# FE151 – Aluminum Association Inc.

## Impact of Vehicle Weight Reduction on a Class 8 Truck for Fuel Economy Benefits

**08 February, 2010**

# Agenda

- Scope and Approach
- Vehicle Modeling in MSC.EASY5
- Vehicle Model and Sub-Model Components
- Drive Cycles
- Vehicle Assumptions
- Model Inputs
- Simulation Results
- Weight Reduction with Less Aero Drag
- $CO_2$ Reduction
- Conclusion
- Appendix

# Scope and Approach

- Ricardo was requested to analyze the effect of weight reduction on Class 8 trucks in terms of fuel economy.
- Vehicle simulations were performed with conventional, lightweight and aluminum intensive tractor and trailer combinations to identify the fuel economy benefits of reducing vehicle weight.
- Vehicle weight conditions included empty trailer, half loaded, and fully loaded (80,000 lbs. GVW)).
- Coefficient of drag ($C_d$) was varied to reflect industry efforts to reduce aerodynamic drag.
- The trucks were simulated over several standard drive cycles and steady state conditions.

# Vehicle Modeling

- A full forward-looking, physics-based model was developed for a Class 8 truck using commercially available MSC.EASY5$^{TM}$ simulation software with Ricardo proprietary data as well as published information.
- The model simulates what happens to the vehicle when the driver applies the accelerator and/or brake pedal in order to achieve a certain vehicle speed at a certain time.
- The simulation runs on a millisecond-by-millisecond basis and predicts the fuel usage and actual speed with time as the model driver follows a certain vehicle speed trace (drive cycle).
- Model physics include torques and inertias as well as detailed sub-models for the influence of factors such as engine accessories.

# Vehicle Model and Sub-Model Components

- Engine
  - Torque curves for full load and closed throttle motoring correlated to published power ratings
  - Fuel consumption rates covering entire speed and load range
  - Idle and redline speeds
  - Rotational inertia
  - Parasitic loads
    - Cooling fan
    - Air compressor
    - Alternator
    - Power steering

# Vehicle Model and Sub-Model Components

- Transmission
  - 10-speed Automated Manual Transmission (AMT)
  - Gear ratios
  - Gear shifting map for all engine throttle positions and vehicle speeds
  - Efficiency for each gear
  - Rotational inertias

- Final Drive Differential
  - Gear ratio
  - Efficiency
  - Rotational inertia

# Vehicle Model and Sub-Model Components

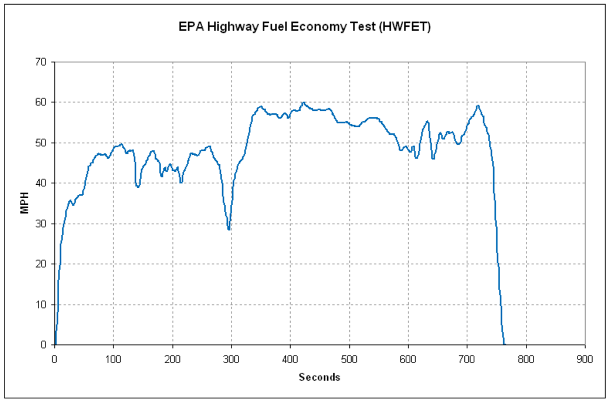
- Vehicle
  - Weight (steer, drive and trailer axles)
  - Center of gravity
  - Wheelbase
  - Frontal Area
  - Coefficient of Drag ($C_d$)

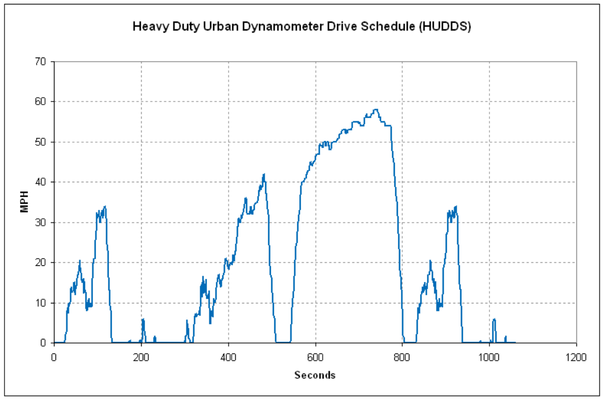
- Wheels / Tires
  - Rolling resistance coefficients
  - Rolling radius
  - Rotational inertia
  - Maximum friction coefficient
  - Slip at peak tire force

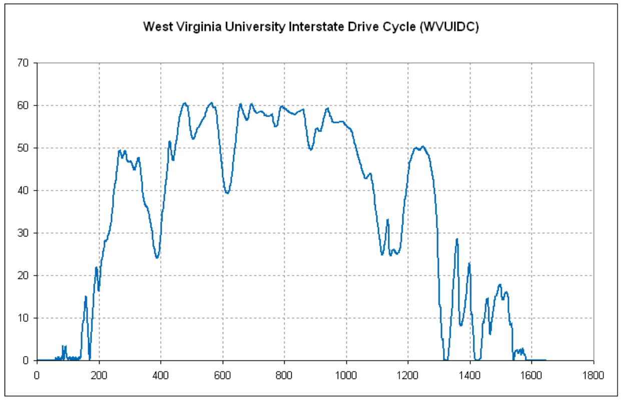
- Driver
  - Drive cycle (time vs. velocity trace)

# Drive Cycles

- Highway Fuel Economy Test (HWFET)
  - One of EPA's official highway cycles designed to measure light duty vehicle fuel economy and emissions on a dynamometer
  - Duty cycle strictly designed for medium to high speed operation with no mid-cycle stops
- Heavy Duty Urban Dynamometer Drive Schedule (HUDDS)
  - One of EPA's official drive cycles for heavy duty vehicles
  - Features several idle and stop-start portions to simulate heavier traffic
  - Contains many acceleration and deceleration events to potentially showcase advantages of weight reduction
- West Virginia University Interstate Drive Cycle (WVUIDC)
  - Created by West Virginia University to simulate interstate operation
  - Speeds vary from medium to high, including many moderate acceleration opportunities







# Vehicle Assumptions

- Fully loaded weight is 80,000 lbs. (36,287 kg) for all configurations (conventional, lightweight, aluminum).
- Rolling resistance coefficient is improved by 3% when switching from steel to aluminum wheels.
- Truck is modeled to represent:
  - 2 wheels on steer axle
  - 8 wheels on 2 drive axles
  - 8 wheels on 2 trailer axles
- Driveline velocity dependent spin losses are accounted for in addition to constant rolling resistance.

# Model Inputs

- Vehicle Specifications:
  - Frontal area: 10.68 $m^2$
  - Coefficient of drag ($C_d$): varied from 0.45 to 0.65
  - Vehicle mass (max. GVW): 80,000 lbs. (36,287 kg)
    - Configurations simulated as shown below:

| CONFIGURATION | | | | | |
|---|---|---|---|---|---|
| TRACTOR | | TRAILER | | CARGO | TOTAL [lbs] |
| Conventional | 16,000 | Conventional | 13,500 | 0 | 29,500 |
| Conventional | 16,000 | Conventional | 13,500 | 25,250 | 54,750 |
| Conventional | 16,000 | Conventional | 13,500 | 50,500 | 80,000 |
| Lightweight | 15,500 | Lightweight | 12,500 | 0 | 28,000 |
| Lightweight | 15,500 | Lightweight | 12,500 | 25,250 | 53,250 |
| Aluminum Intensive | 14,500 | Aluminum Intensive | 11,700 | 0 | 26,200 |
| Aluminum Intensive | 14,500 | Aluminum Intensive | 11,700 | 25,250 | 51,450 |

# Model Inputs

- Wheel / Tire Specifications:
  - Wheel / Tire rolling radius: 0.512 m
  - Wheel / tire rotational inertia:
    - Steer axle: 11.54 kg-m$^2$
    - Drive axle / trailer: 7.33 kg-m$^2$
  - Tire revs/mile: 500
  - Tire coefficient of rolling resistance:
    - Steer axle: 0.005
    - Drive axle / trailer: 0.0051

