

Analysis of an Aerodynamic Coefficient to Characterize Vehicle Driving Cycles

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Abstract

The energy usage simulation of conventional, advanced hybrid, and electric vehicles in computer packages relies on the estimation of the forces acting on a vehicle during a standardized driving cycle. Of particular interest in this research is the force of aerodynamic drag, which increases exponentially with vehicle speed, making it especially important for electric vehicles, which have a limited range. A driving cycle can be quantified in many different ways, including average speed and kinetic intensity (which includes a metric called aerodynamic speed). The use of an aerodynamic metric, whether kinetic intensity or aerodynamic speed, was shown in this study to be of use when estimating the percentage of total energy lost to wind resistance over a driving cycle. This could be useful in vehicle design in order to determine how the greatest energy savings can be achieved and whether improving the aerodynamics of a vehicle should be the first design priority rather than improving drivetrain efficiency, reducing mass, or other considerations.

Keywords: BEV, HEV, energy consumption, modeling, simulation

1 Introduction

Recently, vehicle energy efficiency has become both a consumer demand and an environmental necessity with the advent of climate change. Government regulation is also leading vehicle manufacturers to improve efficiency and reduce fossil fuel consumption. Internal combustion vehicles are becoming more and more efficient due to in part to weight reduction, powertrain efficiency improvements, and more aerodynamic designs. The hybridization and electrification of transportation promise even greater energy consumption reductions and thus less greenhouse gas emissions. Hybrid electric vehicles (HEVs), including those simulated in this study, use electric motors and battery energy storage in addition to a conventional internal combustion engine (ICE) to recapture energy under braking and improve efficiency through use of the electric motor. Battery electric vehicles (BEVs) forgo the use of internal combustion entirely and use more powerful motors and larger energy storage systems (ESS) than HEVs in order to run entirely on electrical energy from the grid. The inherent efficiency of electric motors allows BEVs to be much more energy efficient than their gasoline counterparts, and battery storage has no emissions

at the vehicle level. Only upstream generation emissions are produced, which can be lower than internal combustion engine emissions depending on the energy generation type. Plug-in hybrid vehicles (PHEVs) use a combination of internal combustion and battery storage like HEVs but can be plugged in to recharge the battery, usually leading to an increased battery size and a larger all-electric range.

All vehicle powertrain systems must overcome several forces to propel the vehicle, namely aerodynamic drag, rolling resistance, and the force of gravity [1, 2]. The inertia of the vehicle must be overcome as well and varies depending on the vehicle's rate of acceleration. The force of gravity acts on the vehicle when climbing an incline, and pulls the vehicle forward when descending. This force is proportional to the vehicle's weight, as is the rolling resistance of the tires. The rolling resistance comes from the deformation of the vehicle's tires when moving. Additional resistance in the components of the drivetrain can be included and is sometimes lumped together with the rolling resistance. Aerodynamic drag is proportional to the square of the vehicle's speed.

Aerodynamic drag is the main focus of this paper, as it is an important determinant of electric vehicle range which is one of the main barriers to electric vehicle adoption in the minds of today's drivers. Vehicle range is more important in electric vehicles since it is often lower than the range of fossil fuel powered vehicles to begin with, and it takes longer to charge an electric vehicle's battery than to fill up a fuel tank. Reduced aerodynamic drag leads to increased vehicle range for any type of vehicle, but this may be the difference between a useful electric vehicle range and not being able to get where you need to go.

2 Background

2.1 Forces on a Road Vehicle

As previously mentioned, the main forces acting against the vehicle's tractive force (force provided by a gasoline engine or an electric motor) during driving are those of aerodynamic drag, rolling resistance from the tires, and the force of gravity when the road is inclined [1, 2]. Reducing the energy use of the vehicle is the main goal of many of these simulations and this can be achieved by either reducing the effect of these forces on the vehicle or by improving the efficiency of the drivetrain itself. Of particular interest in this research is the force of aerodynamic drag.

Aerodynamic drag consists of two components: shape drag and skin friction [1]. Shape drag is caused by the vehicle pushing against the air in front of it in order to move forward. The air must move out of the way and around the vehicle. In pushing the air in front, the vehicle creates a high pressure front region resisting its motion and a low pressure region in back, pulling it back as well. This drag is determined by the frontal area and overall shape of the vehicle. The skin friction is caused by the difference in velocity of the surrounding air to the air next to the vehicle. This difference in speed of the air molecules causes a friction that adds to the drag as well. The aerodynamic drag is quantified as a function of vehicle speed, frontal area, air density, and coefficient of drag, as shown in the equation

$$F_{AD} = \frac{\rho}{2} A_F C_D v^2 \quad (1)$$

where F_{AD} is the force of aerodynamic drag in N, ρ is the air density which in this paper is taken to be 1.2 kg/m^3 , A_F is the frontal area in m^2 , and C_D is the unitless coefficient of drag. Improvements in the vehicle's aerodynamics in terms of the frontal area and coefficient of drag can greatly reduce the effect of this force and lead to improved fuel consumption or energy efficiency. However, the effect of these improvements can vary greatly depending on the type of driving cycle since the cycle determines the vehicle speed, and quantifying this effect could be very useful in vehicle development.

