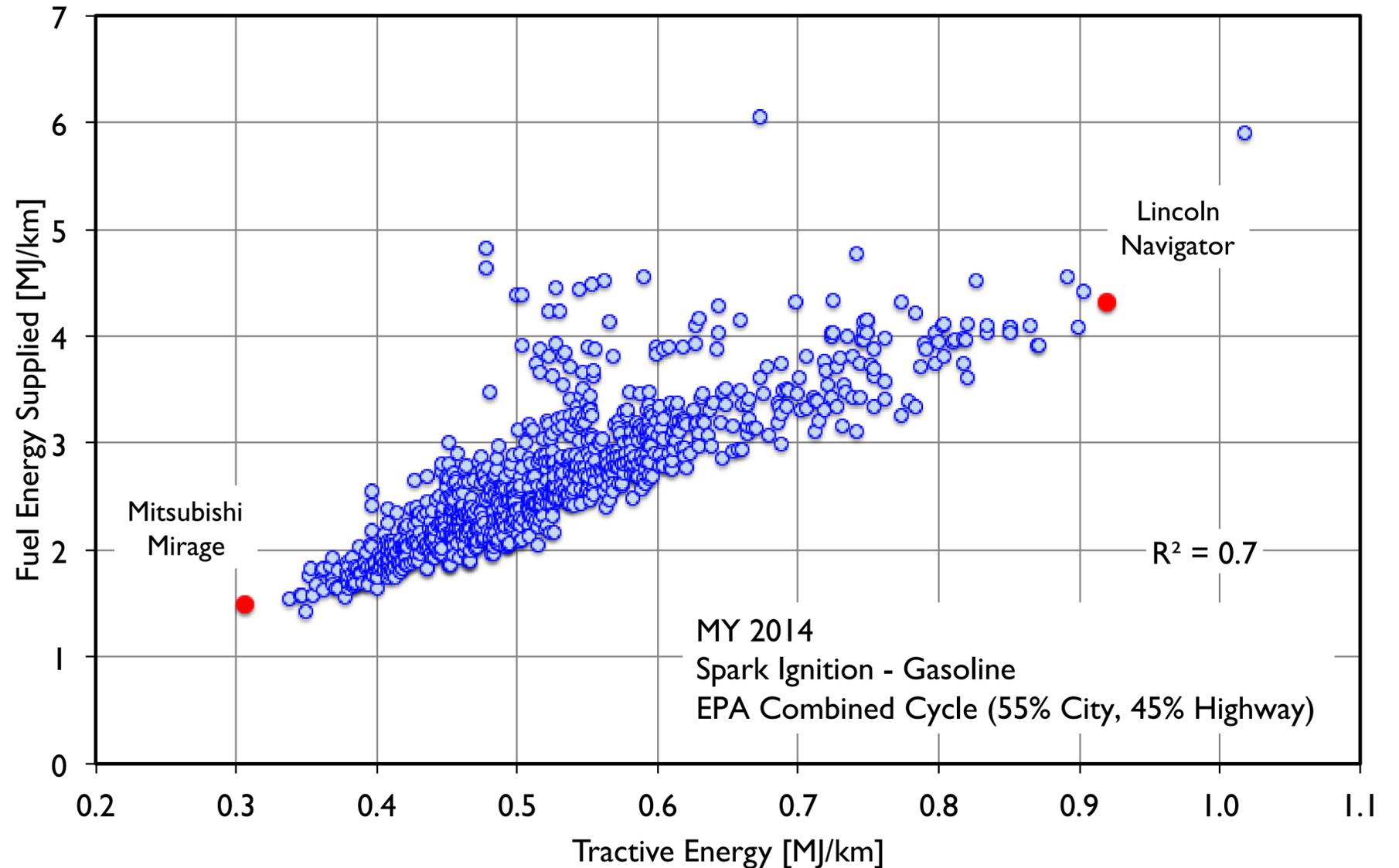
- An organization analogy is used to categorize the contributors to tailpipe CO₂ emissions. The organization has two departments:
 - Vehicle Load
 - Energy Conversion Efficiency
- The departments interact; e.g., changes in the Vehicle Load yield changes to the Energy Conversion Efficiency.
- Vehicle manufacturers and suppliers develop the Vehicle Load and Energy Conversion Efficiency elements.
- Consumers, nature, and government agencies control/define the Drive Cycle Attributes.



The research project is focused on vehicle load elements.

Fuel Consumption vs. Tractive Energy.

- Vehicle load is best assessed by evaluating the tractive energy (the product of resistance and distance).
- For a given powertrain type and drive cycle, tractive energy is the first order determinant of fuel energy requirements; accounting for ~70% of the variation in fuel consumption among spark-ignition/gasoline powered vehicles.



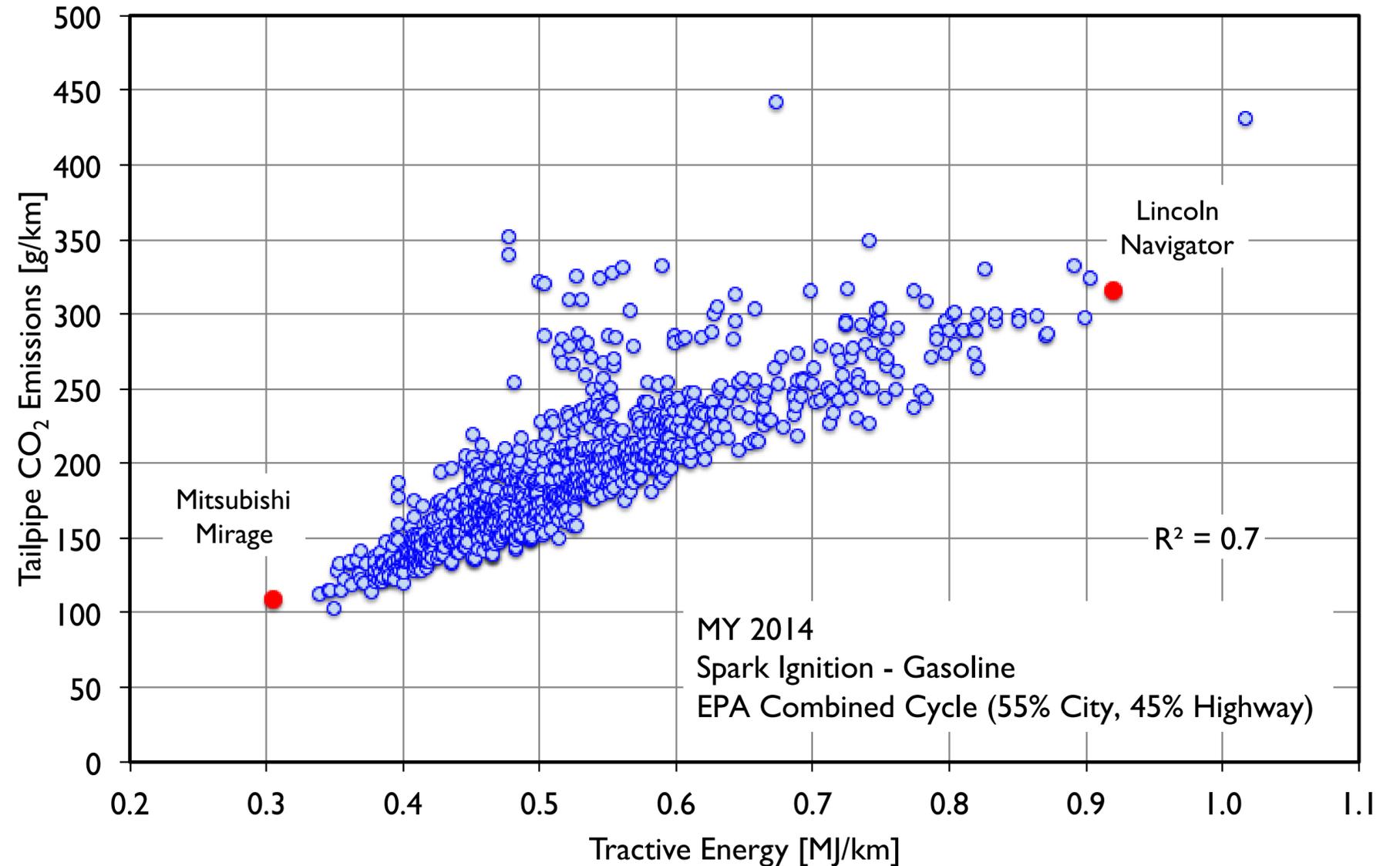
Analysis Source: CONTROLTEC
Data Source: epa.gov/otaq/tcldata.htm

The research project is focused on determining the potential to reduce tractive energy by improving the vehicle load elements.

Tailpipe CO₂ Emissions vs. Tractive Energy.

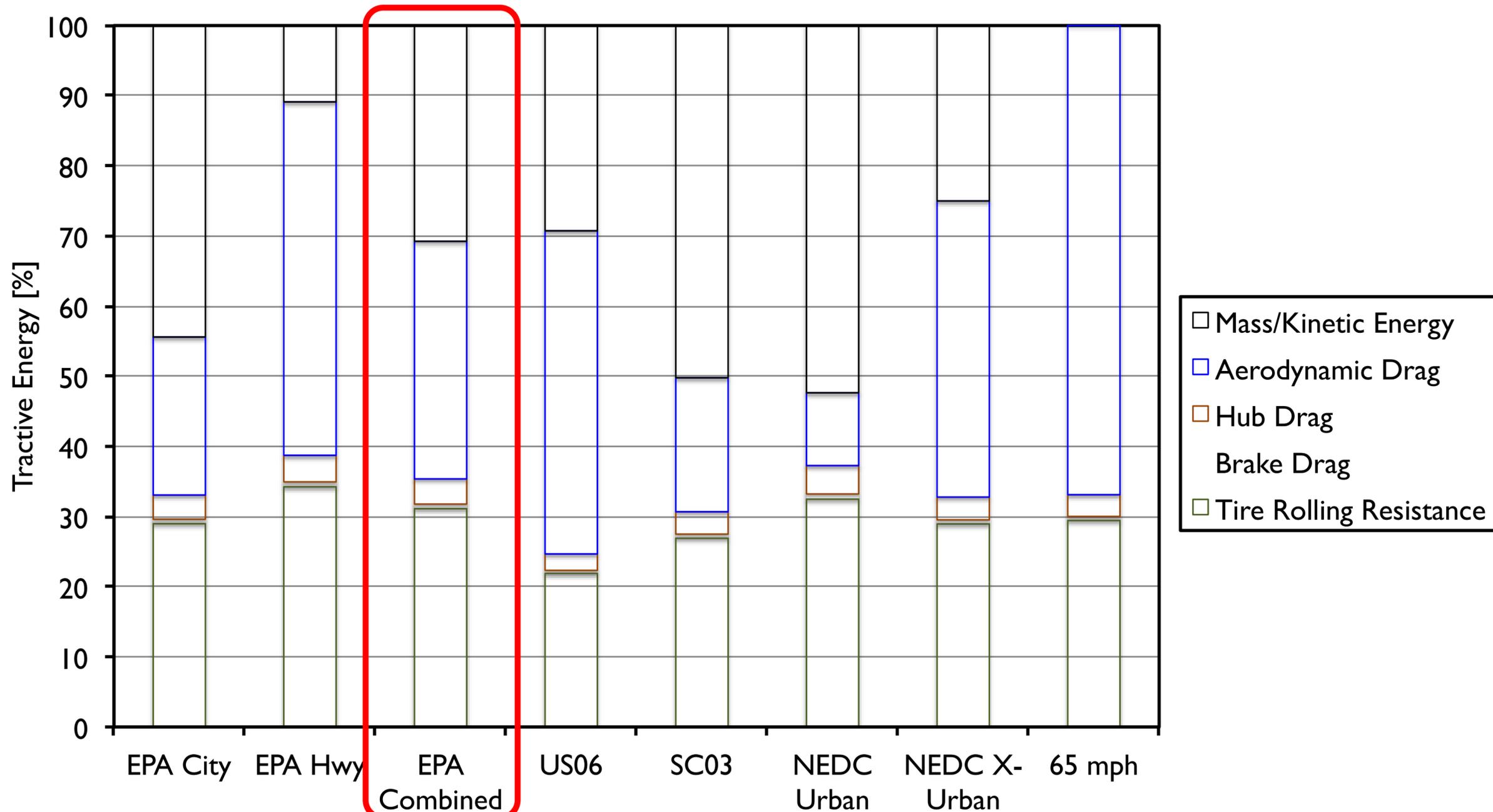
- The fuel energy supplied, combined with the carbon density of the fuel, determines the CO₂ emissions.
- The energy specific CO₂ emissions for the primary fuels is shown in the table below.

Fuel	Energy Specific CO ₂ Emissions [gCO ₂ /MJ]
Diesel	75.5
Gasoline	73.1
E85	69.8
CNG	55.7



The research project is focused on determining the potential to reduce tractive energy as a means of reducing tailpipe CO₂ emissions.

Vehicle Load Elements. Contribution to Tractive Energy.



Source: CONTROLTEC; C-Segment Sedan

The relative importance of vehicle load elements depends upon the drive cycle. The research project is focused on the EPA combined cycles (55% city, 45% highway).

Tractive Energy vs. Vehicle Load Elements.

- The reduction of individual vehicle load elements does not provide a 1:1 reduction of tractive energy.
- For the EPA combined cycles, mass reduction provides the largest reduction of tractive energy followed by aerodynamic drag, and tire rolling resistance.
- Mass reduction affects both kinetic energy and tire rolling force.

Vehicle Load Reduction Affect EPA Combined Cycles (55% City/45% Highway)
10% Mass Reduction \approx 5.6% Tractive Energy Reduction
10% Aerodynamic Drag Reduction \approx 3.6% Tractive Energy Reduction
10% Tire Rolling Resistance Reduction \approx 2.1% Tractive Energy Reduction

Average of multiple types of light-duty vehicles
Source: CONTROLTEC

Reduction of vehicle load elements do not have a 1:1 affect on tractive energy and tailpipe CO₂ emissions.

Assessment of Model Year 2014 Vehicles Non-Mass Load Attributes

- Determine the aerodynamic drag and tire rolling resistance performance of every model year 2014 vehicle available in California (1358 model variants).
- Identify top performing vehicles, by class, for aerodynamic drag and tire rolling resistance.
- To support the subsequent load reduction scenarios, define best-in-class (BIC) aerodynamic drag and tire rolling resistance based on the top-performing vehicles.
- Cross-reference vehicle features with aerodynamic drag and tire rolling resistance performance to determine best design practices.