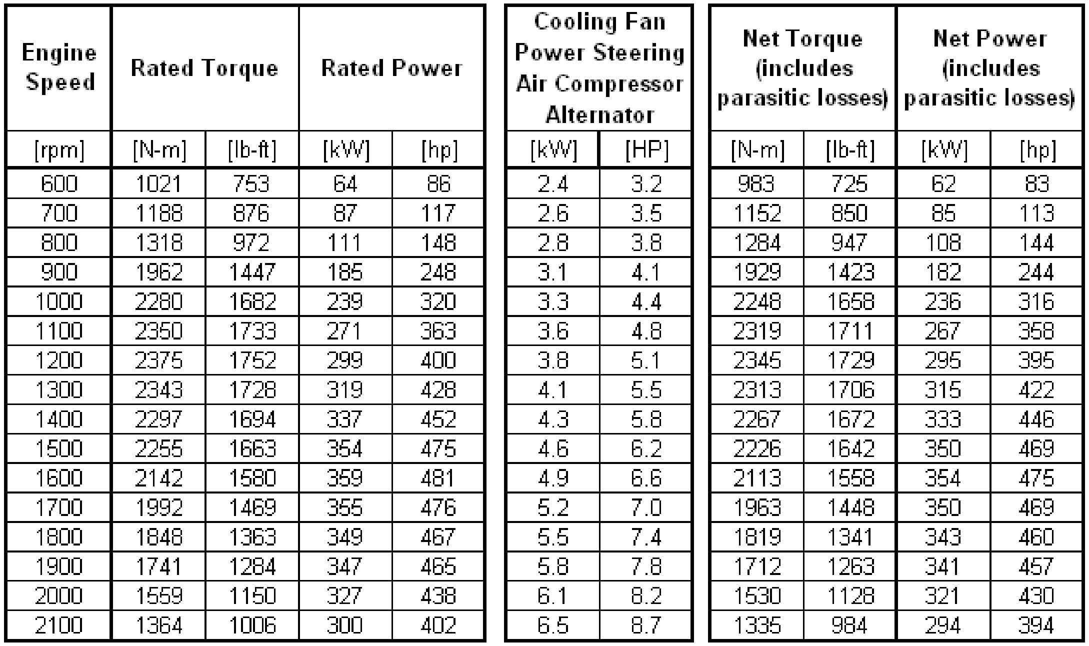
- Transmission and Drivetrain
  - Transmission gear ratios:

| **Gear** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Ratio** | 10.96 | 8.18 | 6.07 | 4.46 | 3.32 | 2.46 | 1.83 | 1.36 | 1.00 | 0.74 |

  - Final drive ratio: 2.70
  - Axle efficiency (including driveshaft / U-joints): 0.96

# Model Inputs

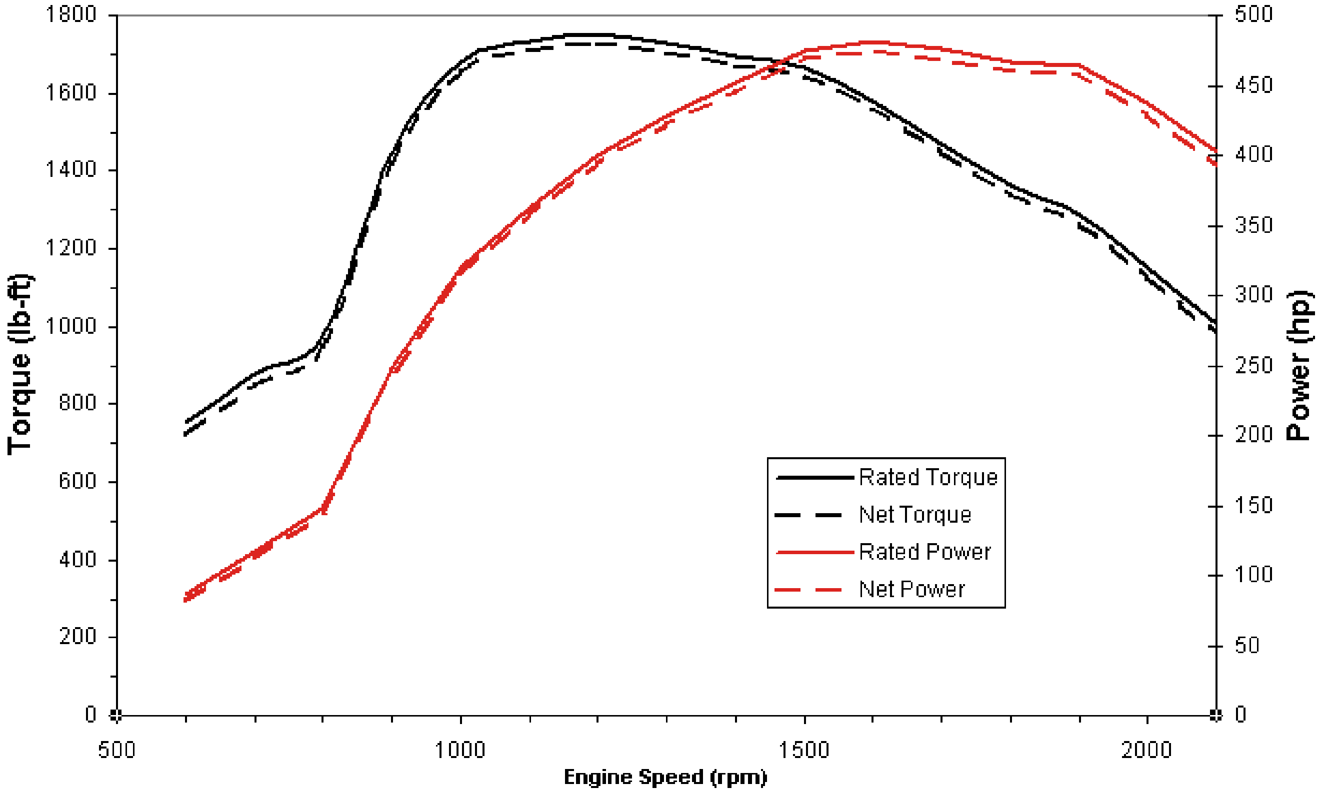
- Engine Specifications:
  - Fuel map represents 2010 engine with speed / load points throughout RPM range
    - In general, a 2010 engine with emissions aftertreatment will consume slightly more fuel when compared to an equivalent 2007 engine, particularly in the lower load range
  - Displacement: 13L
  - Fuel: light diesel (840 g/L)
  - Peak torque: 1752 lb-ft (2375 N-m) at 1200 rpm
  - Peak power: 481 hp (359 kW) at 1600 rpm
  - Idle speed: 600 rpm; Max engine speed: 2100 rpm
  - Engine rotational inertia: 1.258 kg-m$^2$



| Engine Speed | Rated Torque | | Rated Power | | Cooling Fan Power Steering Air Compressor Alternator | | Net Torque (includes parasitic losses) | | Net Power (includes parasitic losses) | |
|---|---|---|---|---|---|---|---|---|---|---|
| [rpm] | [N-m] | [lb-ft] | [kW] | [hp] | [kW] | [HP] | [N-m] | [lb-ft] | [kW] | [hp] |
| 600 | 1021 | 753 | 64 | 86 | 2.4 | 3.2 | 983 | 725 | 62 | 83 |
| 700 | 1188 | 876 | 87 | 117 | 2.6 | 3.5 | 1152 | 850 | 85 | 113 |
| 800 | 1318 | 972 | 111 | 148 | 2.8 | 3.8 | 1284 | 947 | 108 | 144 |
| 900 | 1962 | 1447 | 185 | 248 | 3.1 | 4.1 | 1929 | 1423 | 182 | 244 |
| 1000 | 2280 | 1682 | 239 | 320 | 3.3 | 4.4 | 2248 | 1658 | 236 | 316 |
| 1100 | 2350 | 1733 | 271 | 363 | 3.6 | 4.8 | 2319 | 1711 | 267 | 358 |
| 1200 | 2375 | 1752 | 299 | 400 | 3.8 | 5.1 | 2345 | 1729 | 295 | 395 |
| 1300 | 2343 | 1728 | 319 | 428 | 4.1 | 5.5 | 2313 | 1706 | 315 | 422 |
| 1400 | 2297 | 1694 | 337 | 452 | 4.3 | 5.8 | 2267 | 1672 | 333 | 446 |
| 1500 | 2255 | 1663 | 354 | 475 | 4.6 | 6.2 | 2226 | 1642 | 350 | 469 |
| 1600 | 2142 | 1580 | 359 | 481 | 4.9 | 6.6 | 2113 | 1558 | 354 | 475 |
| 1700 | 1992 | 1469 | 355 | 476 | 5.2 | 7.0 | 1963 | 1448 | 350 | 469 |
| 1800 | 1848 | 1363 | 349 | 467 | 5.5 | 7.4 | 1819 | 1341 | 343 | 460 |
| 1900 | 1741 | 1284 | 347 | 465 | 5.8 | 7.8 | 1712 | 1263 | 341 | 457 |
| 2000 | 1559 | 1150 | 327 | 438 | 6.1 | 8.2 | 1530 | 1128 | 321 | 430 |
| 2100 | 1364 | 1006 | 300 | 402 | 6.5 | 8.7 | 1335 | 984 | 294 | 394 |

