

# FY13 RWDC Surface Challenge Detailed Background



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## Relationship between Software Tools

PTC will make the software packages Creo Elements/Pro (computer-aided design), Mathcad (work-flow and calculation tool) and Windchill (collaboration tool) available to the teams. It is expected that teams will use Creo in combination with FloEFD Pro (aerodynamic analysis software provided by Mentor Graphics) to complete the vehicle and aerodynamics modeling. Teams will be provided a basic solid model of the combination truck in Creo, on which they will add different aerodynamic features to assess using FloEFD Pro.

Teams will also be provided a challenge-specific version of the Future Automotive Systems Technology Simulator (FASTSim) developed by the U.S. Department of Energy's (DOE) National Energy Renewable Energy Laboratory (NREL). The tool runs within Microsoft Excel and has been tested in Excel 2007 and 2010. The tool will include a baseline heavy-duty combination truck model which is representative of the baseline vehicle described elsewhere in this document. Using FASTSim's simple user interface, teams will explore the fuel economy impact of changes to the truck's aerodynamic design, tire rolling resistance, vehicle weight, and engine efficiency.

FASTSim provides rapid calculation (roughly 3-seconds for each simulation) of the fuel economy expected for various vehicle designs. Teams will be able to explore design changes simply by entering different input values into FASTSim, but implementing such changes in reality requires significant engineering effort. Manufacturers can influence rolling resistance by changing tire materials, construction techniques and inflation pressures, but also must consider how design changes influence handling and durability. Lighter materials can help take weight out of a vehicle but also impact crashworthiness. And engine designers must consider the effect on both fuel efficiency and pollutant emissions, such as particulate matter (PM), oxides of nitrogen (NOx) and carbon monoxide (CO), when making engine and after-treatment design decisions. For simplicity, teams will only have to consider the cost implications of explored improvements to rolling resistance, vehicle weight and engine efficiency. But to get a taste for the real-world experience of generating design improvements, teams will use the additional software tools to identify design changes leading to improved vehicle aerodynamics.

## Physical Parameters of Baseline Model

With respect to the Creo and FloEFD Pro modeling, the aerodynamic improvements teams implement must be based off the provided CAD model which reflects the physical dimensions below:

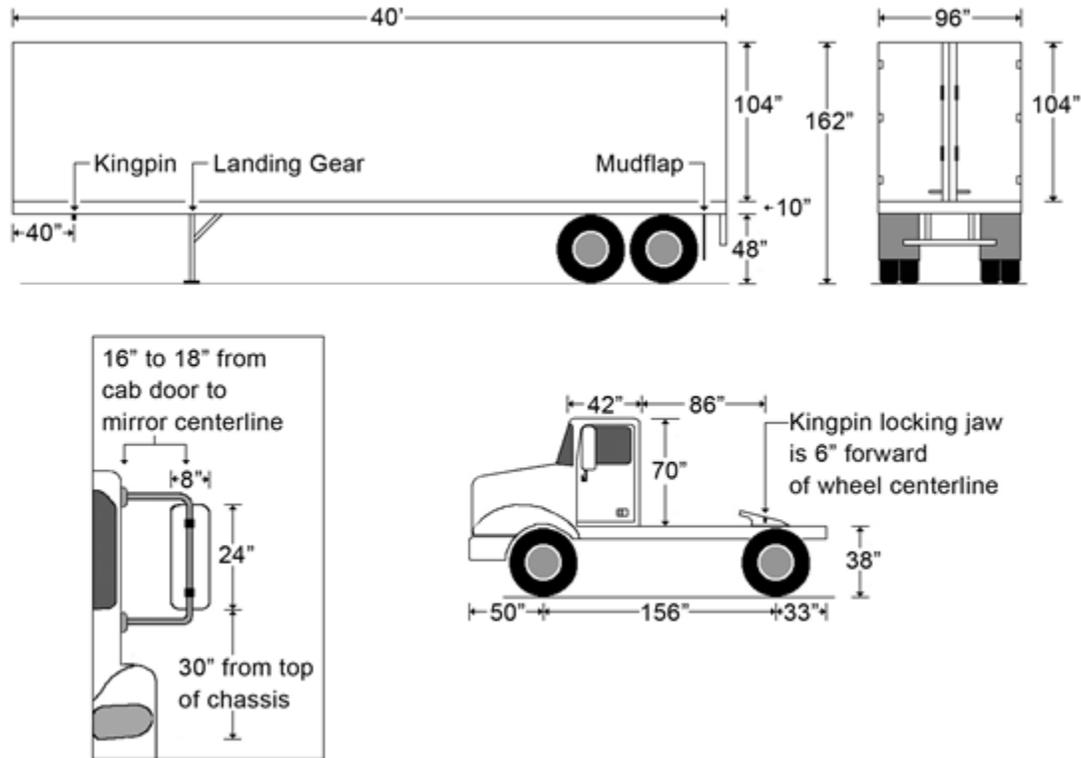


Figure 1. Physical Dimensions of Baseline Tractor-Trailer

The truck to be designed shall consist of a tractor and single box trailer combination. The physical parameters of your modified design shall remain within the following parameters:

### Tractor size:

Width: 96 inches

Length between centerline of front axle and front bumper: 40 inches

Wheelbase (distance between front axle and midline of rear drive axle): 130 inches

Length between midline of rear drive axle and rear of tractor: 52 inches

Length between midline of rear drive axle and back of cab: 96 inches

Kingpin insert or "fifth wheel" located directly above midline of rear drive axle. (This is where the trailer attaches to the tractor.)

Cab height (from chassis to top of cab): 70 inches (considered high roof)

Cab depth (driver's compartment) from front to back: 42 inches (considered a day cab because there is no sleeping compartment)

Cab shape: any shape that can incorporate a rectangular driver's compartment with the above dimensions for cab height, cab depth, and tractor width

Height from ground to bottom of chassis: 32 inches

Number of Axles: total of two (one front steer axle, one rear drive axle)

Tires: 295/75 R 22.5 14

Tire pressure: 100 psi

Weight: 13,500 lbs.

**Trailer:**

Width: 96 inches

Height from top of chassis (trailer floor) to top: 104 inches

Chassis: 10 inches

Height from ground to bottom of chassis: 48 inches

Total height of trailer from ground to top: 162 inches

Length: 480 inches (40 feet)

Shape of trailer body: Rectangular

No. of Axles: Two rear non-drive tandem

Tires: 295/75 R 22.5 14

Tire pressure: 100 psi

Tare Weight: 11,500 lbs.

Cargo Weight: 30,000 lbs.

The trailer shall be attached to the tractor through a "fifth wheel" or kingpin.

Distance from front of trailer to kingpin: 40 inches

## Federal Regulations

Two new standards for trucks are expected to result in significant savings and benefit over the lifetime of vehicles built for model years 2014-2018, including:

- Saving a projected 530 million barrels of oil and reducing carbon pollution emissions by about 270 million metric tons.
- Saving vehicle owners and operators an estimated \$50 billion in fuel costs.
- Yielding an estimated \$49 billion in societal benefits.
- Ensuring long-term savings for vehicle owners and operators above their initial upfront costs – a semi-truck operator could pay for the technology upgrades in under a year and realize net savings of \$73,000 through reduced fuel costs over the truck’s useful life. Additionally, the Environmental Protection Agency estimates the standards will improve air quality by reducing particulate matter and ozone, resulting in societal benefits ranging from about \$1.3 billion to \$4.2 billion in 2030.

The two new Federal standards listed below are specific to combination tractors (commonly known as big rigs or semi-trucks) that fall in the Class 8 category (signifying a gross combination weight rating of over 33,000 lbs.), have a day cab with a high roof (no sleeping compartment) and haul a 19-ton payload over specified driving conditions:

### Final Model Years 2014-2016 Combination Tractor Standards

EPA Emissions Standard

NHTSA Fuel Consumption Standard

92 g CO<sub>2</sub> /ton-mile

9.0 gal/1,000 ton-mile

The **ton-mile** metric refers to a combination of the vehicle payload and a distance driven. So, for a vehicle with a 19-ton payload, 9.0 gal/1,000 ton-mile indicates that the vehicle should consume no more than 9\*19 or 171 gallons to drive 1,000 miles, which is equivalent to a maximum fuel consumption of 17.1 gal/100 mile. While the rest of the world most often uses fuel consumption (albeit in metric units of L/100 km), most people in the U.S. reference fuel economy, which is the inverse of fuel consumption. A maximum fuel consumption of 17.1 gal/100 miles is equivalent to a minimum fuel economy of 100/17.1 or 5.85 miles per gallon (mpg).

Note that for a given driving distance fuel consumption relates directly to fuel used, whereas fuel economy relates non-linearly. The figure below illustrates this by plotting fuel consumed for 15,000 miles of driving (a representative annual distance for many vehicles) against fuel economy. The steepness of the left side of the curve underscores the large per-vehicle fuel savings that results from improving the fuel economy of low-mpg vehicles (e.g., increasing from 3 mpg to 4 mpg saves 1,250 gallons, while increasing from 15 mpg to 20 mpg saves 250 gallons for this 15,000 mile example).