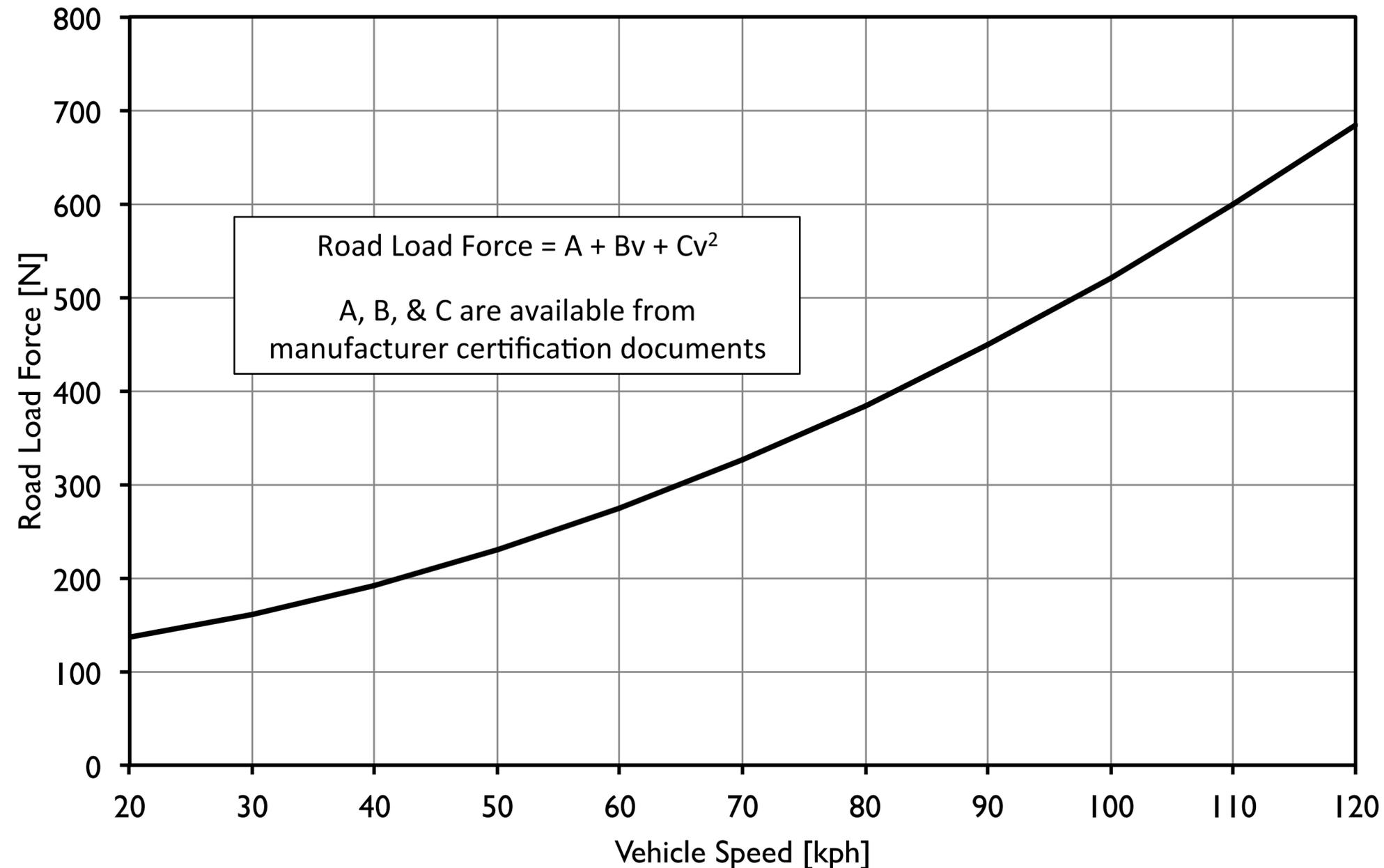
- For the current research, the coefficient of drag, C_d is the best measure of aerodynamic efficiency.
- C_d was reported by the manufacturers for only 47% of the vehicles in the MY 2014 data set.
- Even if all of the vehicles in the data set had a manufacturer-reported C_d value, wind tunnel design, features, and test conditions are not standardized across the industry, consequently, using the manufacturer-reported C_d values could favor one manufacturer over another.

Challenge #1: A consistent method is required to estimate C_d for all vehicles in the data set.

- For the current research, the rolling resistance coefficient (RRC) is the best comparison metric for tire rolling resistance.
- Tire rolling resistance is not reported by manufacturers and current information is not available. Government-funded tire RRC studies, while quite valuable, cannot be directly applied to this study.

Challenge #2: A consistent method is required to estimate the tire RRC for every vehicle in the data set.

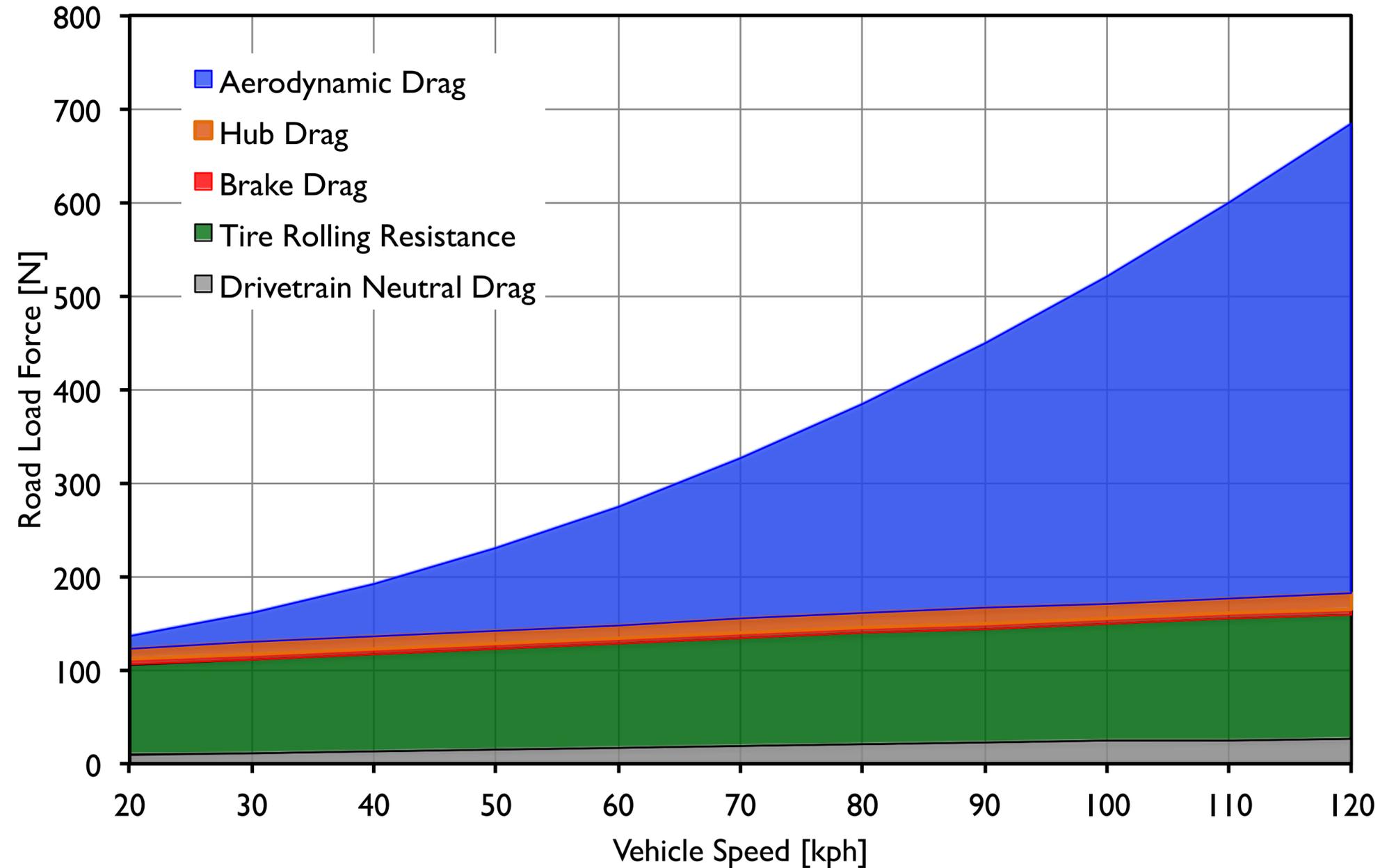
Solution: Decompose the Road Load.



Data Source: epa.gov/otaq/tclldata.htm; C-Segment Sedan

Vehicle certification requires manufacturers to provide the road load force as a function of speed for all models and variants.

Solution: Decompose the Road Load.

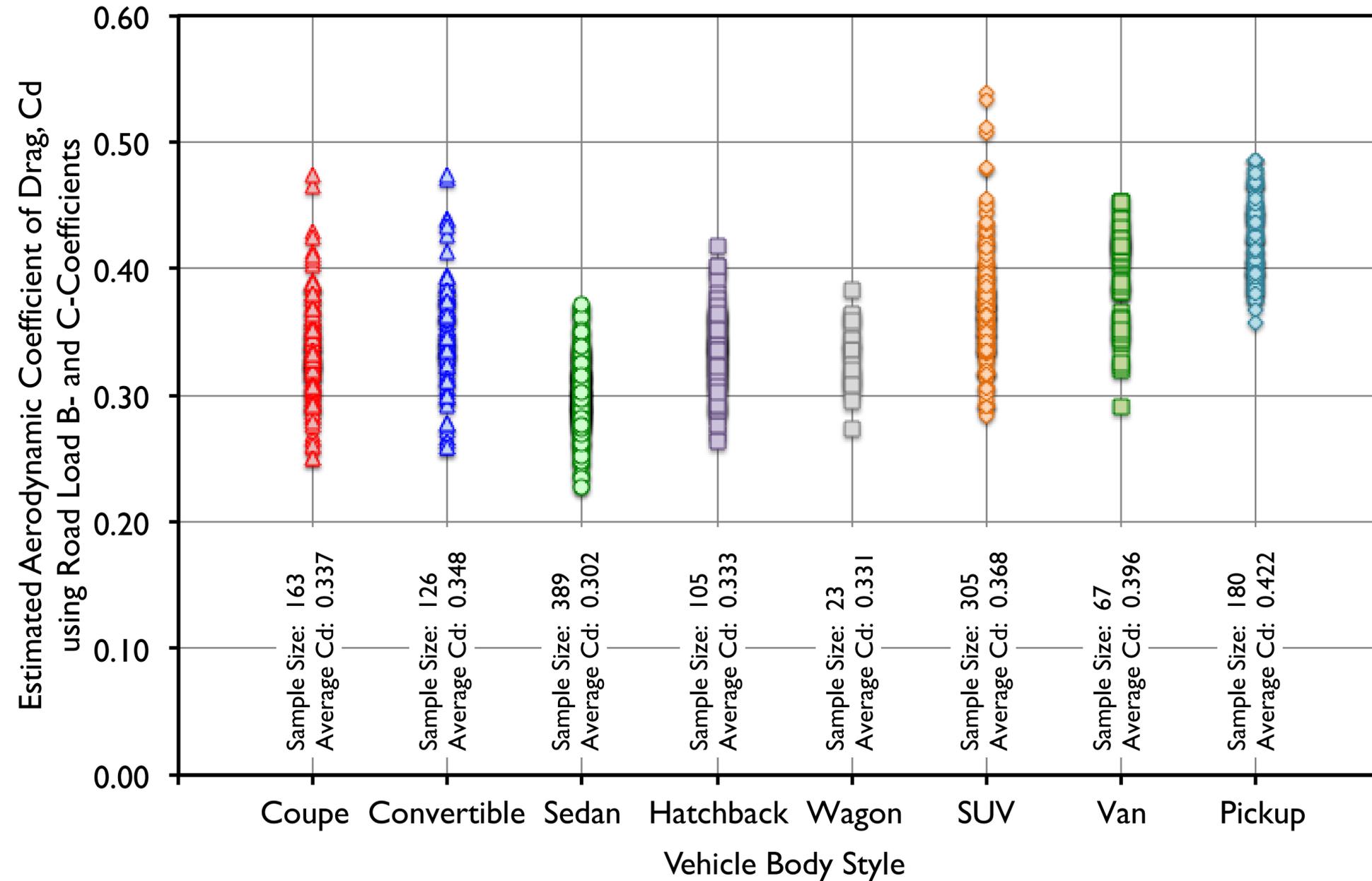


Analysis Source: CONTROLTEC; C-Segment Sedan

Through physics-based analytics, the road load data were decomposed for all 1358 vehicles in the data set.

Aerodynamic Drag

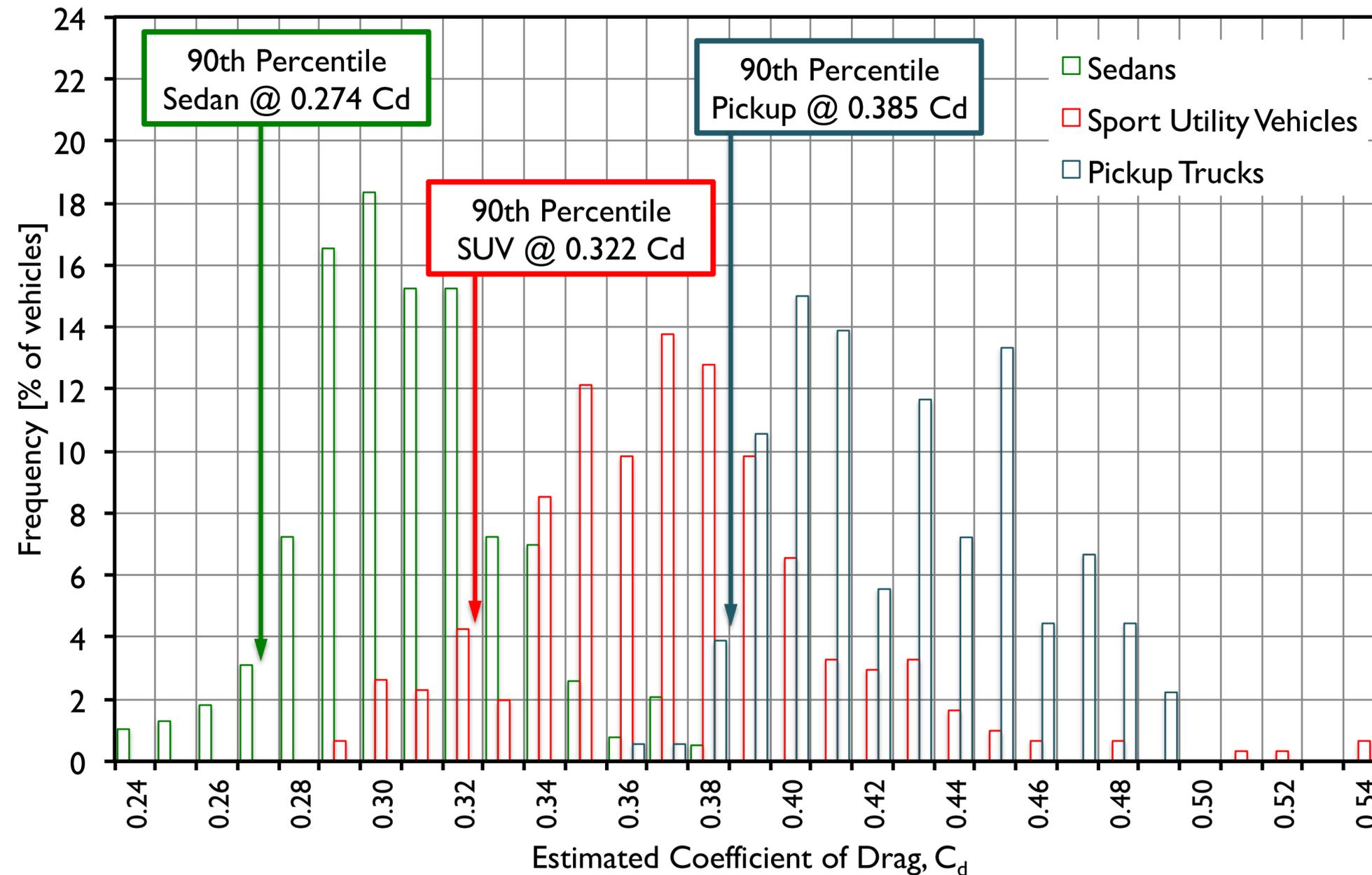
Estimated C_d . MY 2014 Results.