# Model Inputs

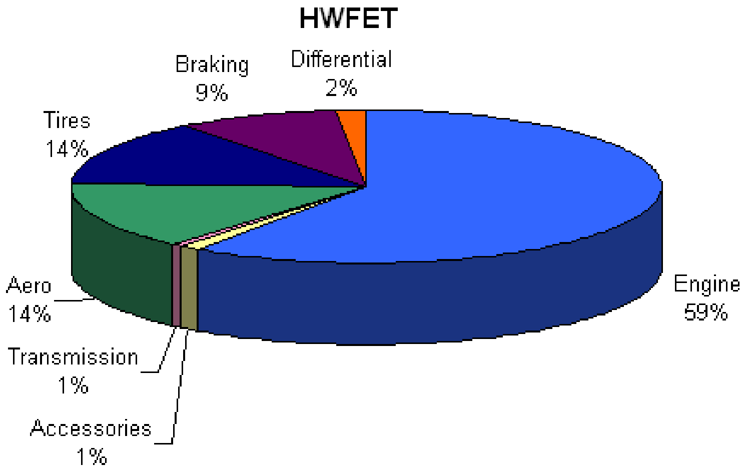
## Engine Performance Curves



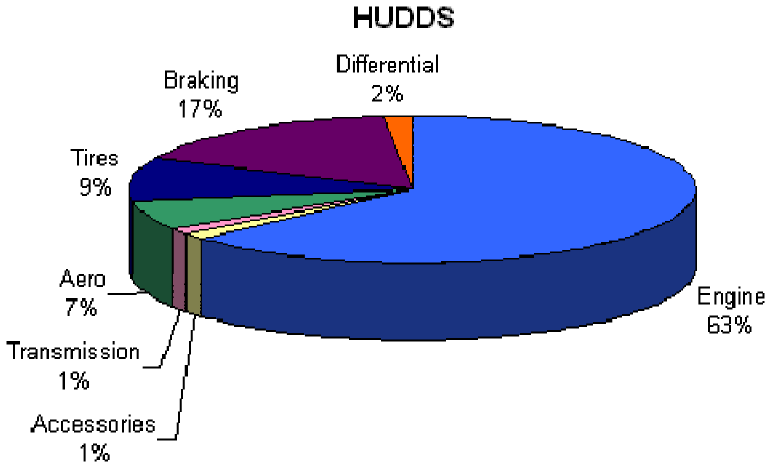
*Net torque and power includes fan, alternator, power steering, and air compressor load

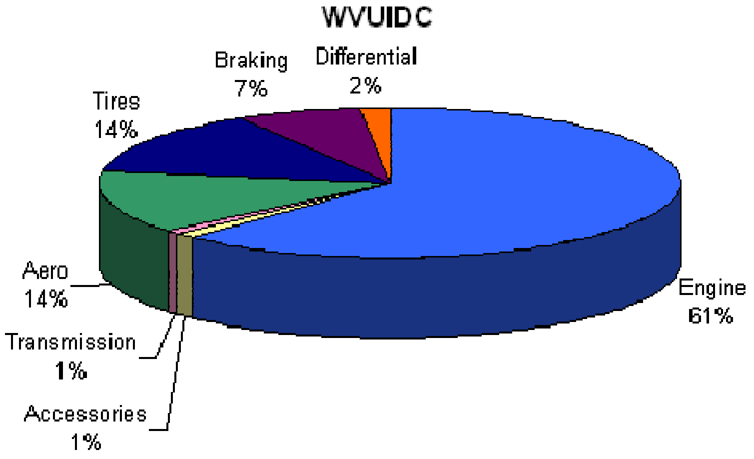
# Simulation Results – Fuel Energy Distribution

## Fully loaded conventional vehicle (80,000lbs GVW) with 0.6 $C_d$



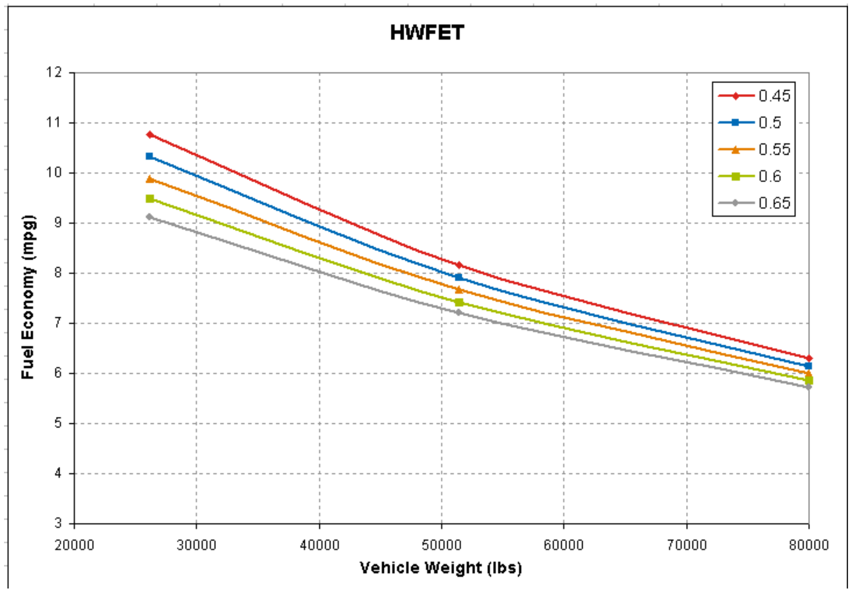
- Engine slice represents fuel energy lost to engine friction, pumping, heat rejection, exhaust, etc.
- Remainder of pie shows the distribution of engine output
- Reduction in vehicle weight translates to less energy lost to braking and tire rolling resistance



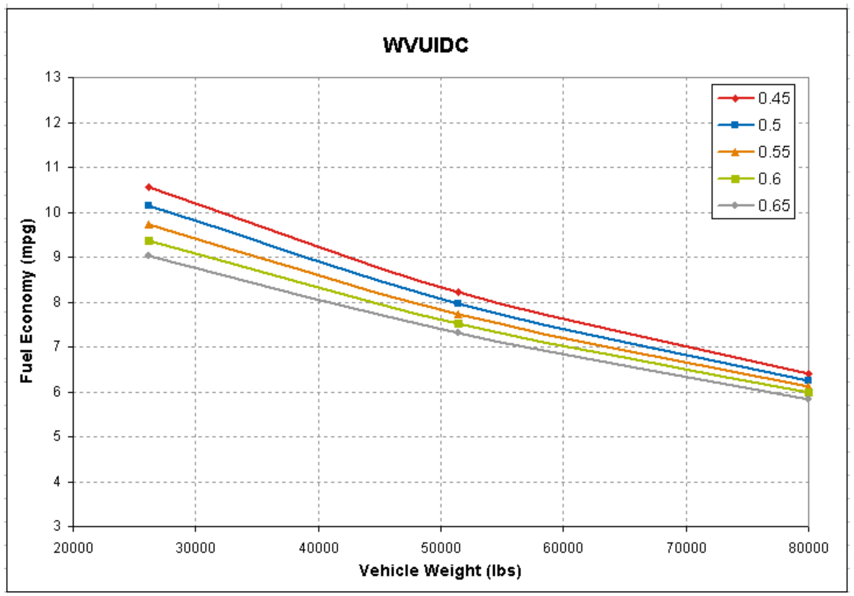


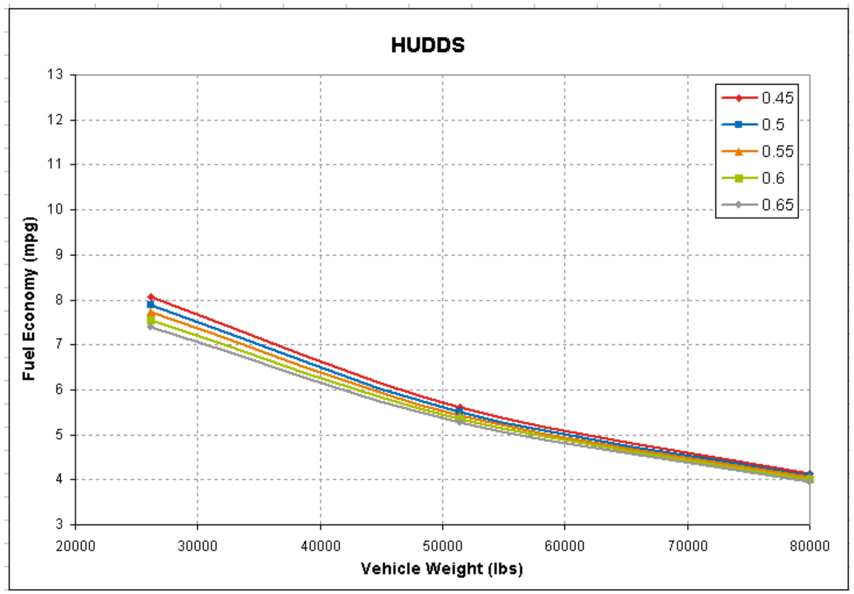
# Simulation Results – Fuel Economy vs Vehicle Weight