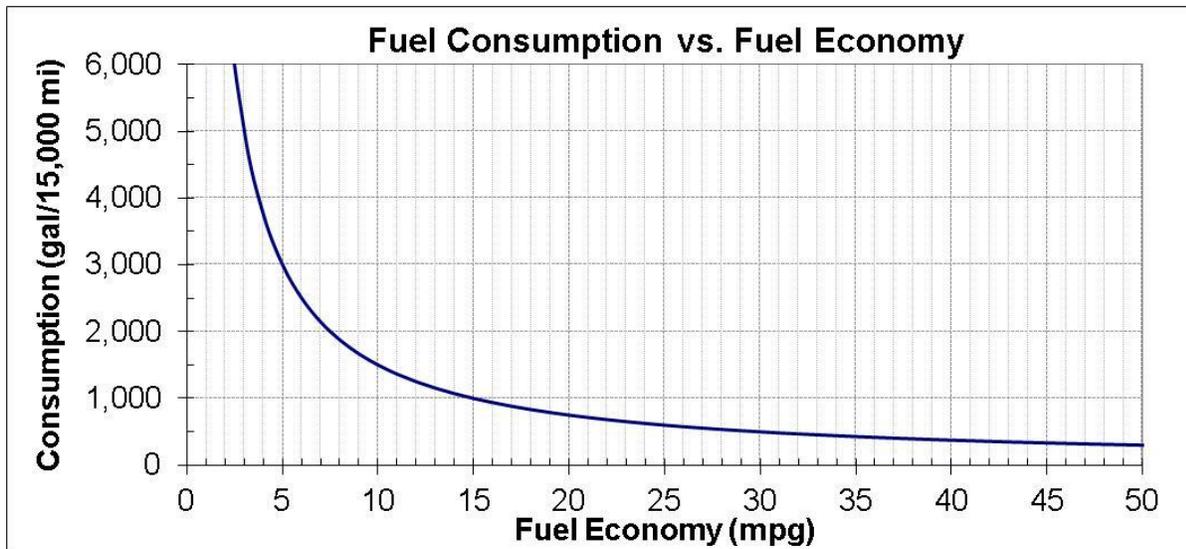


Figure 2. Fuel Consumption vs. Fuel Economy Graphic

For the purposes of this challenge, satisfying the 6.0mpg minimum fuel efficiency standard outlined in the challenge statement will be considered sufficient to demonstrate compliance with the EPA Emission Standards and the NHSTA Fuel Consumption Standards. The tractor and trailer must also comply with two additional regulations:

- **Part 393 – Parts and Accessories Necessary for Safe Operation.** In Title 49 of the Code Federal Regulations, Part 393 has safety requirements for lights, brakes, windows, fuel system, rear view mirrors, coupling, tires, exhaust, rear impact guards, emergency equipment, frames, cab, wheels, suspension, and steering. Some of these parts (e.g., rear view mirrors) protrude from the body of the truck. Teams will have to determine if such protruding parts affect the aerodynamics.
- **Section 658.16(b)(4) – Exclusions from Length and Width Determinations in Title 23 of the Code of Federal Regulations.** Any device added to the rear end of the trailer to improve aerodynamics must comply with the following provisions:
  1. Does not carry cargo;
  2. Does not extend beyond 5 feet of the rear of the vehicle;
  3. Does not obscure tail lamps, turn signals, marker lamps, identification lamps, or safety devices such as hazardous material placards or conspicuity markings;
  4. Has neither the strength, rigidity nor mass to damage a vehicle, or injure a passenger in a vehicle that strikes a vehicle so equipped from the rear.

## Mathematical Background for FASTSim

To aid students in developing an understanding of the physics incorporated into the FASTSim software, the following example calculations are included for reference.

### Example Calculations:

This mathematical example describes the relationship between vehicle characteristics (mass, aerodynamics, speed, etc.) and the amount of fuel required to drive the vehicle.

“Force” is the interaction between two objects. When a force is applied to an object over a distance, “work” is done. Work can be thought of as a transfer of “energy” from one object to another. The rate at which this energy transfer occurs is referred to as “power”.