Estimated C_d was computed by combining the derivative of the road load curves with estimated frontal area.

- Selection of best-in-class aerodynamic efficiency requires classification as body styles and vehicle function impact the level of achievable C_d .
- Based on the evaluation of the data and sample size, vehicles were classified by eight basic body styles.
- A best-in-class aerodynamic drag is required for each vehicle classification.
- The distribution of aerodynamic drag across each vehicle class was evaluated to select values that were representative of the best available for MY 2014.

Aerodynamic Drag. Distribution Example.



In recognition of vehicle types and measurement and analysis variability, the best-in-class aerodynamic drag was defined as the 90th percentile of the distribution for each vehicle class.

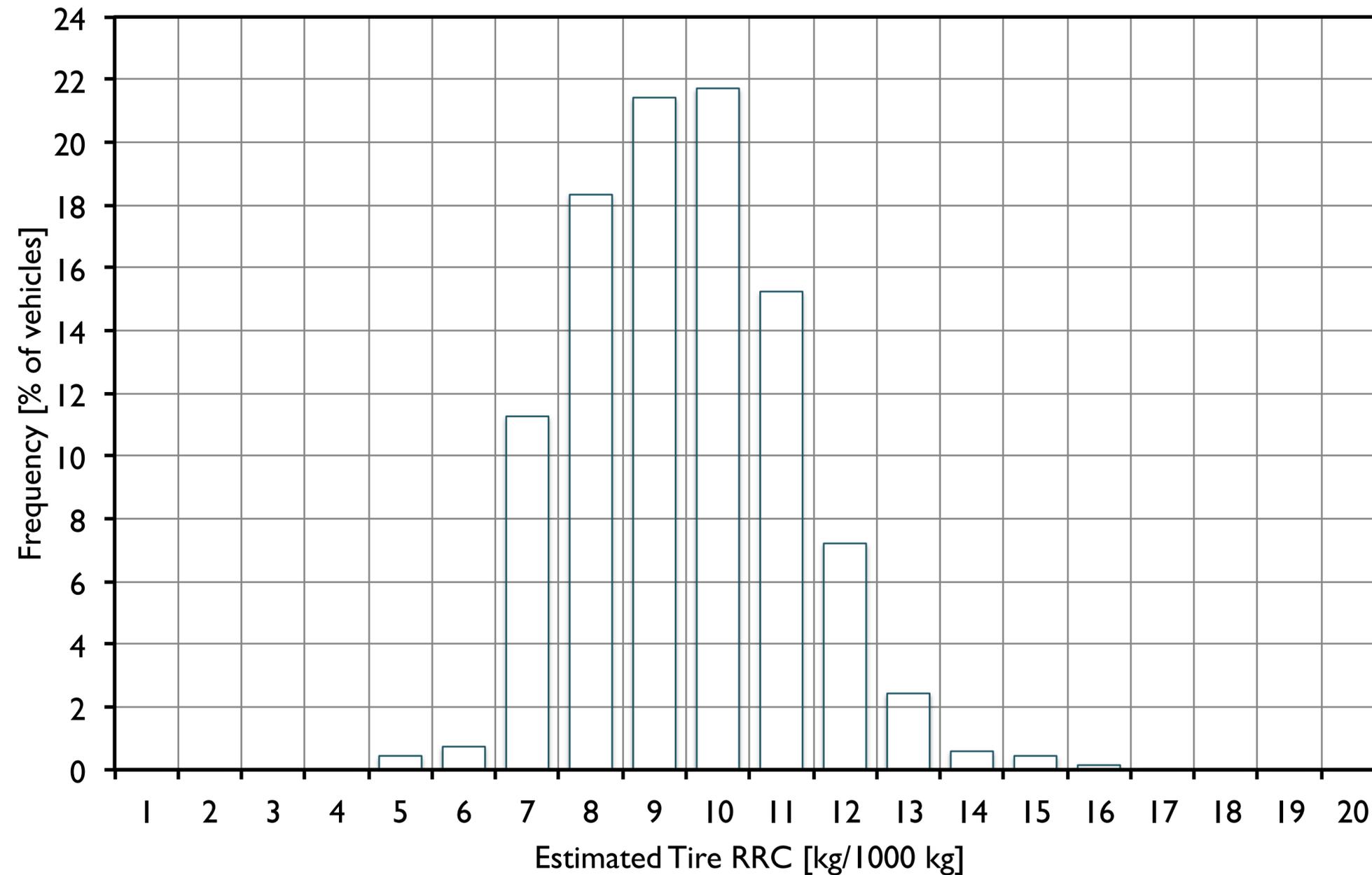
Best-in-Class (BIC) Aerodynamic Drag.

Vehicle Classification	Sample Size	MY 2014 Median Cd	Best-in-Class Evaluation Cd	Best-in-Class vs. Median
	[-]	[-]	[-]	[%]
Coupe	163	0.334	0.293	12
Convertible	126	0.346	0.300	13
Sedan	389	0.301	0.274	9
Hatch & Wagon	128	0.335	0.295	12
SUV	305	0.365	0.322	12
Minivan	19	0.348	0.320	8
Full-Size Van	48	0.418	0.358	14
Pickup	180	0.419	0.385	8

The best-in-class (90th percentile) C_d was 8 to 14% lower than the median performance.

Tire Rolling Resistance

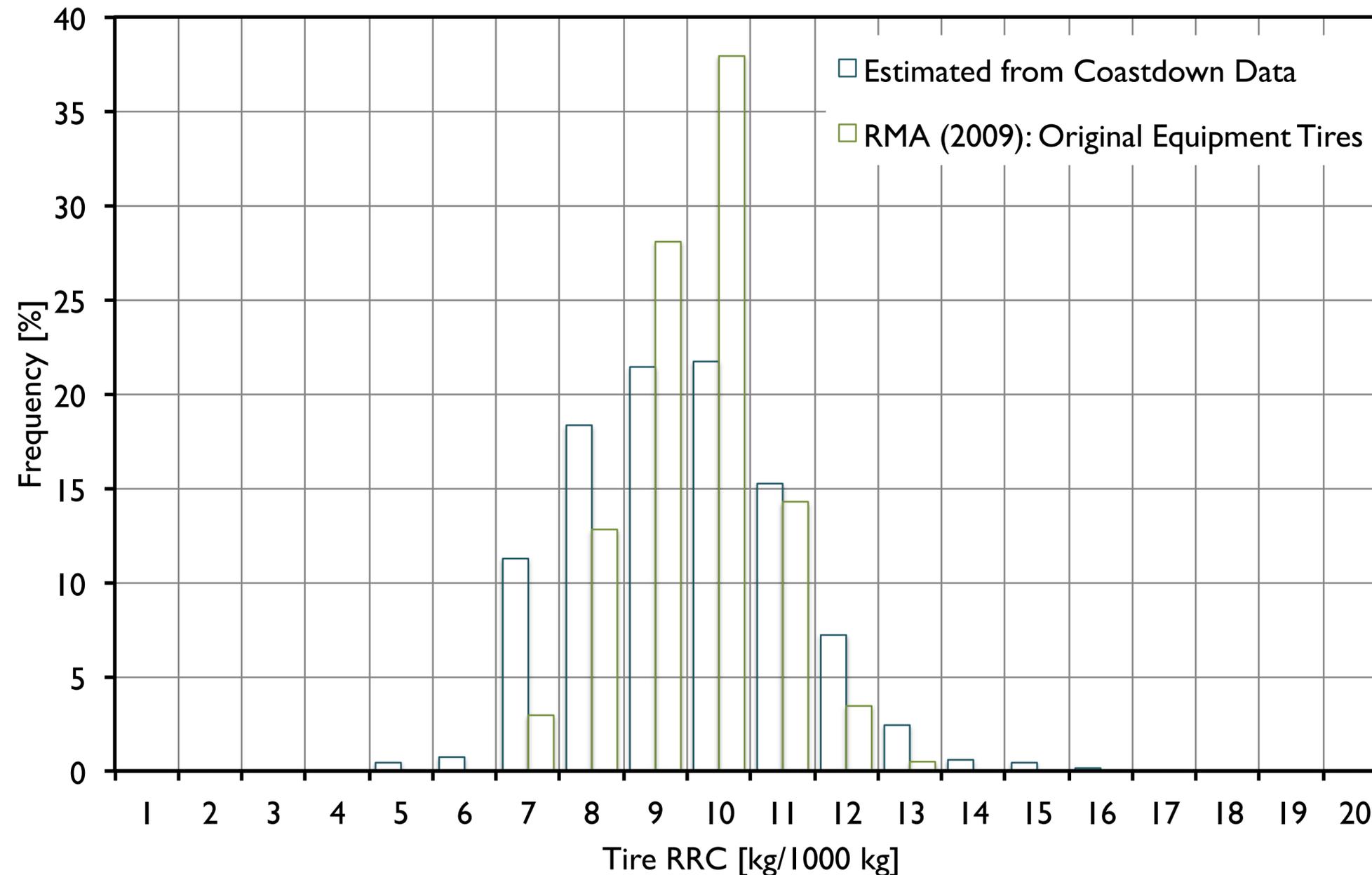
Estimated Tire RRC. MY 2014 Results.



Tire RRC was determined by force decomposition: $F_{\text{tire}} = F_{\text{total}} - F_{\text{aero}} - F_{\text{brake}} - F_{\text{hub}} - F_{\text{driveline}}$

The average estimated tire RRC was 9.0 kg/1000 kg.

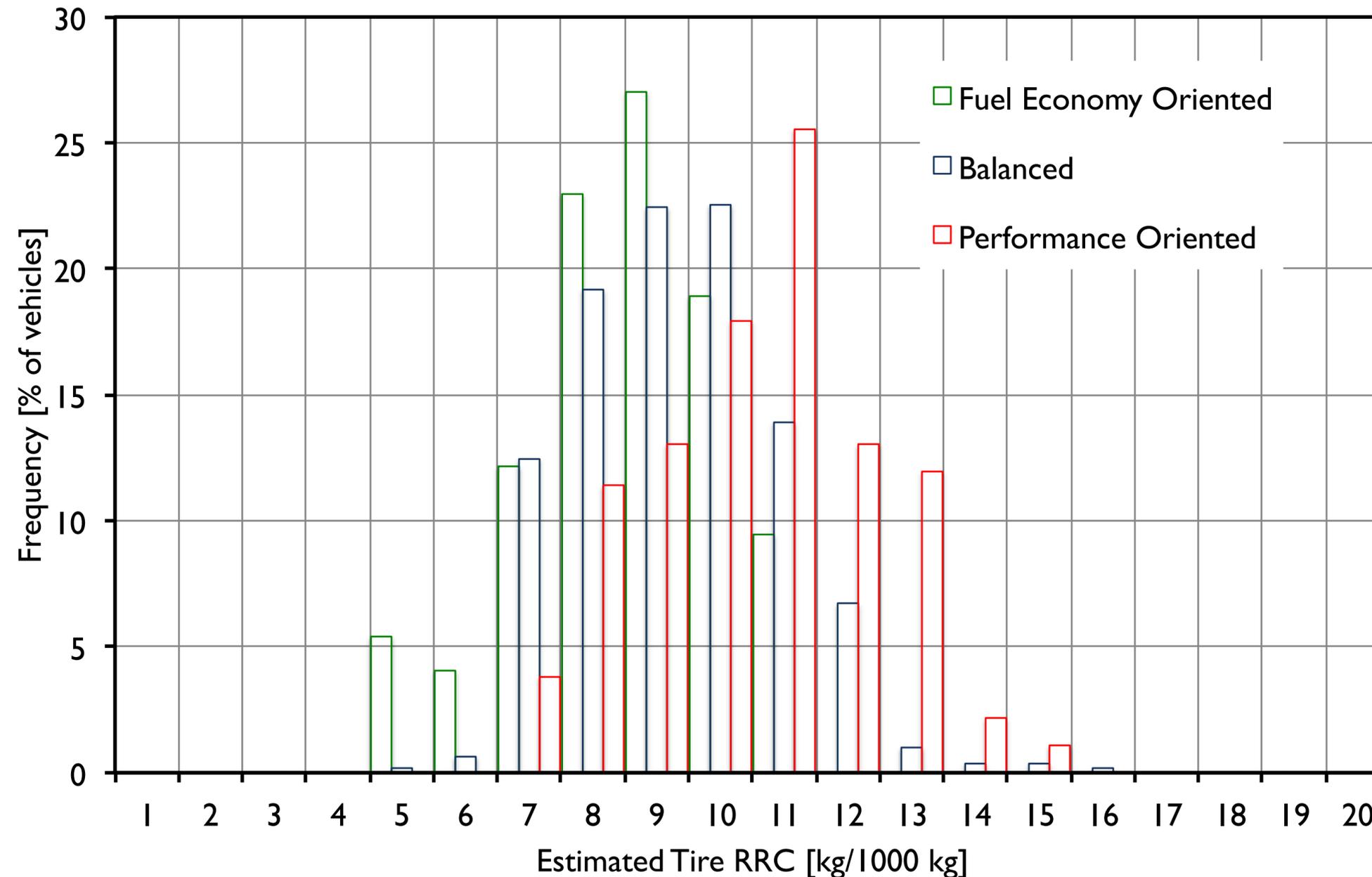
MY 2014 Estimated Tire RRC vs. 2009 RMA Data.



Original Equipment Tires Data Source: Rubber Manufacturers Association (RMA), August 2009

By comparison, the 2009 RMA OE data average was 9.2 kg/1000 kg. The range of the estimated RRC is larger than the RMA data, in part due to the wider range of tires represented on the MY 2014 vehicles.

- Selection of best-in-class tire rolling resistance requires classification as tire requirements to satisfy vehicle performance impact the level of achievable RRC.
- Based on the evaluation of the data and sample size, tires were classified by one of three categories.
- The distribution of tire RRC across each vehicle class was evaluated to select values that were representative of the best available for MY 2014.