## At varying $C_d$ values for the Aluminum Intensive Truck



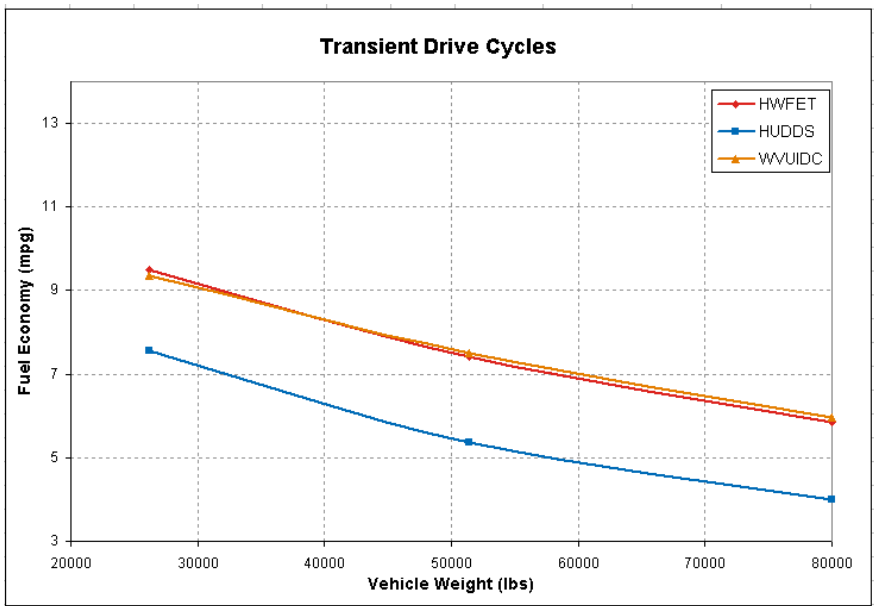
- HWFET and WVUIDC fuel economy varies more with changing $C_d$ due to higher vehicle speeds in the cycle when compared to the lower speed HUDDS

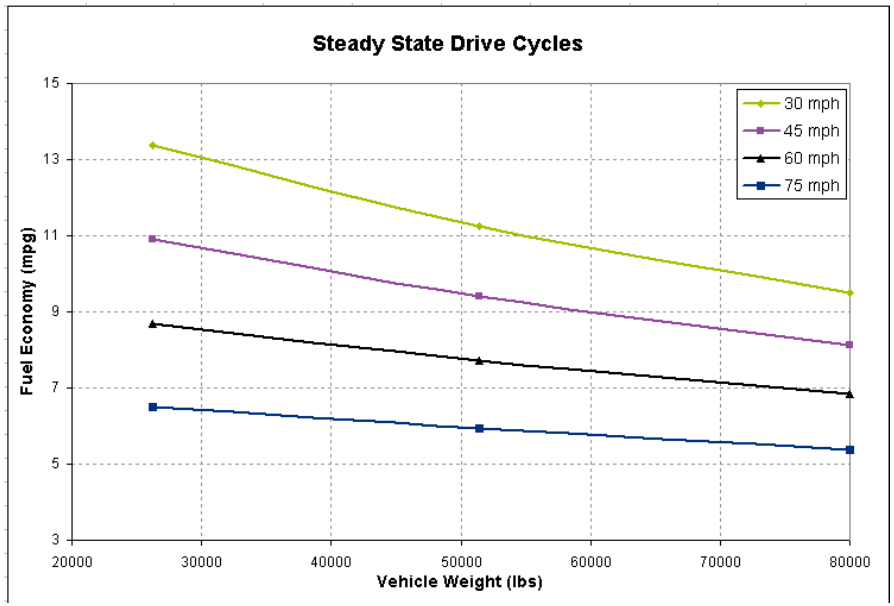




# Simulation Results – Fuel Economy vs Vehicle Weight

## At 0.6 $C_d$ for the Aluminum Intensive Truck





- HWFET, HUDDS, and WVUIDC all show similar upward trending curve of fuel economy vs. gross vehicle weight
- Steady state points reflect greater change in fuel economy as weight is reduced at lower speeds due to smaller ratio of aero loss to total loss

# Simulation Results – Fuel Economy Improvement vs Weight Reduction

## At 0.6 $C_d$

- The following graphs show the improvement in fuel economy that is achieved for the reduction in weight when comparing the aluminum intensive truck to the lightweight and conventional steel trucks at half and no load conditions
- The following is an example calculation of the fuel economy improvement and weight reduction for the aluminum vs lightweight scenario:

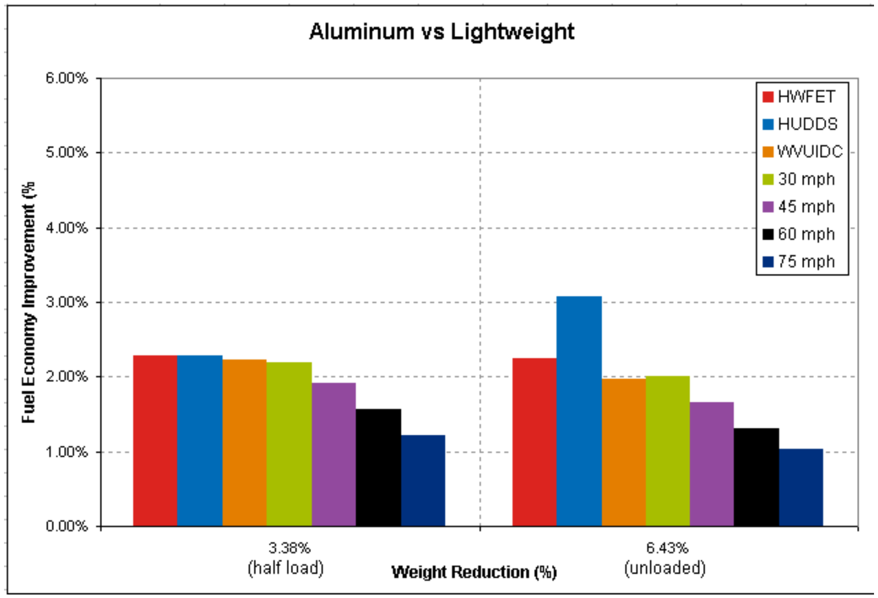
aluminum half loaded truck weight = 51450 lbs
lightweight half loaded truck weight = 53250 lbs

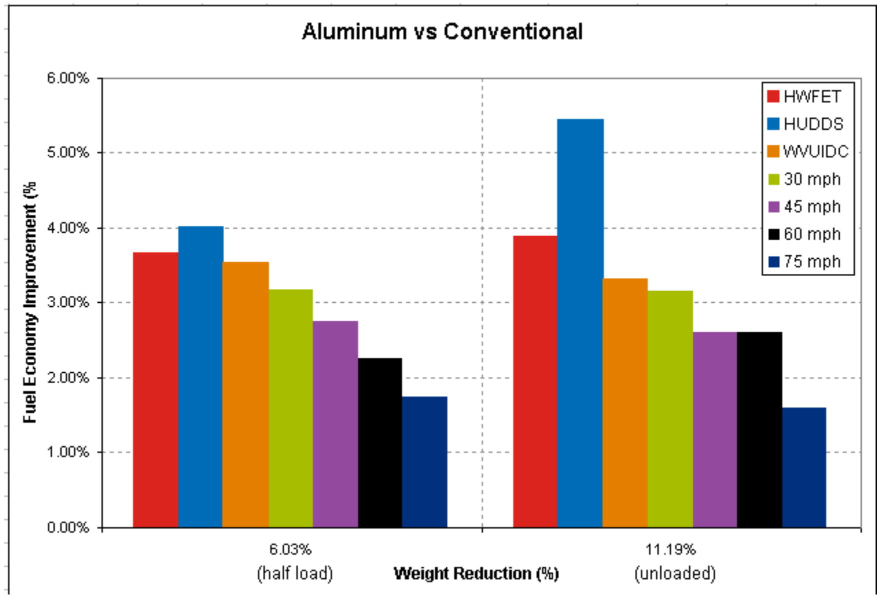
weight reduction = $1-\frac{51,450}{53,250}\times 100 = 3.38\%$

aluminum half loaded truck FE = 8.17 mpg
lightweight half loaded truck FE = 7.97 mpg

FE improvement = $\left(\frac{8.17}{7.97}-1\right)\times 100 = 2.51\%$

- On average, the fuel economy improvement at full load (80,000lbs GVW) was 0.7% when switching from conventional steel to aluminum intensive wheels