Figure 1 shows the forces of aerodynamic drag, F_{AD} , rolling resistance, F_{RR} , and the component of gravity resisting motion acting on a vehicle climbing a hill with speed v . Note that rolling resistance is split between the two axles. Equation 2 shows the summation of these resistive forces acting on a moving vehicle:

$$F_R = F_{AD} + F_{RR} + F_{gxT} \quad (2)$$

where F_R is the total road load force, F_{AD} is the force of aerodynamic drag, F_{RR} is the tire rolling resistance, and F_{gxT} is the force of gravity. Expanding the terms of this equation, we get

$$F_R = \frac{\rho}{2} A_F C_D v^2 + mg \cos \beta [C_{rr0} + C_{rr1}v] + mg \sin \beta \quad (3)$$

where ρ is the density of air, A_F is the frontal area of the vehicle, C_D is the coefficient of drag of the vehicle, v is the vehicle speed, m is the vehicle mass, and g is the acceleration due to gravity ($9.81m/s^2$). β is the angle of the road, and C_{rr0} and C_{rr1} are the first and second coefficients of rolling resistance. If the vehicle is moving on flat ground, the cosine term becomes one and the third element of the summation is dropped due to the sine term becoming zero. The aerodynamic drag term in Equation 3 includes the velocity squared, which causes the velocity component of the total force to increase exponentially with speed by a factor of 2. There is also a linear velocity term in the rolling resistance force section. This is the formulation for rolling resistance used in the ADVISOR 2003 simulation program and therefore is used in this research. There are similar formulas that use a squared velocity term instead and have a different unit and value for C_{rr1} [2].

As shown in Fig. 2, the force of aerodynamic drag begins to dominate compared with the force of rolling resistance at high vehicle speeds since it is exponential while the other forces are either linear or constant. The diagram shows the force required to maintain cruising speeds for a Class 4 medium-duty vehicle from a constant speed of zero to just over 100 km/h.

Fig. 2 does not include a component of gravitational force or any force due to acceleration. When a steep grade or any acceleration is introduced, they will also contribute to the resistance. However, a study by the National Renewable Energy Laboratory (NREL) determined that the effect of grade on vehicle energy consumption is usually less than 3% [3]. All driving cycles used in this study include only flat ground.

2.2 Driving Cycles

Driving cycles are specific speed-time traces for test vehicles to follow. These repeatable cycles are used in the testing of vehicle fuel consumption and performance. For example, several test cycles are used in

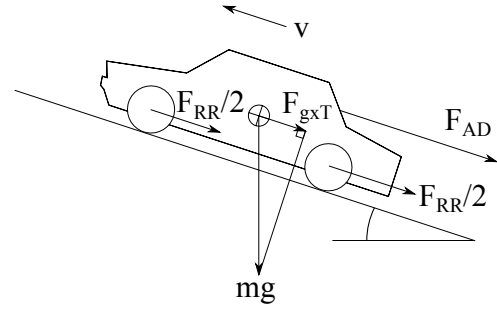


Figure 1: Diagram of the three main forces acting against the motion of a vehicle on an inclined roadway