Recognizing measurement and analysis variability and the need to balance other tire attributes such as traction, noise, and tread wear, the best-in-class tire RRC was defined as the 75th percentile of each tire class.

Best-in-Class (BIC) Tire RRC.

Tire Classification	Sample Size	MY 2014 Median RRC	Best-in-Class Evaluation RRC	Best-in-Class vs. Median
	[-]	[-]	[-]	[%]
Fuel Economy Oriented	74	8.3	7.4	11
Balanced	1100	8.9	7.7	14
Performance Oriented	184	10.3	8.9	14

The best-in-class (75th percentile) tire RRC was 11 to 14% lower than the median performance.

Assessment of Model Year 2014 Vehicles Mass Efficiency

- Generate a metric to quantify mass efficiency.
- Determine the mass efficiency of every model year 2014 vehicle available in California (1358 model variants).
- Identify top performing vehicles, by class, for mass efficiency.
- To support the subsequent load reduction scenarios, define best-in-class (BIC) mass efficiency based on the top-performing vehicles.
- Cross-reference vehicle features with mass efficiency to determine best design practices.

- The original desire of the research was to develop a mass efficiency metric for vehicle sub-systems and apply this to every vehicle in the fleet.
- The reporting of mass reduction technologies is inconsistent among manufacturers.
- Given the lack of information sufficient to develop and apply sub-system mass efficiency metrics, CONTROLTEC enabled its mass model for this research.

Challenge #3: A consistent method is required to estimate mass efficiency for all vehicles in the data set.

- CONTROLTEC developed a light-duty vehicle curb weight model as a means of identifying vehicles with good mass efficiency and opportunities for mass reduction.
- The mass model uses publicly available information to estimate the vehicle weight.
- The model is a combination of continuous and discrete elements that are assembled, like the vehicle itself, to generate an estimate of weight:

Estimated Curb Weight =

f(vehicle type, length, width, height, cargo bed length, tire/wheel size) +

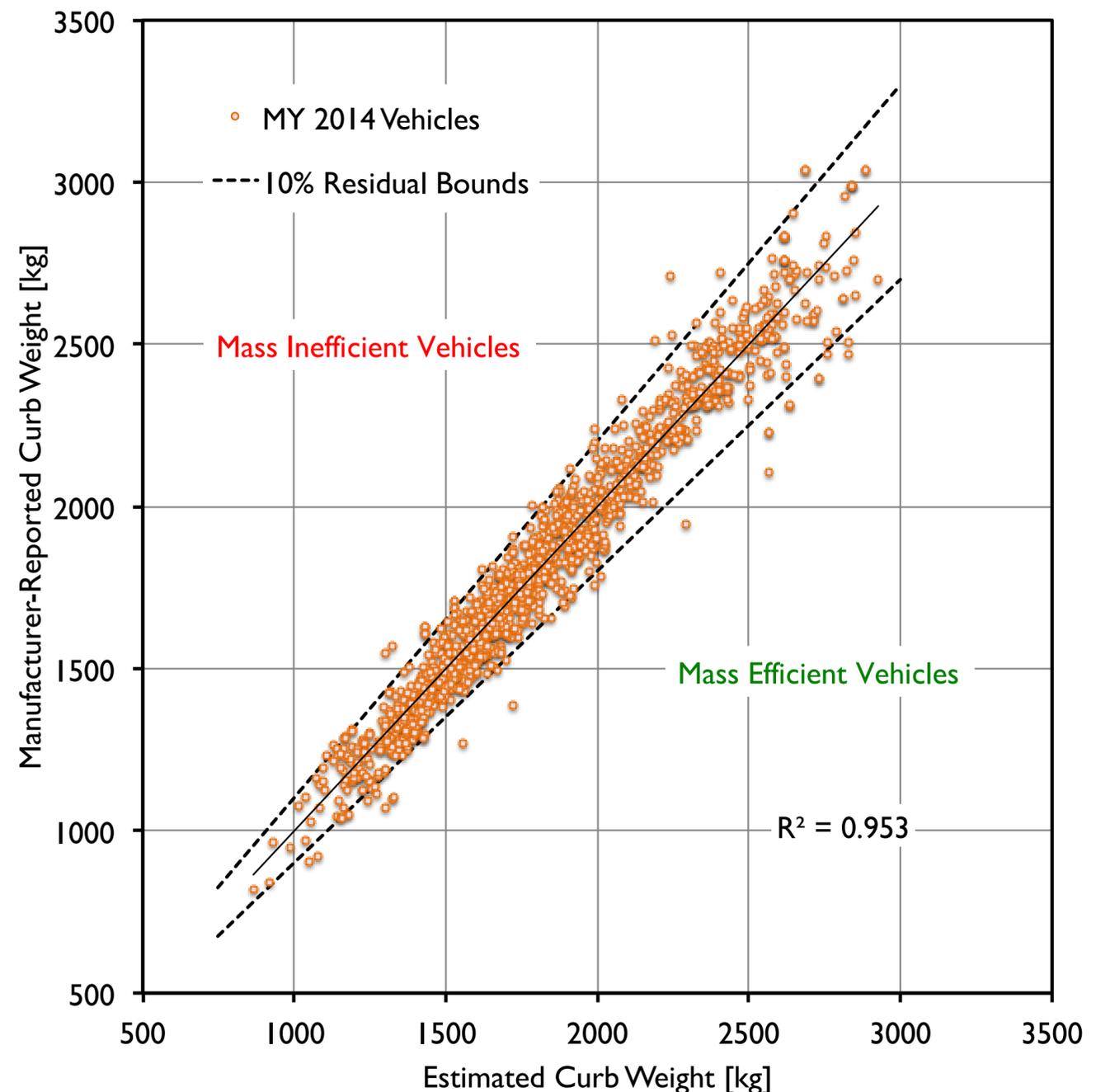
f(engine type, cylinders, engine aspiration, hybrid type, motor size) +

f(transmission type, driveline, drivetrain architecture (FF, FR, etc.)) +

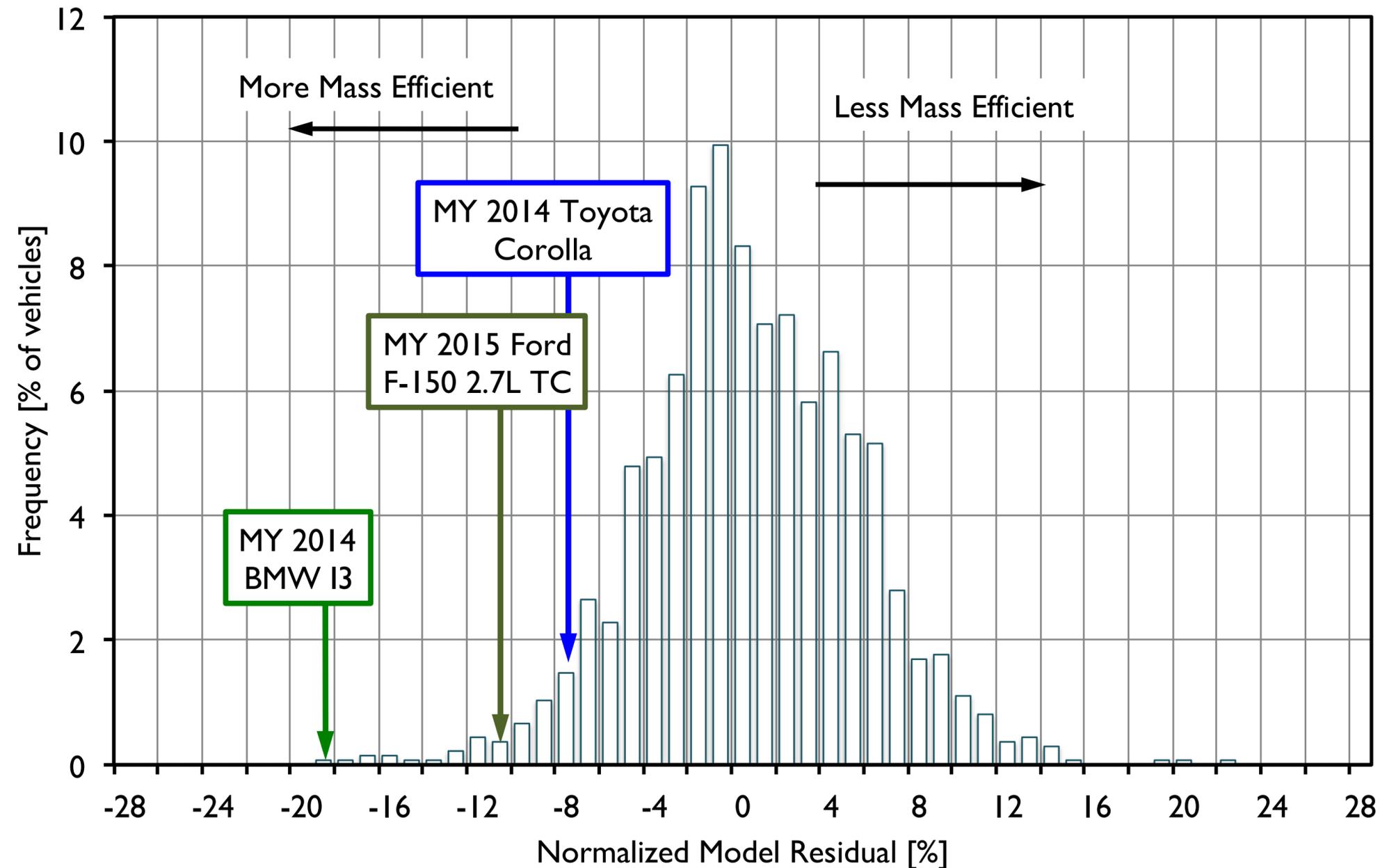
f(fuel tank capacity, fuel type, battery capacity, battery chemistry)

Mass Model Accuracy & Residuals.

- The mass model predicts the mass of a vehicle with an R^2 value of 95%.
- 95% of the MY 2014 vehicles are within +/-10% of the estimate.
- The model residual (actual - estimated) includes elements not captured in the basic specifications, such as structural design and material usage.
- The model residual, therefore, can be used as a proxy for mass efficiency.

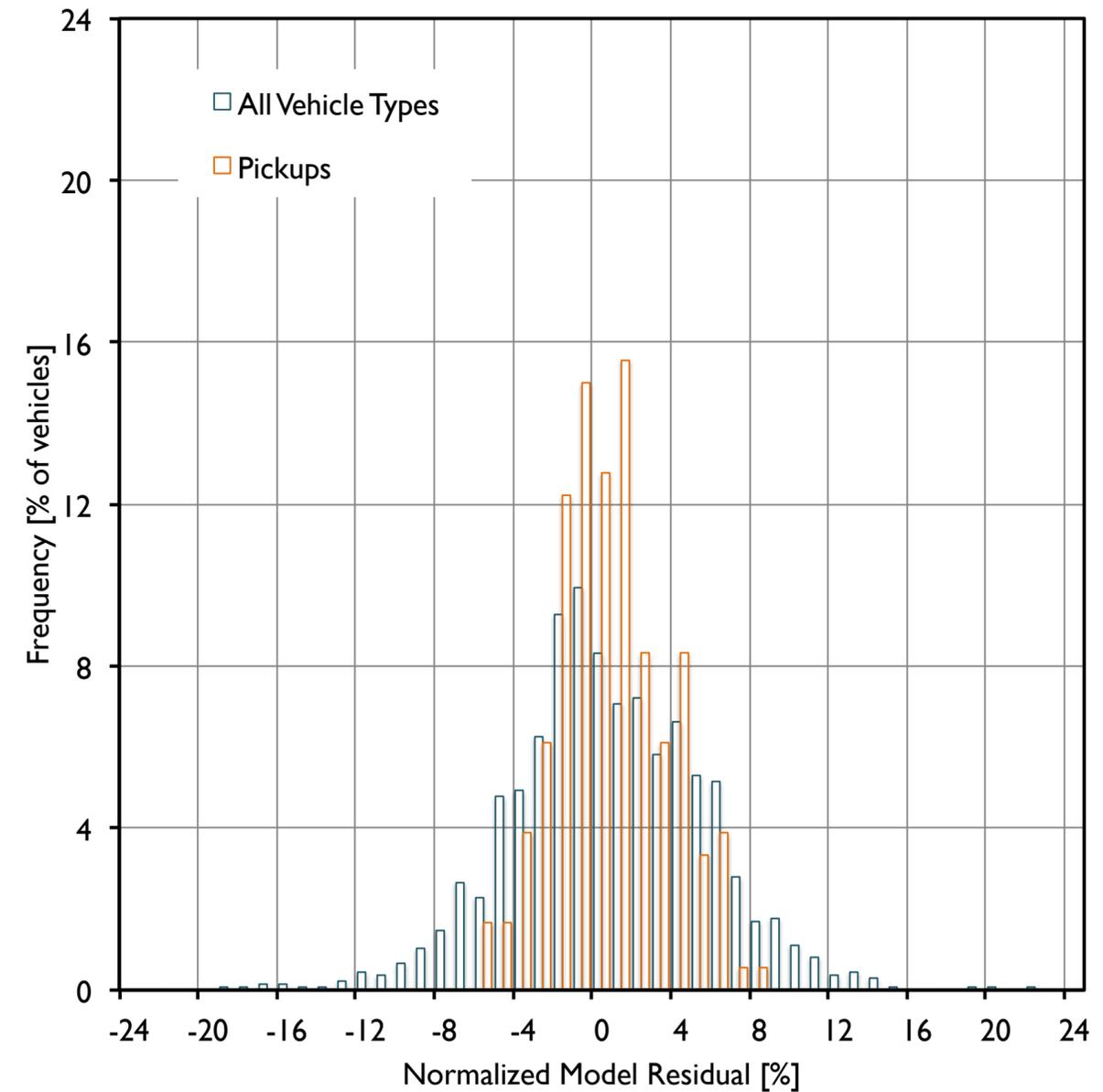
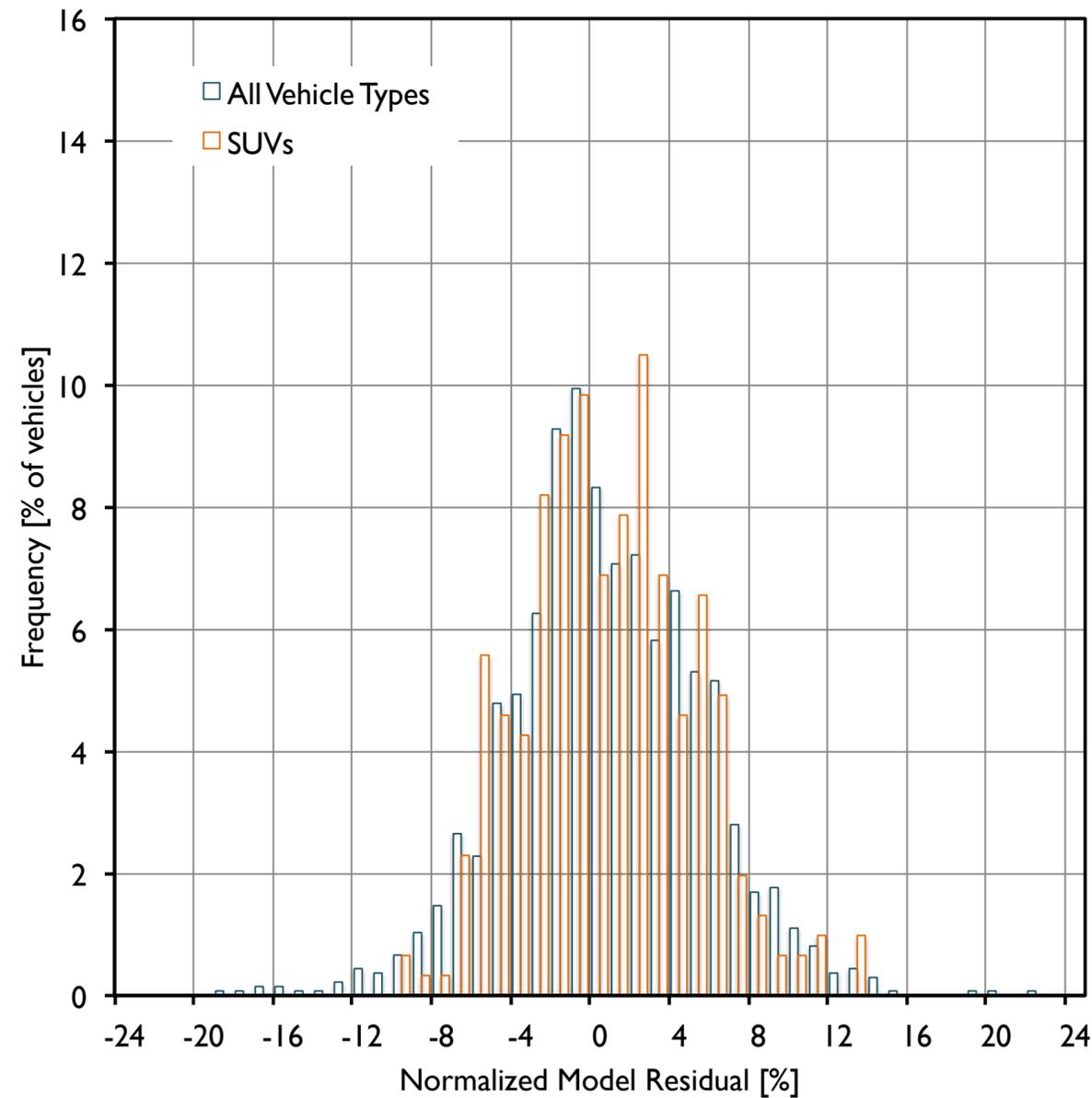