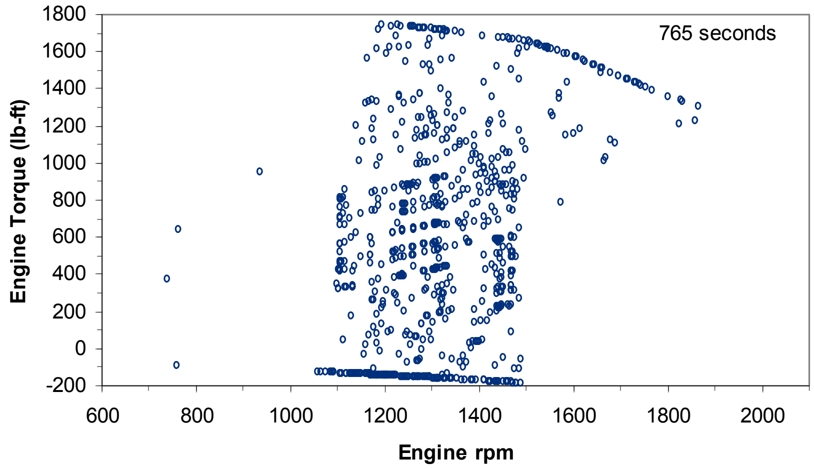




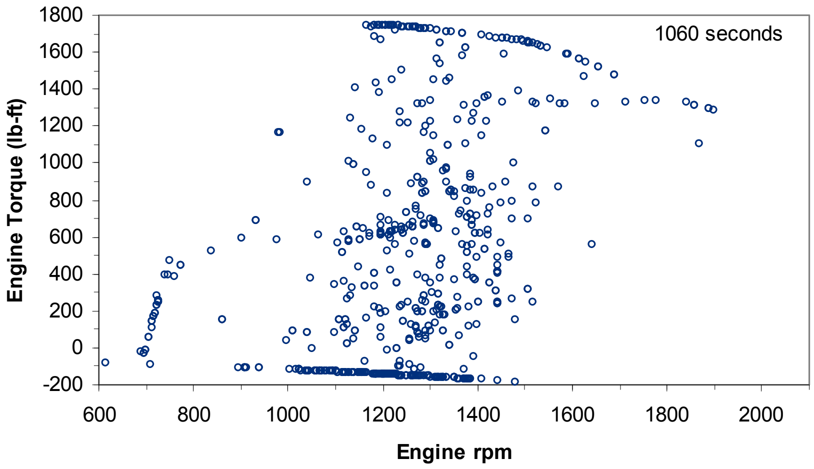
# Simulation Results – Engine Operating Points

## Fully loaded conventional vehicle (80,000lbs GVW)

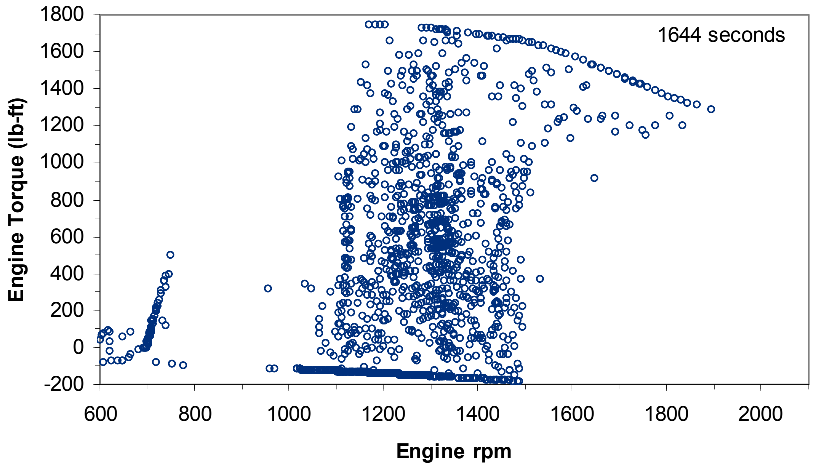
**HWFET**



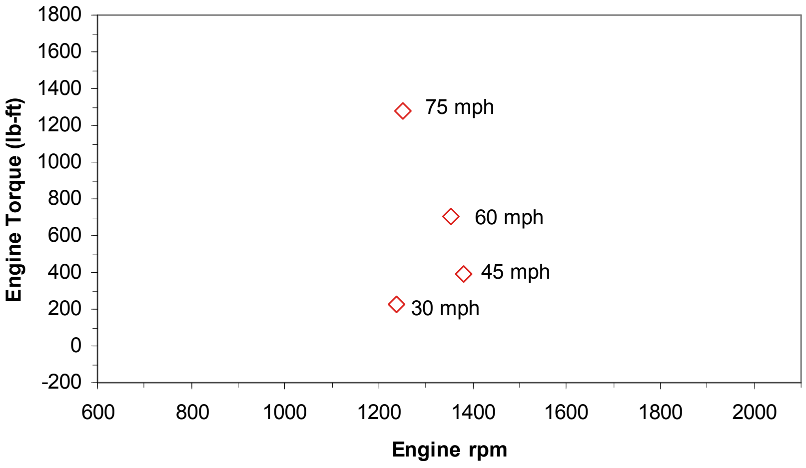
**HUDDS**



**WVUIDC**



**Steady State**



# Weight Reduction Combined with Aero Drag Reduction

- Potential fuel economy savings in the future can be significant with compounding of $C_d$ and vehicle weight reduction.
- Comparison below shows a typical conventional cab and trailer versus an aluminum intensive cab and trailer at various loads:

| | % Improvement in MPG (compared to conventional tractor / trailer with Cd of 0.6) | | | | | |
|---|---|---|---|---|---|---|
| | Aluminum Intensive, baseline Cd of 0.60 | | | Aluminum Intensive with Cd of 0.55 | | |
| Load (lbs) --> | Empty | 25,250 | 53,800 * | Empty | 25,250 | 53,800 * |
| HWFET | 3.9% | 3.7% | 0.7% | 8.2% | 6.9% | 3.3% |
| HUDDS | 5.4% | 4.0% | 0.5% | 7.8% | 5.5% | 1.5% |
| WVUIDC | 3.3% | 3.5% | 1.0% | 7.4% | 6.6% | 3.3% |
| 30 mph | 3.2% | 3.2% | 1.4% | 5.3% | 4.9% | 2.9% |
| 45 mph | 2.6% | 2.8% | 1.2% | 6.6% | 6.3% | 4.1% |
| 60 mph | 2.6% | 2.3% | 1.2% | 7.9% | 7.4% | 5.5% |
| 75 mph | 1.6% | 1.7% | 0.8% | 8.9% | 8.2% | 6.6% |

- At 80,000 lb. GVW – Aluminum intensive vehicle carries 3,300 lbs. more cargo than conventional tractor / trailer combination. A 3% improvement in tire rolling resistance improves overall MPG at maximum GVW.

# Simulation Results – % Fuel Economy Improvement per % Weight Reduction At Various $C_d$

- The following table shows the % of fuel economy improvement per % of vehicle weight reduction
- The average % fuel economy improvement per % weight reduction was 0.33% over the transient drive cycles with a $C_d$ of 0.6
- The average % fuel economy improvement per % weight reduction was 0.22% across the range of steady state points with a $C_d$ of 0.6
- As coefficient of drag improves, the % improvement in fuel economy increases

| | | DRIVE CYCLE | | | STEADY STATE | | | |
|---|---|---|---|---|---|---|---|---|
| | | HWFET | HUDDS | WVUIDC | 30 mph | 45 mph | 60 mph | 75 mph |
| Coefficient of Drag | 0.45 | 0.36 | 0.38 | 0.34 | 0.30 | 0.27 | 0.23 | 0.19 |
| | 0.50 | 0.35 | 0.37 | 0.33 | 0.29 | 0.26 | 0.22 | 0.18 |
| | 0.55 | 0.34 | 0.36 | 0.32 | 0.29 | 0.26 | 0.21 | 0.17 |
| | 0.60 | 0.33 | 0.36 | 0.31 | 0.28 | 0.25 | 0.20 | 0.16 |
| | 0.65 | 0.31 | 0.35 | 0.31 | 0.28 | 0.24 | 0.19 | 0.15 |

An aluminum intensive vehicle at 80,000 lb. GVW can carry 6.5% more cargo weight than a conventional tractor / trailer.

# $CO_2$ Reduction

## At 0.6 $C_d$

- Decreasing $CO_2$ emissions is another benefit of weight reduction. The following shows a comparison between a conventional steel vehicle and an aluminum intensive vehicle over 100,000 miles of duty using EPA's estimation of 22.2 lbs of $CO_2$ output per gallon of diesel used
- The aluminum intensive vehicle would save from 243 gallons of diesel (2.7 tons of $CO_2$) to 777 gallons (8.6 tons of $CO_2$) over the range of duty cycles simulated in the empty and half load scenarios
- At GVW (80,000lbs), an aluminum intensive vehicle would be able to carry 6.5% more payload than the conventional truck
  - Assuming a 6.5% reduction in trips made over 100,000 miles (93,500 miles), the aluminum intensive vehicle would save 777 gallons of diesel (8.6 tons of $CO_2$) to 1612 gallons (17.9 tons of $CO_2$)