When considering the movement of a vehicle on a road surface, four forces must be examined:

1. The force required to accelerate the vehicle,  $F_A$  (measured in Newtons), which is defined as:

$$F_A = m a$$

where  $m$  = the mass of the vehicle (kg),  
and  $a$  = the acceleration of the vehicle ( $m/s^2$ )

2. The force required to overcome the aerodynamic drag of the vehicle,  $F_D$ , defined as:

$$F_D = \frac{1}{2} c_d \rho V^2 A$$

where  $c_d$  = the coefficient of drag of the vehicle,  
 $\rho$  = the density of the air ( $1.2 \text{ kg}/m^3$ ),  
 $V$  = the velocity of the vehicle ( $m/s$ ),  
and  $A$  = the frontal area of the vehicle ( $m^2$ )

3. The force required to overcome the rolling resistance of the tires,  $F_R$ , defined as:

$$F_R = \mu m g \cos(\beta)$$

where  $\mu$  = the coefficient of rolling resistance for the tires,  
 $m$  = the mass of the vehicle (kg),  
 $g$  = gravitational acceleration ( $9.81 \text{ m}/s^2$ ),  
and  $\beta$  = the angle of incline (degrees)

4. The “climbing” force required to move the vehicle up a grade or incline,  $F_c$ , defined as:

$$F_c = m g \sin(\beta)$$

where  $m$  = the mass of the vehicle (kg),  
 $g$  = gravitational acceleration (9.81 m/s<sup>2</sup>)  
and  $\beta$  = the angle of incline (degrees)

Because power is the rate at which a force transfers energy, the *power* required to overcome each of these individual forces is easily calculated by multiplying the force by the velocity of the vehicle. The resulting set of equations is:

$$\begin{aligned} P_A &= m a V \\ P_D &= \frac{1}{2} c_d \rho V^3 A \\ P_R &= \mu m g \cos(\beta) V \\ P_C &= m g \sin(\beta) V \end{aligned}$$

where the power,  $P$ , is measured in watts.

The total power required to move a vehicle on a road surface is the sum of the four equations above:

$$P_{TOTAL} = P_A + P_D + P_R + P_C$$

As previously stated, power is the rate at which energy is transferred, or used. Stated another way, energy is power multiplied by time. For example, the transfer of energy at the rate of 1,200 watts (or 1.2 kW) for one hour would represent 1.2 kilowatt-hours (kWh) of energy. Similarly, power at 50 kW for 15 minutes represents 12.5 kWh of energy (50 kW x ¼ hour = 12.5 kWh)

Using this information, it is possible to calculate how much energy is required to move a vehicle at a given speed for a specified time. It is important to note, however, that these equations represent the power (and energy) required *at the wheels* of the vehicle. One must take into consideration efficiency losses that are present throughout the vehicle powertrain, the most dominant of which is the efficiency of the engine in converting fuel energy into motion. For a vehicle, energy and efficiency are related as:

$$E_{at\ the\ wheels} = E_{fuel} \times \eta_{powertrain}$$

where  $E$  = energy,  
and  $\eta$  = efficiency ( $0 < \eta < 1$ )

If a vehicle, as in the previous example, requires 12.5 kWh of energy at the wheels to travel a given speed for 15 minutes, and that vehicle’s powertrain is only 20% efficient, then it would require 62.5 kWh of fuel energy to cover the distance. (12.5 kWh / 0.20 = 62.5 kWh). Assuming that this vehicle was powered by gasoline, and assuming that gasoline has an energy density of 36 kWh per gallon, this 15-minute trip would require approximately 1.74 gallons of fuel. (62.5 kWh / (36 kWh/gallon) = 1.74 gallons.)

While these equations are useful in calculating the power, energy, and fuel required to move a vehicle at a steady speed, it would be far too complicated to manually solve these equations for a real drive cycle

that involves varying speeds and grades over time. To determine the power requirements of a vehicle on a realistic drive cycle (or a standard test cycle), simulation software is used to iteratively solve the equations at each incremental time-step of the cycle.

The figure below shows an example of the full Heavy Heavy-Duty Diesel Truck (HHDDT) cycle referenced in the challenge statement. The cycle lasts for 4000 seconds and includes periods vehicle idling at zero speed, accelerating, decelerating and driving at roughly constant speeds.