For this research, the mass model residuals were used as a proxy for mass efficiency.



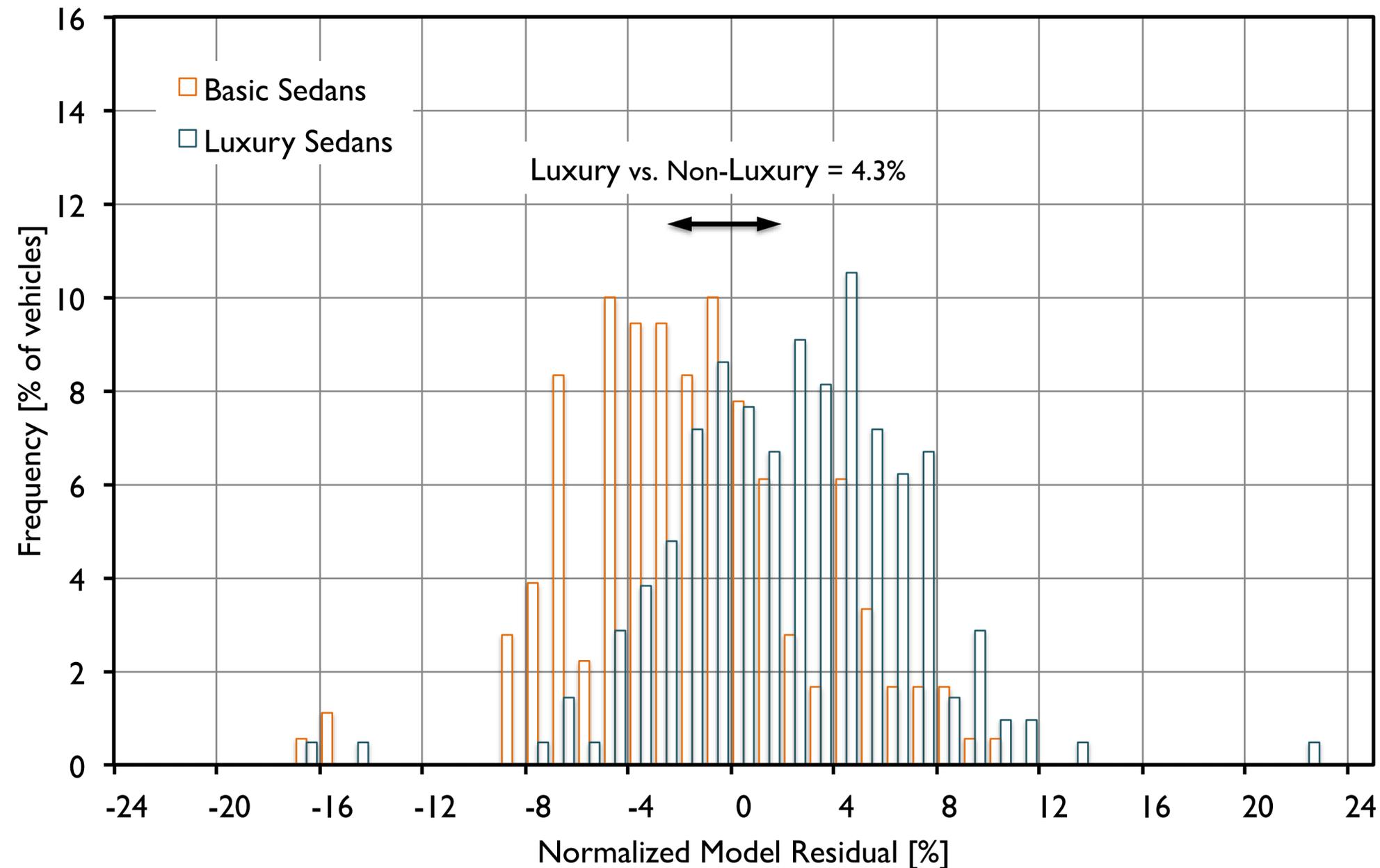
Exploring vehicles with negative residuals can reveal successful light-weighting practices and technologies.

Mass Efficiency Distribution. Examples.



The mass model is vehicle type neutral and, therefore, classification by body style is not required when defining best-in-class. The distribution of pickup trucks is narrower than SUVs due to the commonality of design elements across the manufacturers.

Mass Efficiency. Luxury Vehicles.



Note: Vehicle type based on Ward's Automotive classification

Due to greater option content, luxury vehicles are, on average, ~4% heavier than non-luxury vehicles.

- Selection of best-in-class mass efficiency requires classification as vehicle type and/or option level can impact the achievable mass efficiency.
- Given the neutrality of the mass model to vehicle type and size, only two categories were used for mass efficiency: non-luxury & luxury.
- The distribution of the mass model residuals was evaluated to select values that were representative of the best available for MY 2014.
- Recognizing measurement and analysis variability, the best-in-class mass efficiency was defined as the 98th percentile for non-luxury vehicles and 90th percentile for luxury vehicles.
- The 98th percentile corresponds to a 10.3% mass reduction from average.
- The 90th percentile corresponds to a 5.9% mass reduction from average (~10% reduction from a typical luxury vehicle).

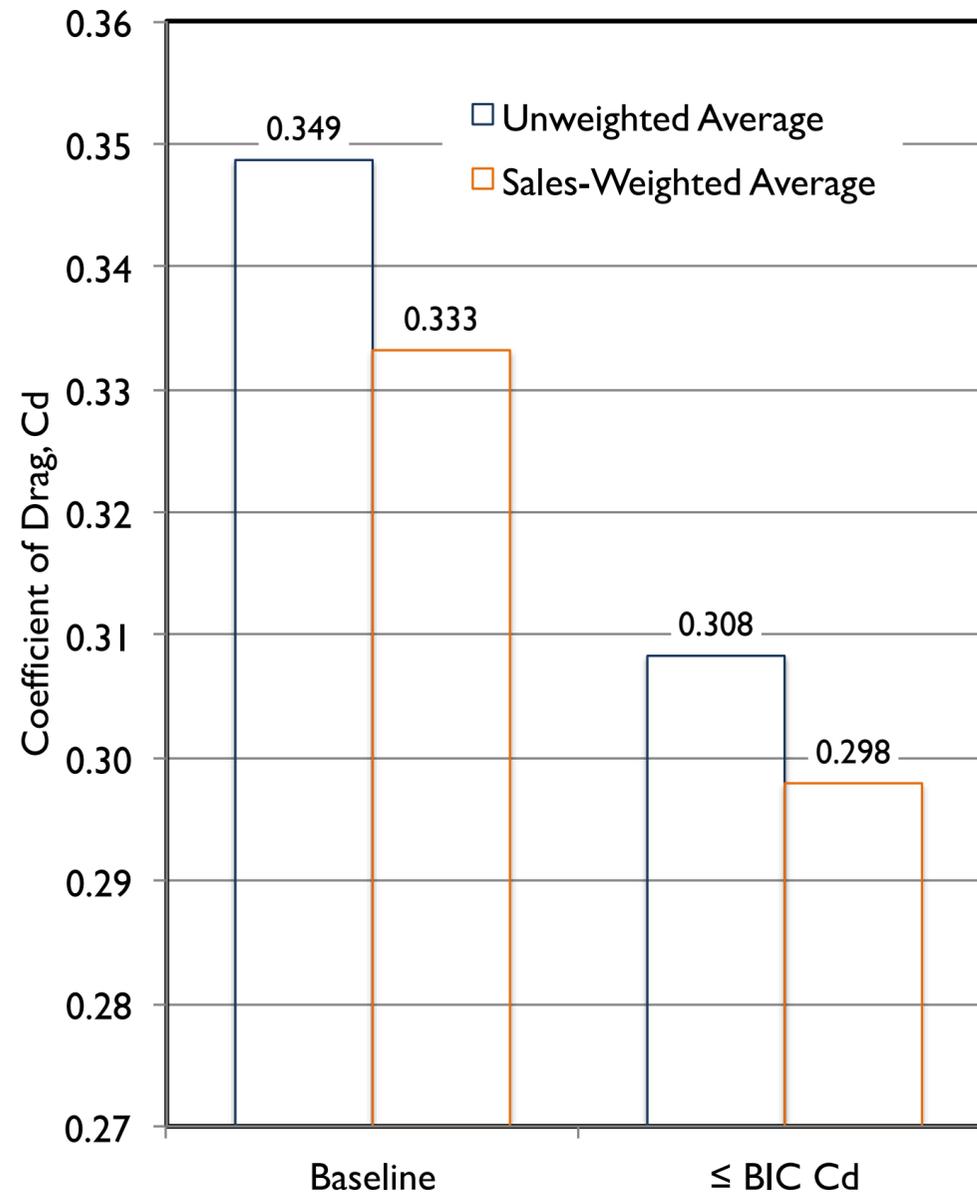
Achieving best-in-class mass efficiency will require ~10% mass reduction.

Vehicle Load Reduction Scenarios

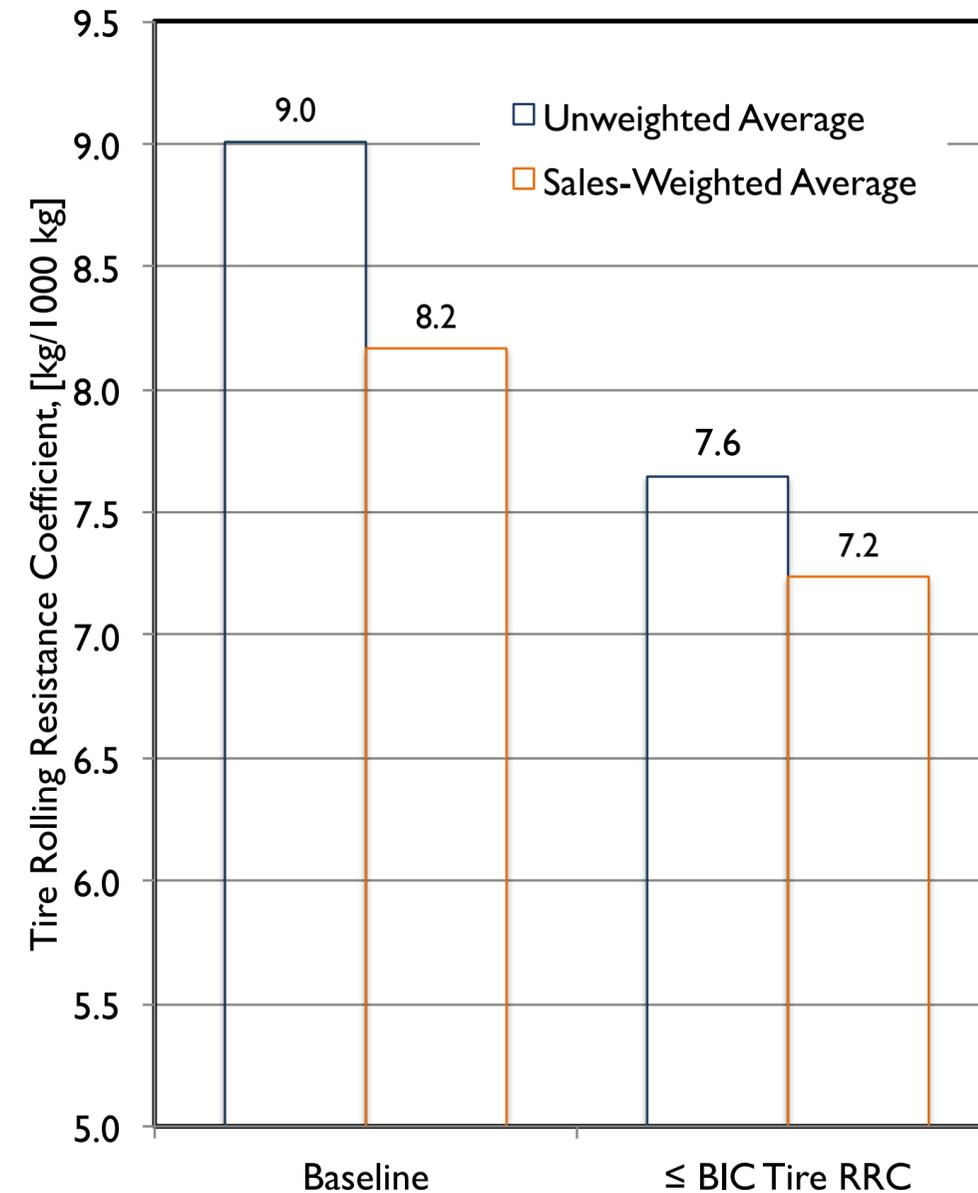
1. Baseline
2. Aerodynamic drag (C_d) reduced to best-in-class
3. Best-in-class C_d plus tire rolling resistance (tire RRC) reduced to best-in-class
4. Best-in-class C_d and tire RRC plus mass efficiency reduced to best-in-class
5. Best-in-class C_d , tire RRC, and mass efficiency plus power source (engine or motor) downsized to maintain baseline performance
6. Best-in-class C_d , tire RRC, and mass efficiency plus power source (engine or motor) downsized to maintain baseline performance plus on-board energy storage (fuel or battery capacity) reduced to maintain baseline range

Over 8,000 individual vehicle simulations were performed.