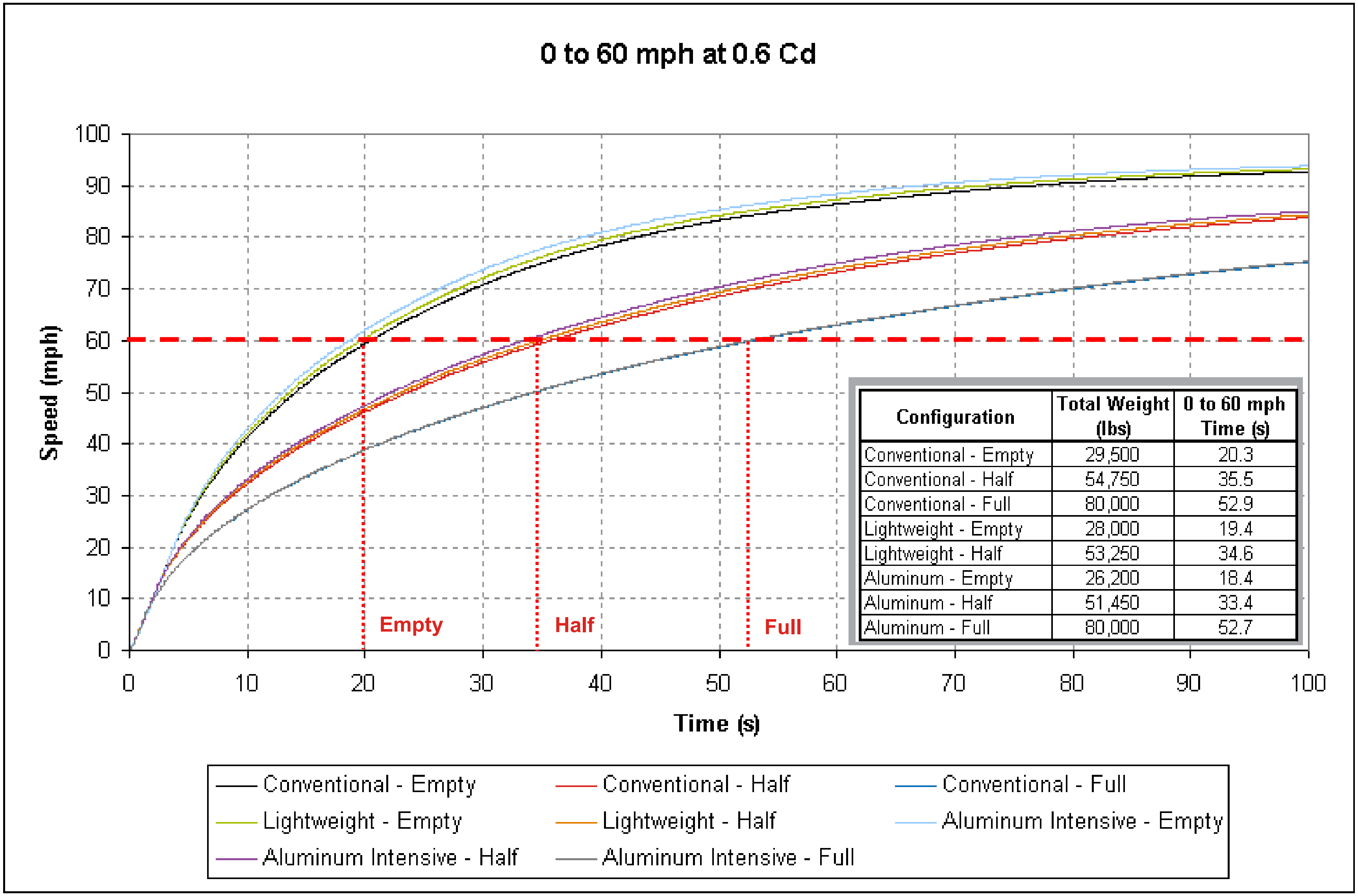
# Conclusion

- Seven Class 8 Truck weights were simulated over the HWFET, HUDDS, and WVUIDC drive cycles along with four steady state points to study the effect of weight reduction on fuel economy
- Coefficient of Drag was also varied from 0.45 to 0.65
- Vehicle weight reduction resulted in fuel economy benefits of 1% to 6% in an unloaded case and 2% to 5% in a half loaded case when comparing conventional steel to aluminum intensive trucks
- Decrease in $C_d$ provided further savings with a trend of lower benefit at low vehicle speeds to higher benefit at high vehicle speeds
- Beyond engine optimization, reducing tire rolling resistance and aerodynamic drag would also provide significant benefits to fuel economy
- Improving fuel economy also reduces $CO_2$ emissions
  - At GVW and 0.6 $C_d$, an aluminum intensive vehicle would save 777 gallons of diesel (8.6 tons of $CO_2$) to 1612 gallons (17.9 tons of $CO_2$) if the number of trips can be reduced by 6.5% over 100,000 miles

# APPENDIX

# Acceleration Performance Benefits of Weight Reduction

## 0 to 60 mph Performance



0 to 60 mph at 0.6 Cd

| Configuration | Total Weight (lbs) | 0 to 60 mph Time (s) |
|---|---|---|
| Conventional - Empty | 29,500 | 20.3 |
| Conventional - Half | 54,750 | 35.5 |
| Conventional - Full | 80,000 | 52.9 |
| Lightweight - Empty | 28,000 | 19.4 |
| Lightweight - Half | 53,250 | 34.6 |
| Aluminum - Empty | 26,200 | 18.4 |
| Aluminum - Half | 51,450 | 33.4 |
| Aluminum - Full | 80,000 | 52.7 |

# Weight Reduction Breakdown

## As provided by the Aluminum Association

### Class 8 Truck - Tractor and Trailer Weight Assumptions

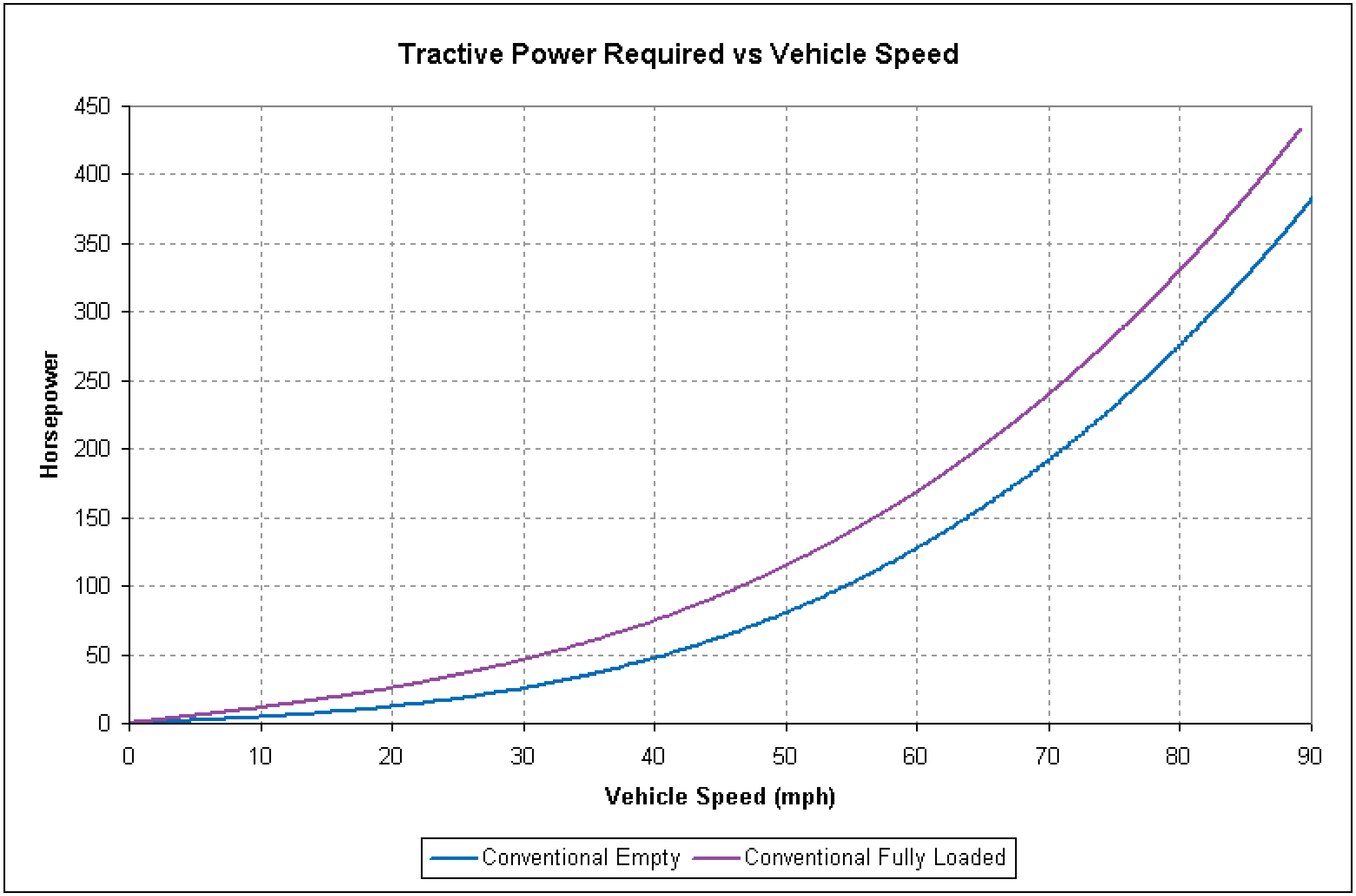
| | Tractor (lbs) | % Weight Reduction | Trailer (lbs) | % Weight Reduction | Tractor + Trailer (lbs) | % Weight Reduction |
|---|---|---|---|---|---|---|
| Conventional | 16,000 | | 13,500 | | 29,500 | |
| Lightweight | 15,500 | 3.1% | 12,500 | 7.4% | 28,000 | 5.1% |
| Aluminum Intensive | 14,500 | 9.4% | 11,700 | 13.3% | 26,200 | 11.2% |
| Total Weight Savings:<br>Conventional --> Al. Intensive | 1,500 | | 1,800 | | 3,300 | |