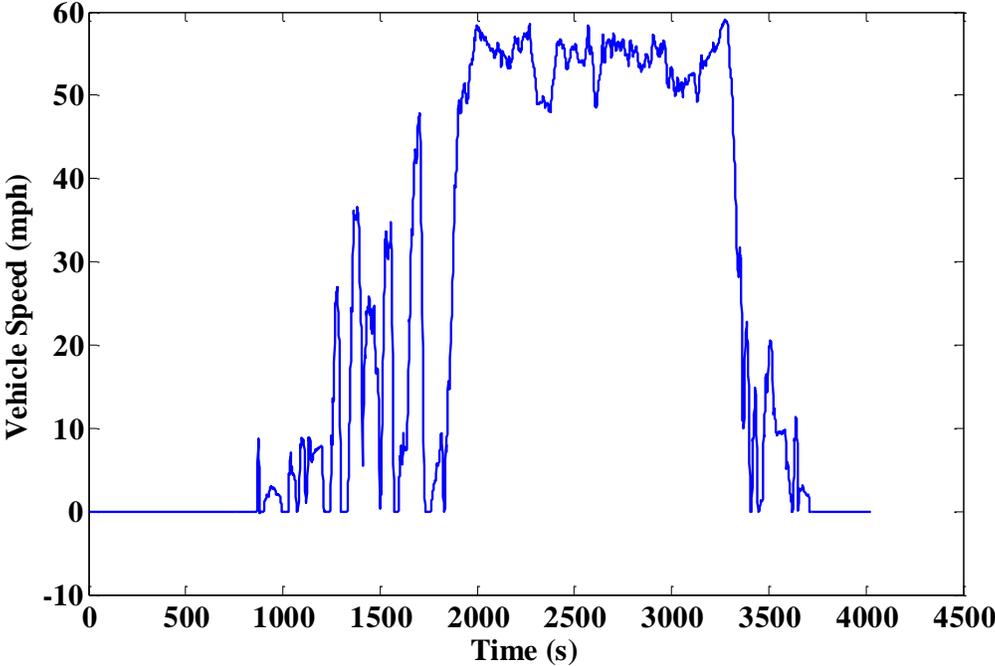


Figure 3. Example Illustration of the full Heavy-Duty Diesel Truck (HHDDT) cycle

# FASTSim User Instructions and Documentation

A specifically-tailored version of FASTSim will be made available to student teams. General instructions on using this version follow.

1. Double click to open the file FASTSimForRWDC\_v01.xlsm.
2. Enable macros by clicking on the “Option” button next to the security warning (which should appear at the top of the file) and select “Enable this content” then “OK”.
3. The only tab that you really need to work in is “Design Challenge”.
4. Modify the parameter values in the four orange input cells to evaluate their impact on the vehicle fuel economy. The permissible range for each input parameter is given below (where the first number listed for each parameter is the baseline value):
  - Drag coefficient: 0.7963-0.5574
  - Rolling resistance coefficient: 0.0085-0.0068
  - Glider mass (kg): 10,452-8,184
  - Engine efficiency improvement: 0%-8%
    - Engine 1 = 0%
    - Engine 2 = 4%
    - Engine 3 = 8%

Note that the fuel economy and cost calculations automatically update as the input parameter values are changed, and that the input cell turns **red** if the value is out of range.

## Documentation

Costs for efficiency improvement technologies

- Drag coefficient: \$150 per % drag reduction
- Glider mass: \$4.40 per kg glider mass reduction (\$2/lb)
- Rolling resistance coefficient: \$35 per % rolling resistance reduction
- Engine efficiency: \$875 per 1% engine efficiency improvement
  - Engine 1 = \$0 (Baseline)
  - Engine 2 = \$3,500
  - Engine 3 = \$7,000

Assumptions

- Annual miles of travel per year: 15,000
- Diesel fuel cost: \$4.50/gallon
- Payback period: 3.5 years
- Baseline fuel economy: 4.86 MPG

Calculations

- Fuel expenditures over 3.5 years (\$):  $3.5 * 15,000 * 4.5 / [\text{MPG}]$  (B26)
- Baseline fuel expenditures over 3.5 years (\$):  $3.5 * 15,000 * 4.5 / 4.86$  (B27)

- Fuel cost savings=Baseline fuel expenditure – Fuel expenditure (B28)
- Total cost is the difference between technology costs and fuel cost savings (B24-B28)

Note that the FASTSim file includes other visible tabs for added reference and that many other tabs are also present but are hidden. If teams are interested in exploring the full capability of FASTSim they may view the hidden tabs by right-clicking on the bottom tab of any worksheet, selecting “unhide” then the name of the new worksheet to view. The tab called “FullFASTSimDocumentation” would be a good place to start. If teams begin exploring and modifying the open-source code within FASTSim it is highly recommended that they save and maintain an un-modified version of the tool first.