Aerodynamic Drag

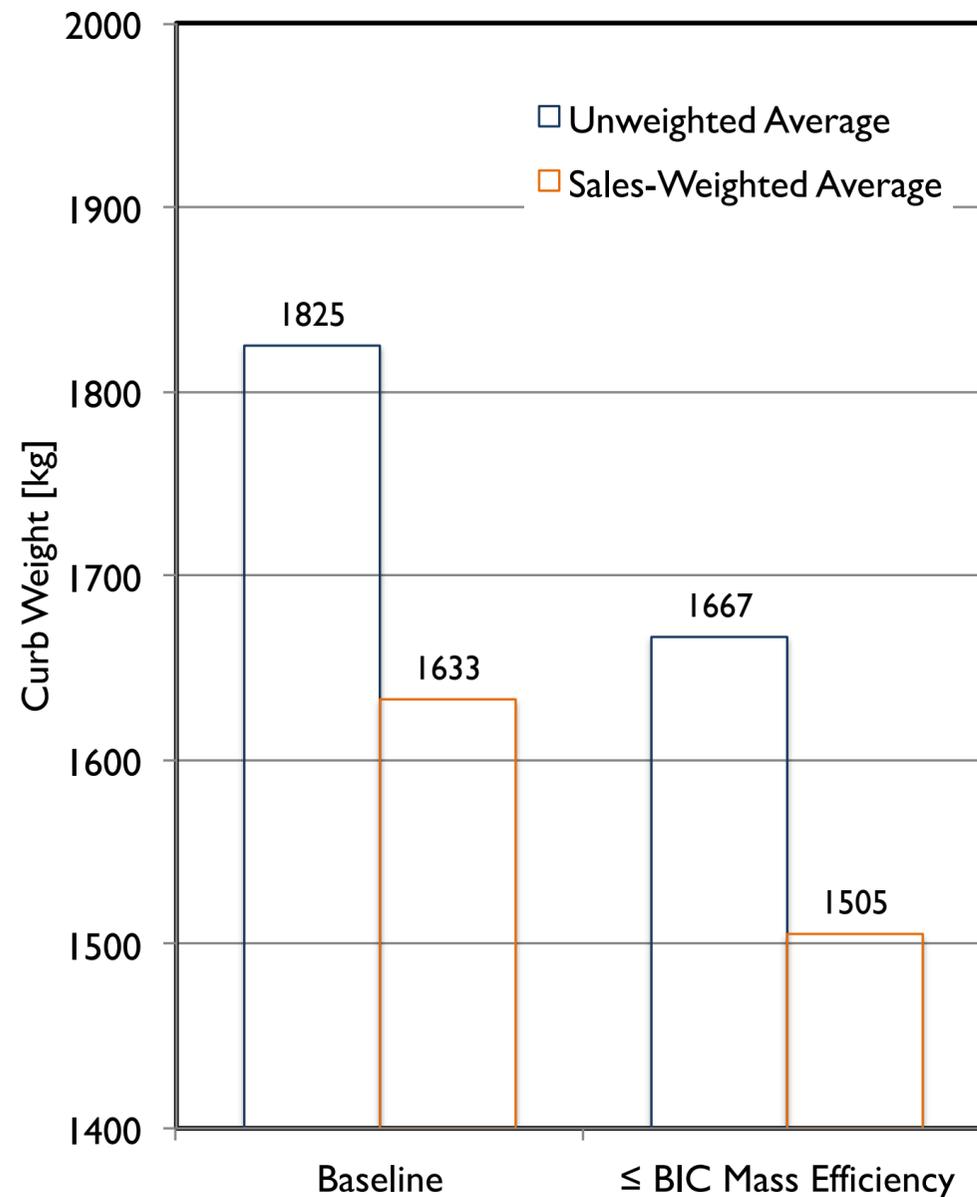


Tire RRC

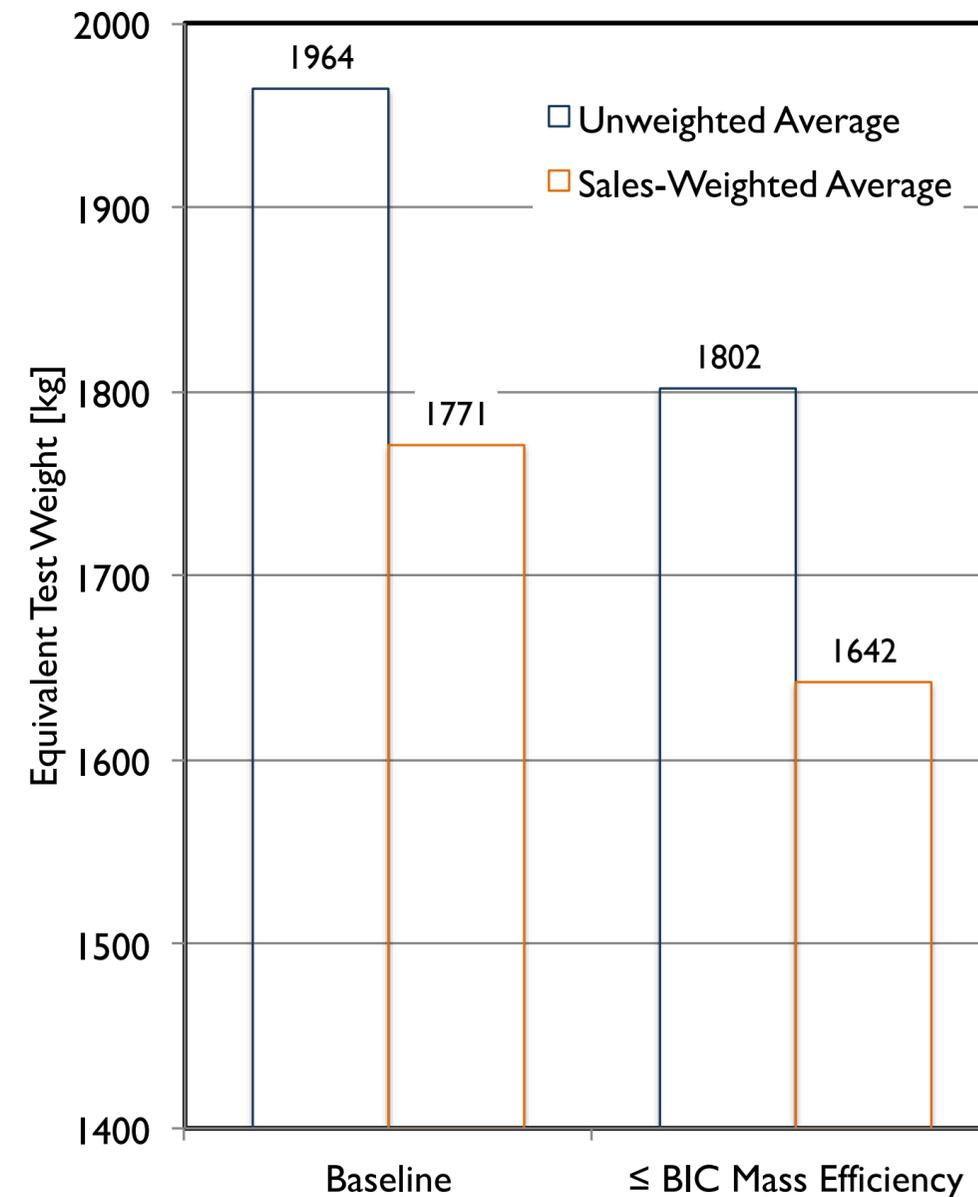


Applying best-in-class C_d resulted in a 10.6% reduction of sales-weighted aerodynamic drag. Applying best-in-class tire RRC resulted in an 11.4% reduction of sales-weighted tire rolling resistance. Sales-weighted values for C_d and tire RRC were lower than the unweighted averages.

Curb Weight

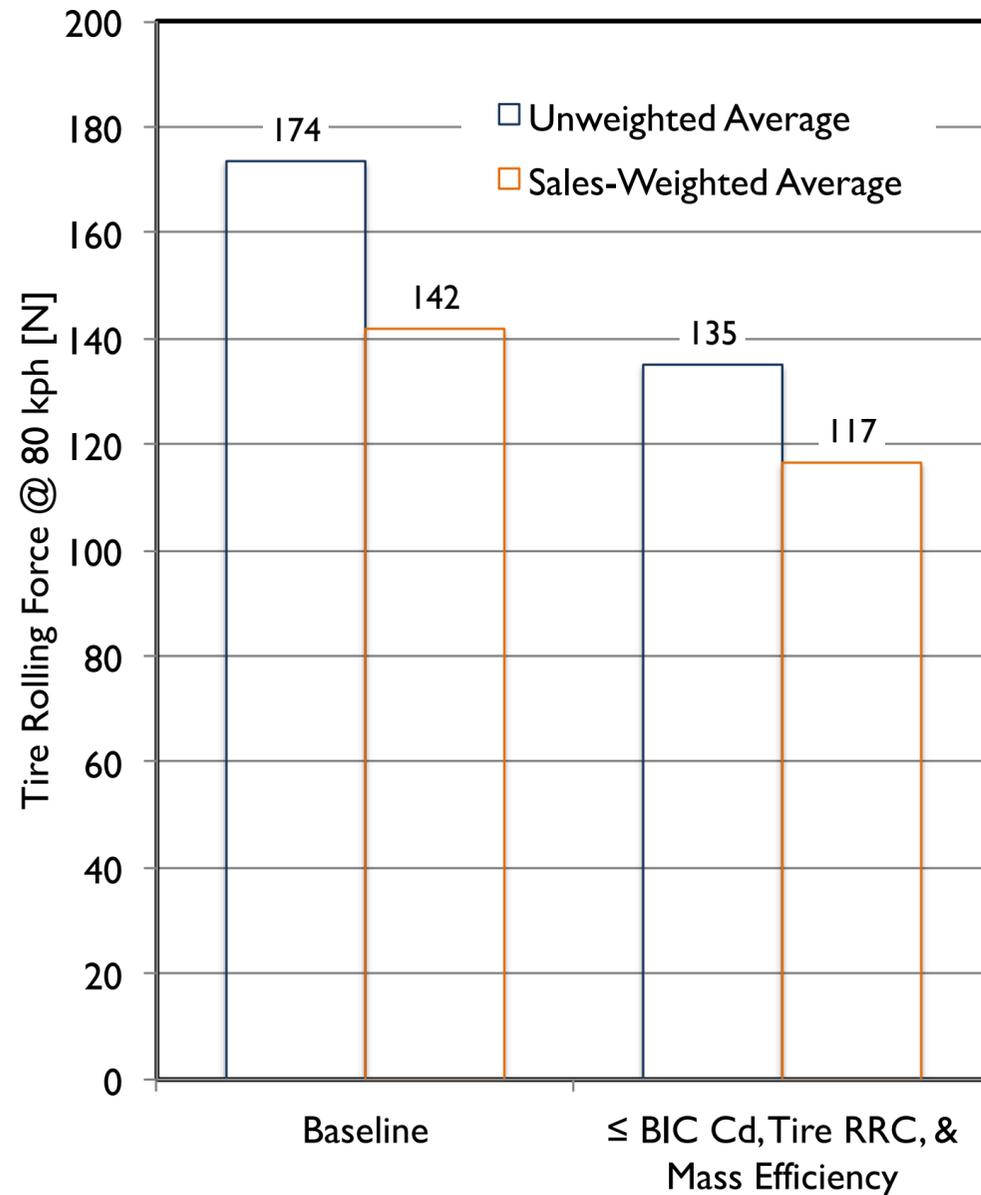


Equivalent Test Weight

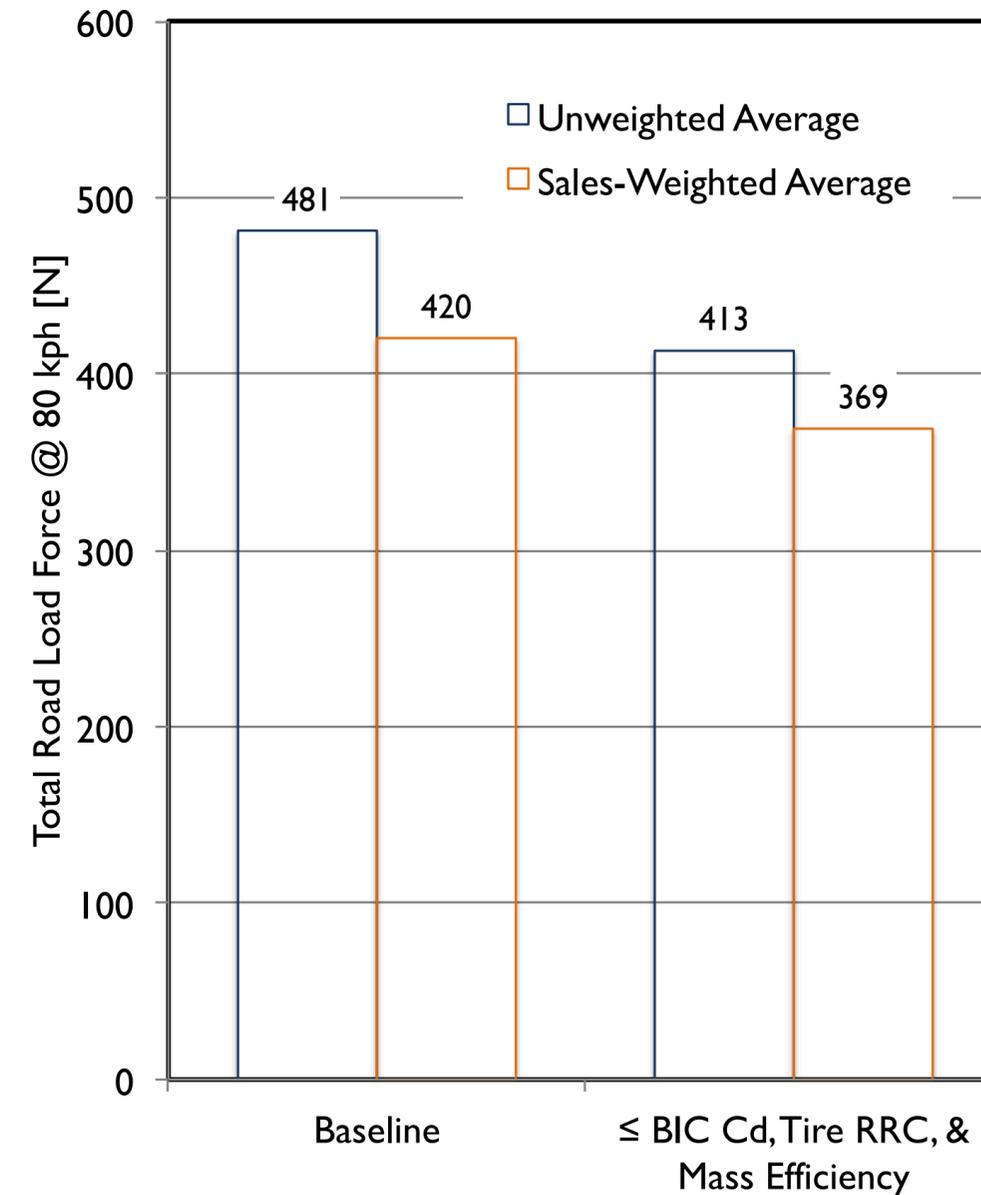


Applying best-in-class mass efficiency resulted in a 7.8% and 7.3% reduction of sales-weighted curb weight and equivalent test weight (ETW), respectively. Sales-weighted values for mass were lower than the unweighted average. The absolute change in curb weight and ETW were approximately the same. The lower percent reduction associated with ETW is due to the larger absolute value.