### Approximate Breakdown of Weight Savings

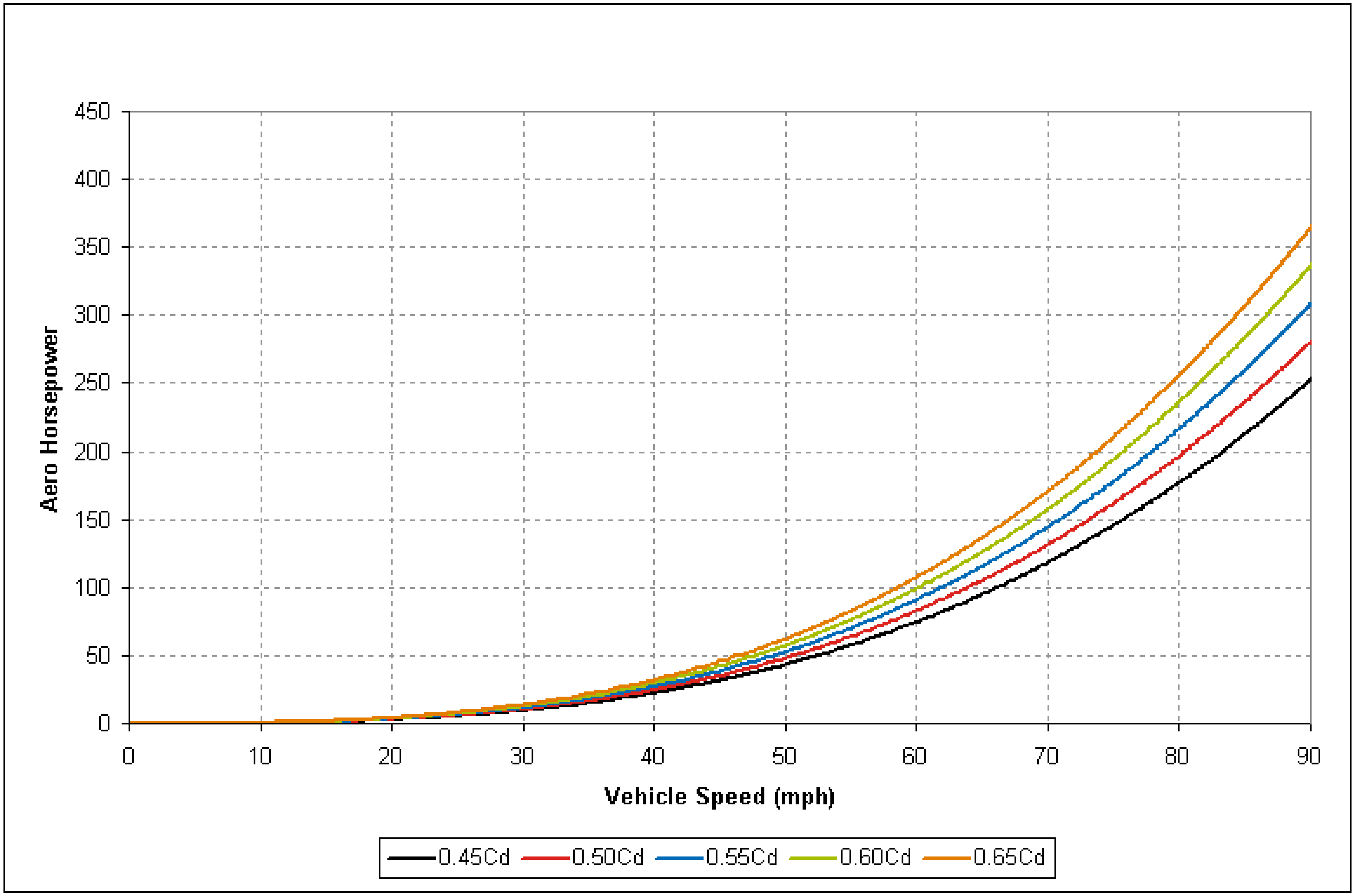
| **Tractor** | (lbs) | **Trailer** | (lbs) |
|---|---|---|---|
| Frame Rails | 440 | Side | 985 |
| Wheels | 350 | Rear | 150 |
| Cab | 330 | Slider | 145 |
| X-member | 70 | Door | 185 |
| Doors | 50 | Landing | 50 |
| Roof | 55 | Wheels | 285 |
| Misc | 60 | | |
| Casting / Suspension | 145 | | |
| Total Weight Savings | 1500 | Total Weight Savings | 1800 |