Tire Force



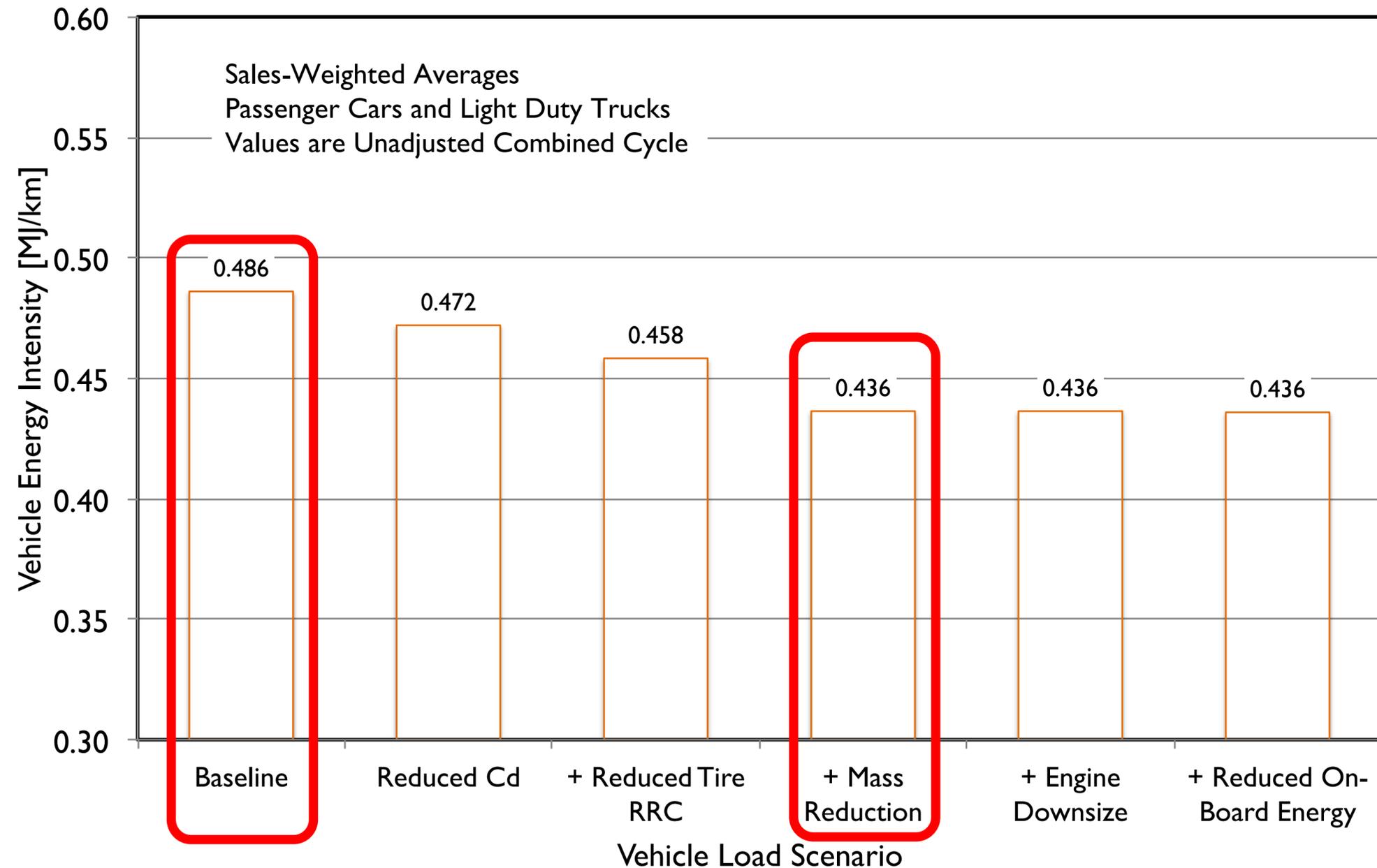
Total Road Load Force



The combination of best-in-class tire RRC and mass efficiency resulted in a 17.8% reduction of sales-weighted tire rolling force at 80 kph. The lower mass contributed to a 6.4% reduction (36% of the total) in tire rolling force. Applying best-in-class aerodynamic drag, tire RRC, and mass efficiency yielded a 12.2% reduction of sales-weighted total road load force at 80 kph.

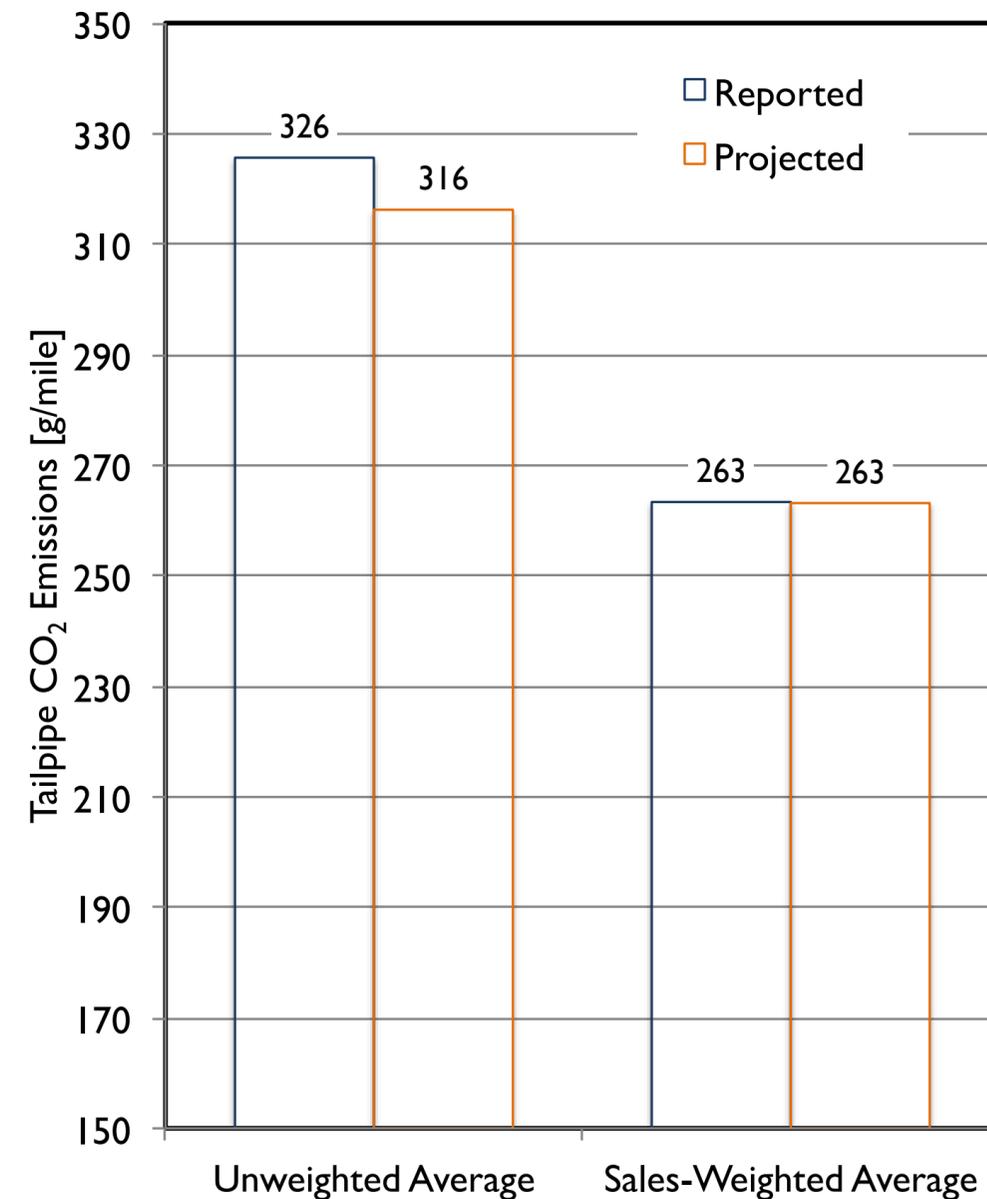
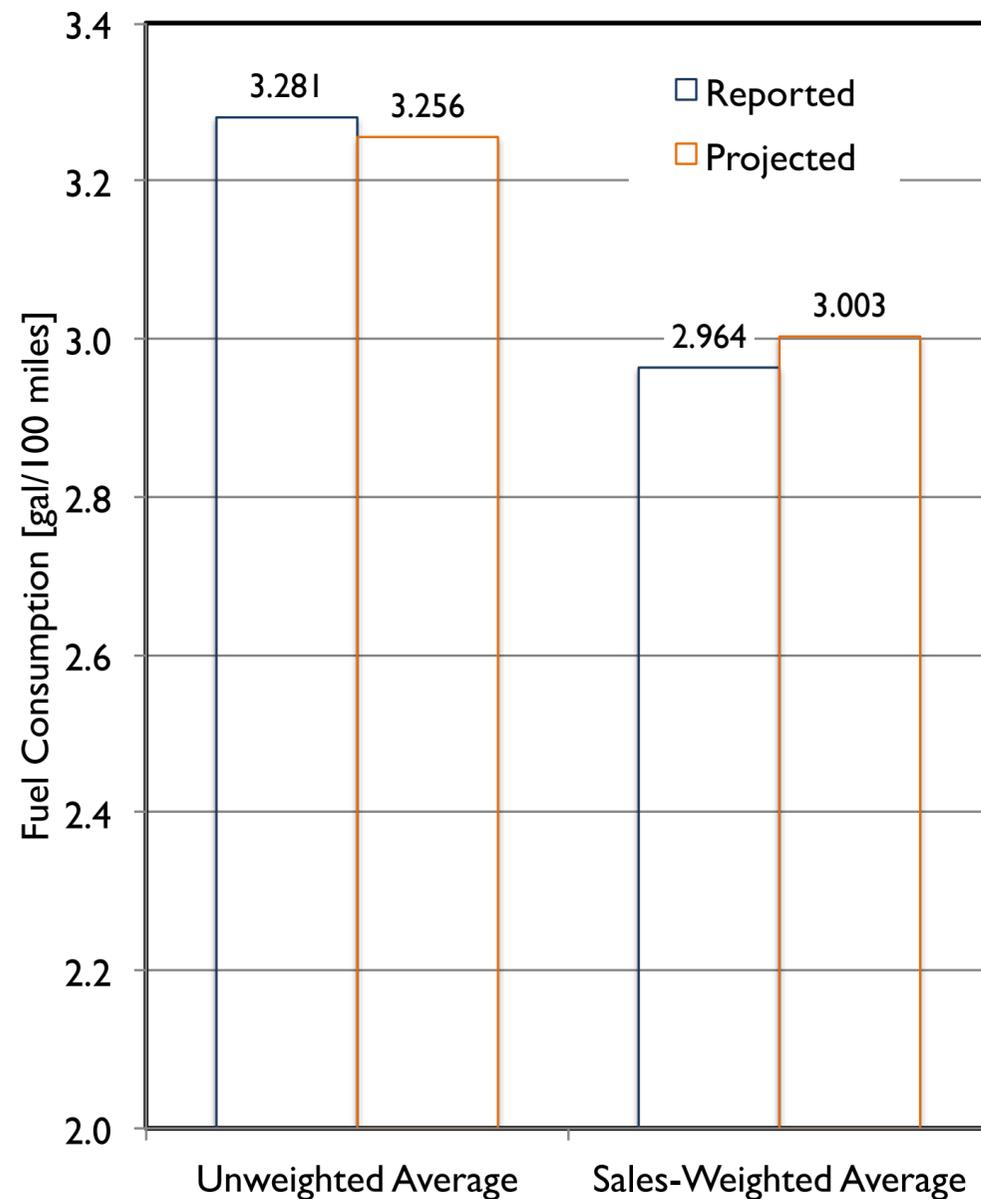
Fuel Economy & CO₂ Emissions Projection Results

Projection Results. Vehicle Energy Intensity.