# Road Load At Empty and Full Load

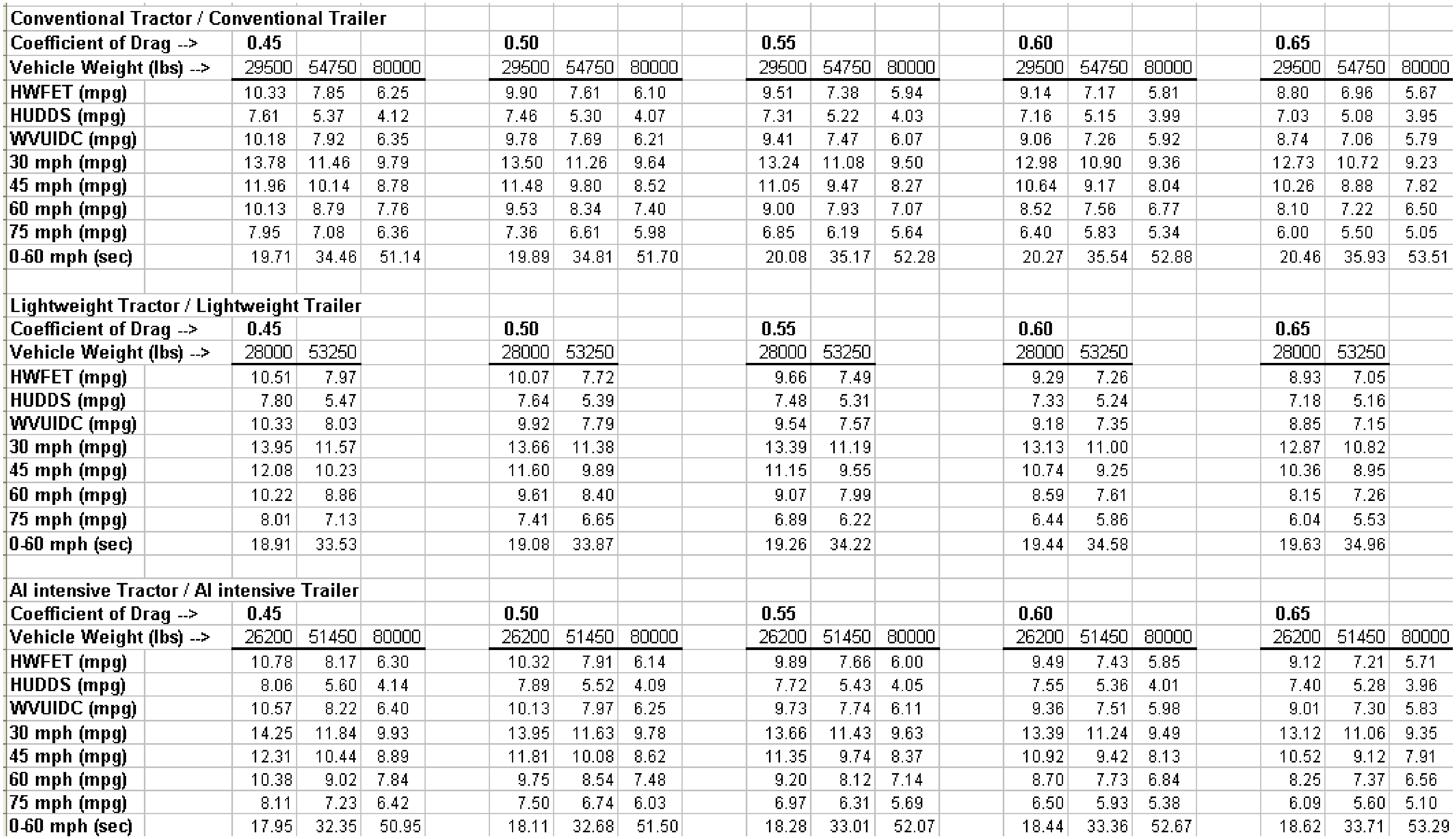
## At 0.6 $C_d$



# Power Lost to Aero Drag at Varying $C_d$



# Simulation Results



| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Conventional Tractor / Conventional Trailer** | | | | | | | | | | | | | | | |
| **Coefficient of Drag -->** | **0.45** | | | **0.50** | | | **0.55** | | | **0.60** | | | **0.65** | | |
| **Vehicle Weight (lbs) -->** | 29500 | 54750 | 80000 | 29500 | 54750 | 80000 | 29500 | 54750 | 80000 | 29500 | 54750 | 80000 | 29500 | 54750 | 80000 |
| **HWFET (mpg)** | 10.33 | 7.85 | 6.25 | 9.90 | 7.61 | 6.10 | 9.51 | 7.38 | 5.94 | 9.14 | 7.17 | 5.81 | 8.80 | 6.96 | 5.67 |
| **HUDDS (mpg)** | 7.61 | 5.37 | 4.12 | 7.46 | 5.30 | 4.07 | 7.31 | 5.22 | 4.03 | 7.16 | 5.15 | 3.99 | 7.03 | 5.08 | 3.95 |
| **WVUIDC (mpg)** | 10.18 | 7.92 | 6.35 | 9.78 | 7.69 | 6.21 | 9.41 | 7.47 | 6.07 | 9.06 | 7.26 | 5.92 | 8.74 | 7.06 | 5.79 |
| **30 mph (mpg)** | 13.78 | 11.46 | 9.79 | 13.50 | 11.26 | 9.64 | 13.24 | 11.08 | 9.50 | 12.98 | 10.90 | 9.36 | 12.73 | 10.72 | 9.23 |
| **45 mph (mpg)** | 11.96 | 10.14 | 8.78 | 11.48 | 9.80 | 8.52 | 11.05 | 9.47 | 8.27 | 10.64 | 9.17 | 8.04 | 10.26 | 8.88 | 7.82 |
| **60 mph (mpg)** | 10.13 | 8.79 | 7.76 | 9.53 | 8.34 | 7.40 | 9.00 | 7.93 | 7.07 | 8.52 | 7.56 | 6.77 | 8.10 | 7.22 | 6.50 |
| **75 mph (mpg)** | 7.95 | 7.08 | 6.36 | 7.36 | 6.61 | 5.98 | 6.85 | 6.19 | 5.64 | 6.40 | 5.83 | 5.34 | 6.00 | 5.50 | 5.05 |
| **0-60 mph (sec)** | 19.71 | 34.46 | 51.14 | 19.89 | 34.81 | 51.70 | 20.08 | 35.17 | 52.28 | 20.27 | 35.54 | 52.88 | 20.46 | 35.93 | 53.51 |
| | | | | | | | | | | | | | | | |
| **Lightweight Tractor / Lightweight Trailer** | | | | | | | | | | | | | | | |
| **Coefficient of Drag -->** | **0.45** | | | **0.50** | | | **0.55** | | | **0.60** | | | **0.65** | | |
| **Vehicle Weight (lbs) -->** | 28000 | 53250 | | 28000 | 53250 | | 28000 | 53250 | | 28000 | 53250 | | 28000 | 53250 | |
| **HWFET (mpg)** | 10.51 | 7.97 | | 10.07 | 7.72 | | 9.66 | 7.49 | | 9.29 | 7.26 | | 8.93 | 7.05 | |
| **HUDDS (mpg)** | 7.80 | 5.47 | | 7.64 | 5.39 | | 7.48 | 5.31 | | 7.33 | 5.24 | | 7.18 | 5.16 | |
| **WVUIDC (mpg)** | 10.33 | 8.03 | | 9.92 | 7.79 | | 9.54 | 7.57 | | 9.18 | 7.35 | | 8.85 | 7.15 | |
| **30 mph (mpg)** | 13.95 | 11.57 | | 13.66 | 11.38 | | 13.39 | 11.19 | | 13.13 | 11.00 | | 12.87 | 10.82 | |
| **45 mph (mpg)** | 12.08 | 10.23 | | 11.60 | 9.89 | | 11.15 | 9.55 | | 10.74 | 9.25 | | 10.36 | 8.95 | |
| **60 mph (mpg)** | 10.22 | 8.86 | | 9.61 | 8.40 | | 9.07 | 7.99 | | 8.59 | 7.61 | | 8.15 | 7.26 | |
| **75 mph (mpg)** | 8.01 | 7.13 | | 7.41 | 6.65 | | 6.89 | 6.22 | | 6.44 | 5.86 | | 6.04 | 5.53 | |
| **0-60 mph (sec)** | 18.91 | 33.53 | | 19.08 | 33.87 | | 19.26 | 34.22 | | 19.44 | 34.58 | | 19.63 | 34.96 | |
| | | | | | | | | | | | | | | | |
| **Al intensive Tractor / Al intensive Trailer** | | | | | | | | | | | | | | | |
| **Coefficient of Drag -->** | **0.45** | | | **0.50** | | | **0.55** | | | **0.60** | | | **0.65** | | |
| **Vehicle Weight (lbs) -->** | 26200 | 51450 | 80000 | 26200 | 51450 | 80000 | 26200 | 51450 | 80000 | 26200 | 51450 | 80000 | 26200 | 51450 | 80000 |
| **HWFET (mpg)** | 10.78 | 8.17 | 6.30 | 10.32 | 7.91 | 6.14 | 9.89 | 7.66 | 6.00 | 9.49 | 7.43 | 5.85 | 9.12 | 7.21 | 5.71 |
| **HUDDS (mpg)** | 8.06 | 5.60 | 4.14 | 7.89 | 5.52 | 4.09 | 7.72 | 5.43 | 4.05 | 7.55 | 5.36 | 4.01 | 7.40 | 5.28 | 3.96 |
| **WVUIDC (mpg)** | 10.57 | 8.22 | 6.40 | 10.13 | 7.97 | 6.25 | 9.73 | 7.74 | 6.11 | 9.36 | 7.51 | 5.98 | 9.01 | 7.30 | 5.83 |
| **30 mph (mpg)** | 14.25 | 11.84 | 9.93 | 13.95 | 11.63 | 9.78 | 13.66 | 11.43 | 9.63 | 13.39 | 11.24 | 9.49 | 13.12 | 11.06 | 9.35 |
| **45 mph (mpg)** | 12.31 | 10.44 | 8.89 | 11.81 | 10.08 | 8.62 | 11.35 | 9.74 | 8.37 | 10.92 | 9.42 | 8.13 | 10.52 | 9.12 | 7.91 |
| **60 mph (mpg)** | 10.38 | 9.02 | 7.84 | 9.75 | 8.54 | 7.48 | 9.20 | 8.12 | 7.14 | 8.70 | 7.73 | 6.84 | 8.25 | 7.37 | 6.56 |
| **75 mph (mpg)** | 8.11 | 7.23 | 6.42 | 7.50 | 6.74 | 6.03 | 6.97 | 6.31 | 5.69 | 6.50 | 5.93 | 5.38 | 6.09 | 5.60 | 5.10 |
| **0-60 mph (sec)** | 17.95 | 32.35 | 50.95 | 18.11 | 32.68 | 51.50 | 18.28 | 33.01 | 52.07 | 18.44 | 33.36 | 52.67 | 18.62 | 33.71 | 53.29 |

# Potential $C_d$ Reduction

- The following shows methods of Cd reduction for ground vehicles as described in SAE paper “Impact of Advanced Aerodynamic Technology on Transportation Energy Consumption”, 2004-01-1306

| Technology | Potential $C_d$ Reduction (%) |
|---|---|
| Surface Shape: Attached Flow | 30% |
| Surface Shape: Separated Flow | 10% |
| Trapped Vortex Separated Flow | 20% |
| Rotating Cylinder Surface Motion | 20% |
| Vortex Generator Flow | 5% |
| High Momentum Undercarriage Flow | 10% |

- Attached flow is the most basic form of aerodynamic shaping, which includes rounding of sharp corners and creating highly contoured vehicles. This can improve $C_d$ by up to 30%.
- Base plates (one form of separated flow alteration) can reduce $C_d$ by up to 10% by reducing base drag of blunt trailing edge airfoils.
- Trapped vortex is another separated flow surface technology which aims to manage gap flow between the cab and trailer by trapping series of vortices before the trailer. This technology on a class 8 truck can better $C_d$ by up to 20%.
- Rotating cylinder surface motion deals with pressure drag reduction and can benefit $C_d$ by up to 20% as well.
- Vortex generators is an established technology that that operates on the boundary layer flow. A class 8 truck can see improvements in $C_d$ of up to 5%.
- By accelerating air flow under the vehicle and guiding it into the trailing wake, high momentum undercarriage flow can reduce $C_d$ by 10%. Such applications can include shaped mud flaps (contraction cone design).