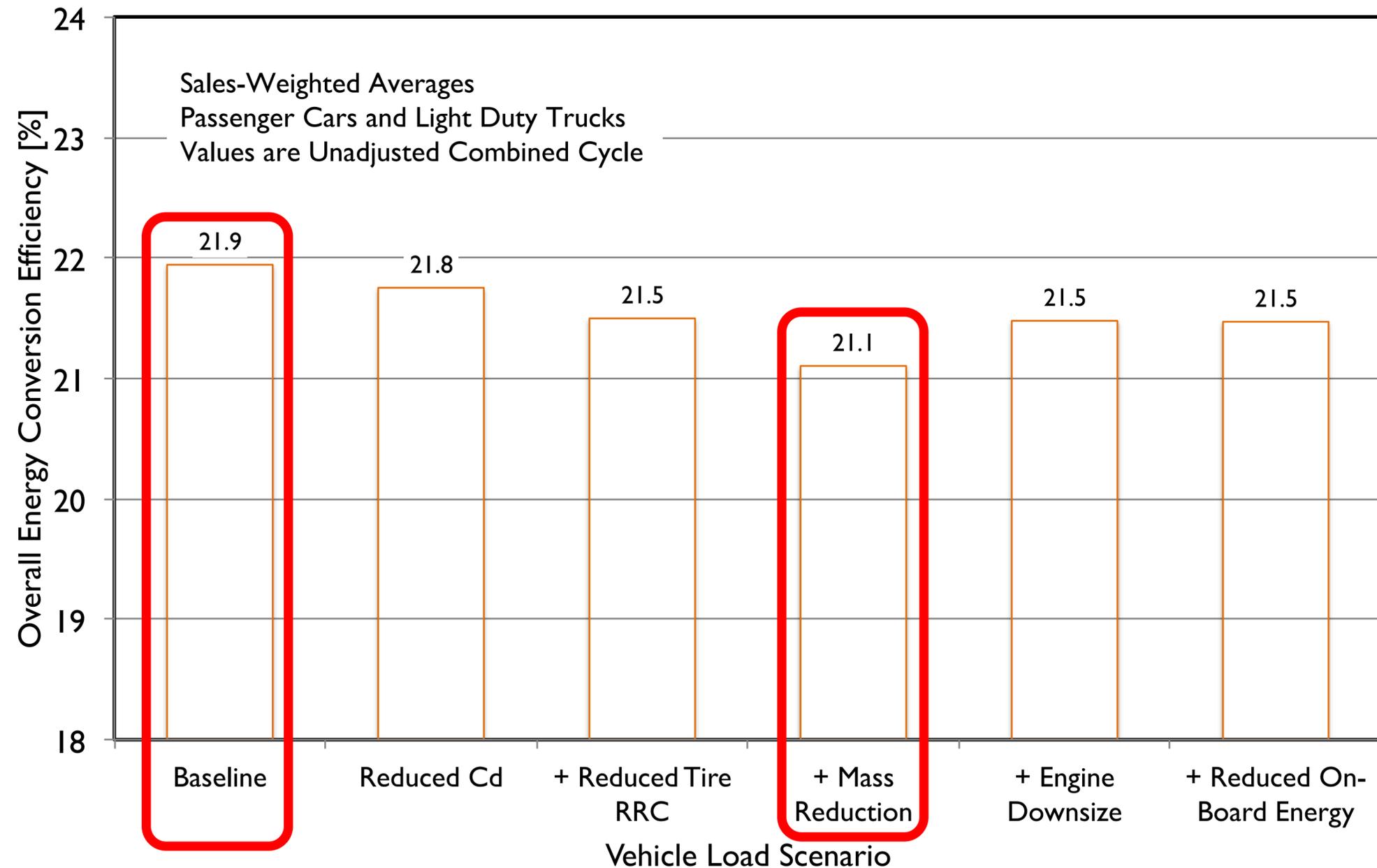
The combination of reduced aerodynamic drag, tire rolling resistance, and mass yielded a sales-weighted reduction of vehicle energy intensity of 10.6%. For ICE-based power sources, downsizing assumed a displacement change only and, therefore, no reduction in weight. Reducing the on-board energy storage had minimal impact on the overall weight and, therefore, the vehicle energy intensity.

Baseline Projections. Fuel Consumption & CO₂ Emissions.



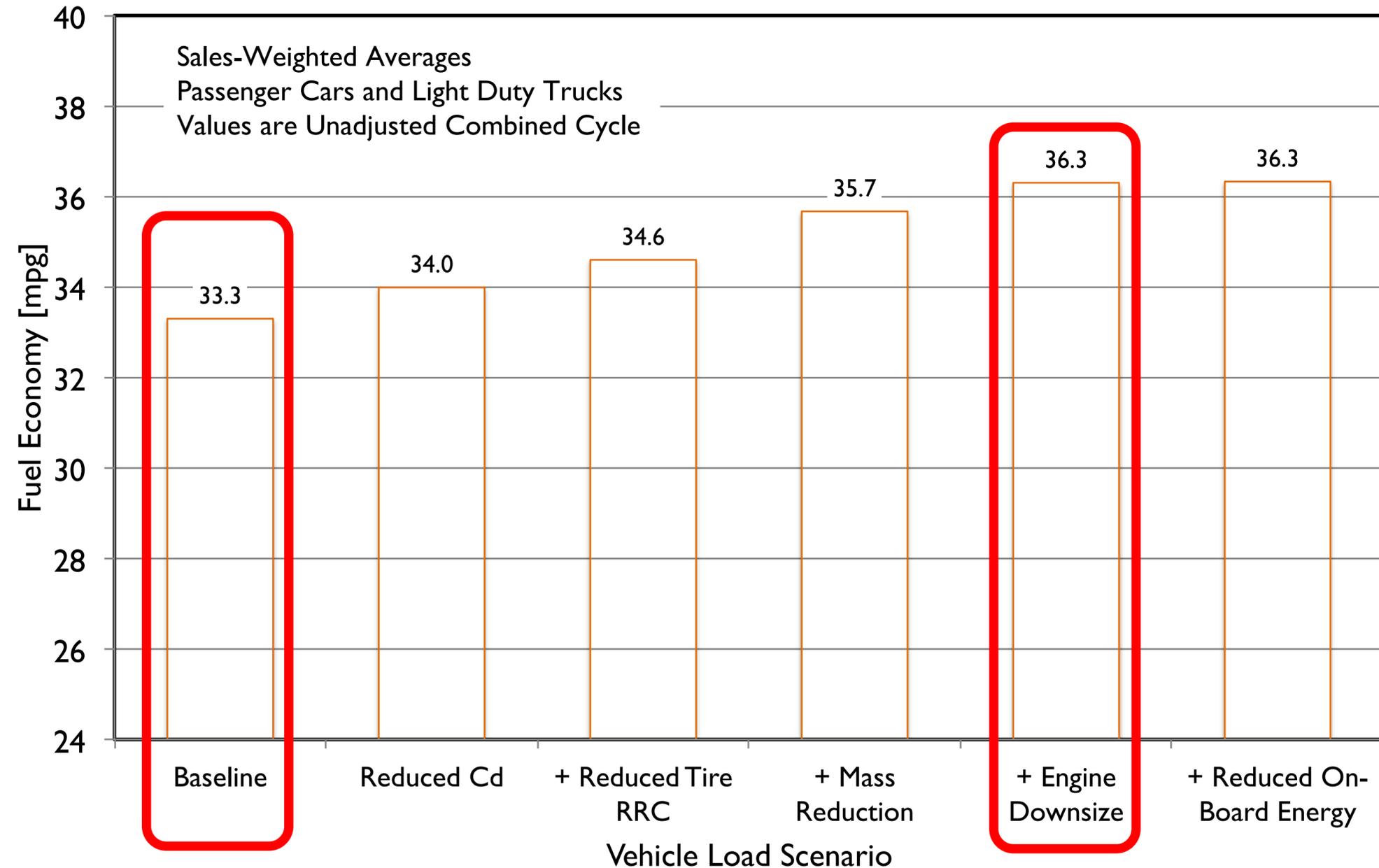
The projected fuel consumption and tailpipe CO₂ emissions are in good agreement with the reported (certification/label) values. Projected fuel consumption averages were ~1% different than reported. The projected unweighted average CO₂ emission were 3% lower than reported while the sales-weighted CO₂ emissions were the same as reported.

Projection Results. Energy Conversion Efficiency.



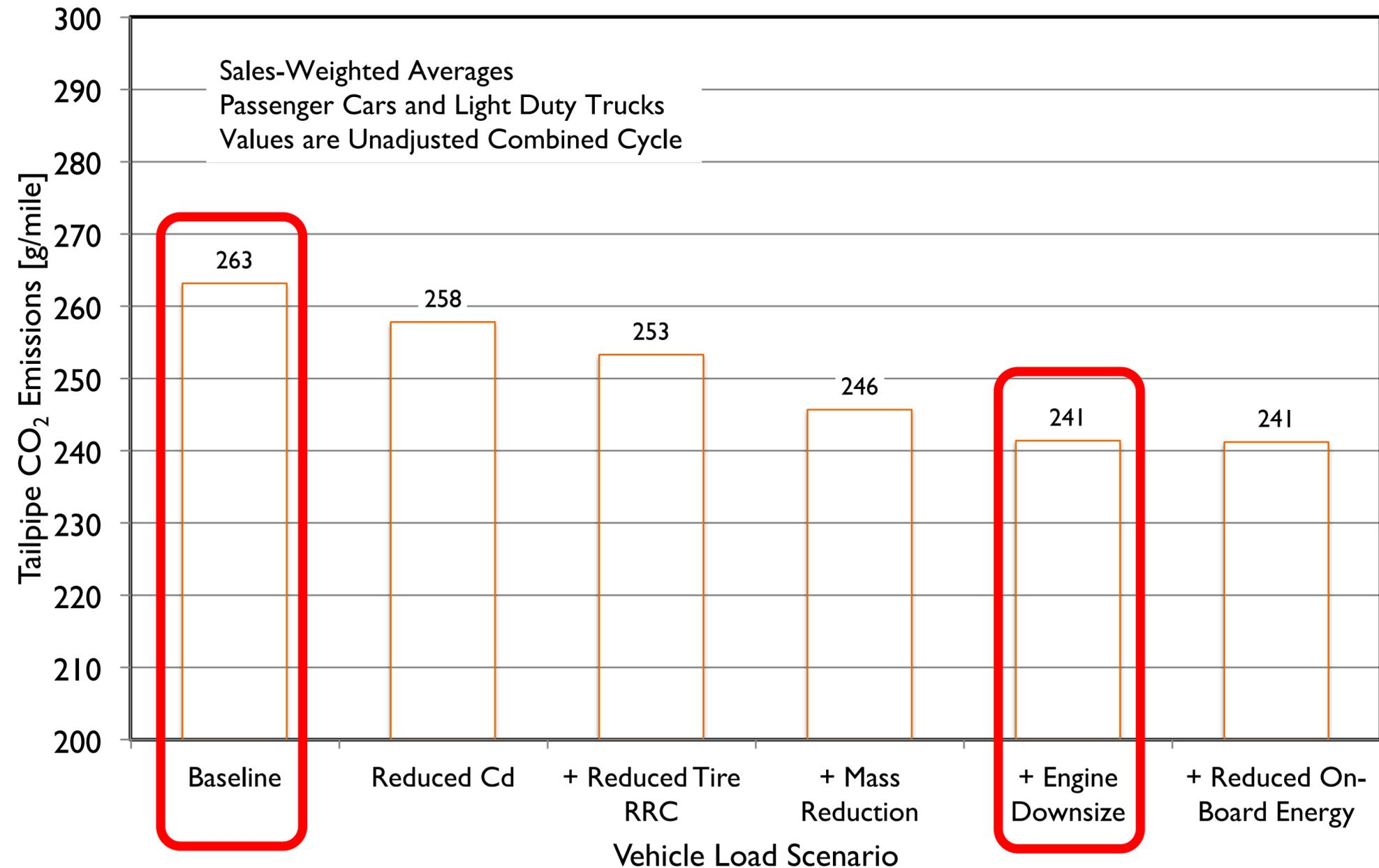
Reducing the vehicle load without changing the power source results in lower overall energy conversion efficiency due to operation at lighter loads. Downsizing the power source to maintain acceleration performance recovers some of the lost efficiency, however, the powertrain system would need to be fully optimized (beyond study scope) to return to the baseline efficiency.

Projection Results. Fuel Economy.



The improvement in fuel economy followed the reduction in fuel energy intensity. A sales-weighted improvement of 3.0 mpg (9.1%) was projected if best-in-class aerodynamic drag, tire rolling resistance, and mass efficiency were applied and the power source was downsized to maintain acceleration performance.

Projection Results. Tailpipe CO₂ Emissions.



The reduction of tailpipe CO₂ emissions followed the fuel energy intensity. A sales-weighted reduction of 22 g/mile (8.3%) was projected if best-in-class aerodynamic drag, tire rolling resistance, and mass efficiency were applied and the power source was downsized to maintain acceleration performance.

- Moving every vehicle to best-in-class aerodynamic drag (or maintaining the C_d if better than the proposed best-in-class value), results in a sales-weighted drag reduction of 10.6%. The reduction in aerodynamic drag resulted in a 3.3% lower vehicle energy intensity for the California fleet which yielded a ~5 g/mile benefit to tailpipe CO₂ emissions.
- Moving every vehicle to best-in-class tire RRC (or maintaining tire RRC if better than the proposed best-in-class value), results in a sales-weighted tire rolling resistance reduction of 11.4%. The lower tire rolling resistance resulted in an additional 2.9% reduction of vehicle energy intensity for the California fleet, yielding an additional ~5 g/mile benefit to tailpipe CO₂ emissions (for a total of ~10 g/mile).
- Moving every vehicle to best-in-class mass efficiency (or maintaining mass efficiency if better than the proposed best-in-class value), results in a sales-weighted curb weight reduction of 7.8%. In addition to the reduced kinetic energy, the lower mass has a secondary benefit of lower tire rolling resistance. The combined effect is an additional 4.8% reduction of vehicle energy intensity for the California fleet, yielding an additional ~7 g/mile benefit to tailpipe CO₂ emissions (for a total of ~17 g/mile).

- All powertrain elements (i.e., engine, motor, transmission, driveline) become less efficient as the operating load is reduced. Consequently, as a result of the reduced aerodynamic drag, tire rolling resistance, and curb weight, the sales-weighted powertrain efficiency dropped from 22.0% to 21.1% (4.3% loss). Re-sizing the power source to maintain acceleration performance (0-60 mph) recovered the efficiency to 21.5%.
- The re-sized powertrain (and subsequent improvement in efficiency), resulted in an additional ~5 g/mile benefit in tailpipe CO₂ emissions (California fleet), for a total benefit of ~22 g/mile.
- To recover all of the lost efficiency, the powertrain system would need to be fully re-optimized/matched. While determining the details of such a re-optimization is out of the scope of this study, it is reasonable to assume that the baseline efficiency (22.0%) could be attained. If the baseline efficiency were to be fully recovered, an additional 5 g/mile reduction in tailpipe CO₂ emissions would be achieved for the California fleet. The total benefit of vehicle load reduction would be ~27 g/mile.

- Using technologies and strategies that exist today, the aerodynamic drag, tire rolling resistance, and mass efficiency of the California light-duty vehicle fleet could be improved to achieve an overall reduction in vehicle load of over 10%.
- Reducing vehicle loads through these plausible reductions in aerodynamic drag, tire rolling resistance, and mass efficiency, along with re-sizing and re-optimizing the powertrain system to maintain equivalent performance, could reduce mobile source tailpipe CO₂ emissions by 8.3% to 10.4%.
- The majority (64% to 80%) of the potential CO₂ emissions benefit is the direct result of the reduced vehicle load. Re-matching the powertrain to take advantage of the lower loads provides the remaining benefit.
- The potential improvement of CO₂ emissions represents nearly one-third of the 34% reduction required to support California's Advanced Clean Cars program.

- Assuming the current fleet mix and powertrain technology deployment, the potential reduction of mobile source CO₂ emissions is between 22 and 27 g/mile.
- Assuming a new vehicle fleet of 1.83 million units per year, the potential reduction in mobile source GHG load is between 40 and 50 metric tons per mile traveled.
- Future changes to fleet mix and powertrain technology deployment will change the absolute levels (i.e., g/mile) of potential mobile source CO₂ emissions reduction, however, the fractional benefit (~8-10%) is expected to remain as long as the internal combustion engine is the dominant light-duty vehicle power source.

Q & A