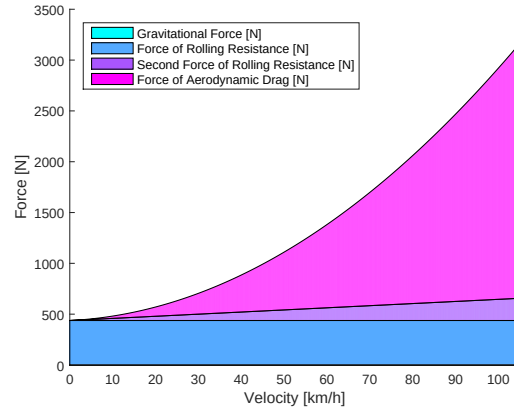


Figure 2: Forces on a vehicle on a flat road at constant speed

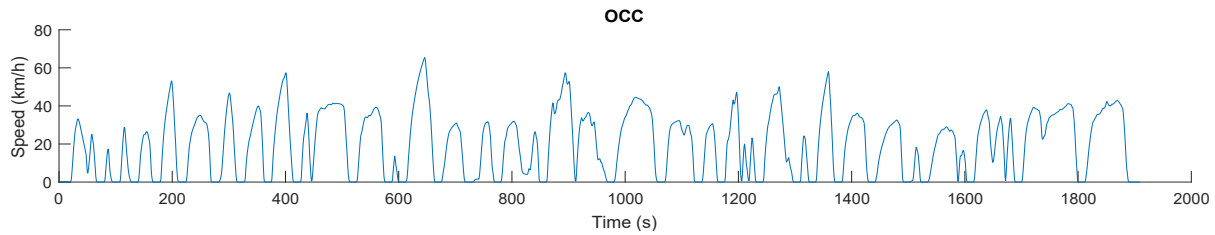


Figure 3: Orange County Cycle (OCC) driving cycle trace of speed over time

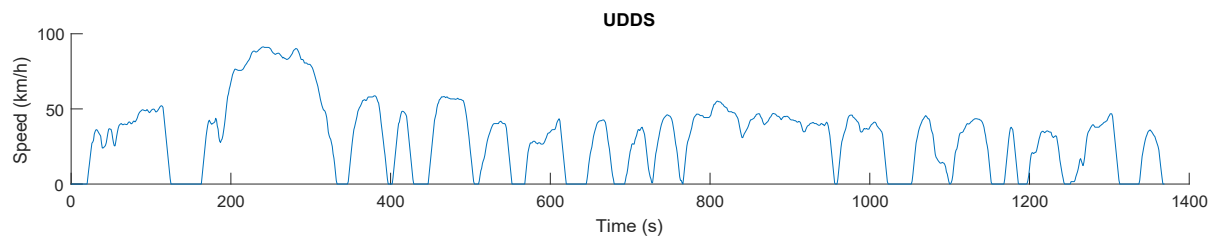


Figure 4: Urban Dynamometer Driving Schedule (UDDS) trace of speed over time

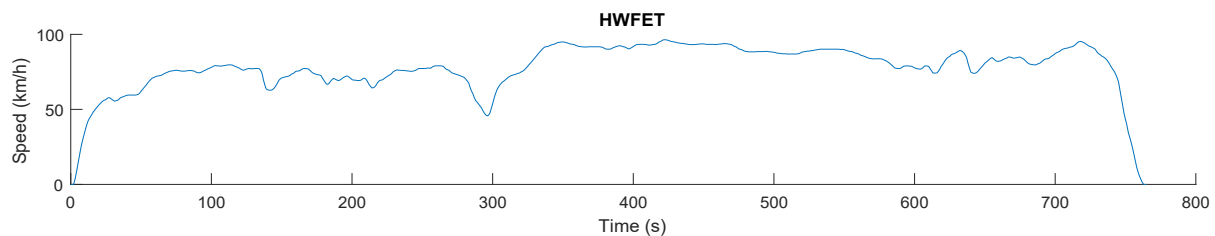


Figure 5: Highway Fuel Economy Test (HWFET) trace of speed over time

the window sticker fuel economy determination in North America, namely the UDDS, HWFET, SC03, and US06 cycles. Additional test cycles may be used for vehicles with a particular vocation, for example garbage collection or delivery vehicles usually make many stops and travel on mostly urban routes.

The energy usage simulation of vehicles in computer packages relies on the estimation of the forces acting on a vehicle during these standardized driving cycles. The Orange County Bus Cycle, is shown in Fig. 3. Standard driving cycles vary significantly in terms of average and maximum speed, as well as acceleration and deceleration rates, and number of start and stop events. These and other metrics can be used to classify driving cycles into groups and to determine which cycles are appropriate for use with certain types of vehicles. For example, the Urban Dynamometer Driving Cycle (UDDS), used for vehicle testing in North America, is considered a city cycle because of its low speed and frequent stops (Fig. 4). The OCC cycle mentioned above is also a city cycle but is specifically tailored to city bus operation. Alternatively, the Highway Fuel Economy Test (HWFET) cycle simulates highway driving as the name suggests (Fig. 5). The HWFET contains no intermediate stops and the driving speeds are much higher than in the OCC or UDDS cycles.

The quantification of driving cycles can be accomplished using a number of metrics that are calculated from the driving cycle speed traces. For example, the maximum speed, average speed, average and maximum acceleration and deceleration rates, GPS location, grade and elevation, and many more. Several of these metrics were chosen for this study based on their relevance to vehicle energy consumption. For instance, the average driving speed (average speed excluding idle time when the vehicle is stopped) is a relevant metric because the energy consumption is linked to vehicle velocity. However, the link may not be as direct as expected, and the same vehicle tested on cycles with the same average driving speed can obtain very different energy consumption results. For example, if one cycle has many stops, high acceleration rates, and a high top speed it could have the same average driving speed as a cycle with

less stops but a lower cruising speed. A vehicle would perform differently on these cycles and would be expected to use more energy on a cycle that includes higher top speeds and higher acceleration rates. Several cycle metrics are shown in Table 2 for various selected driving cycles. Further metrics such as the kinetic intensity can be calculated from the driving cycles using more complex formulas.

In order to study the effect of hybridization and electrification of transport, a metric called the kinetic intensity was developed by a team of researchers [4]. This metric is a combination of the other basic parameters of the cycle such as speed and acceleration as well as climbing grade at each point in time. Driving cycles can be classified based on kinetic intensity and, in general, slower speed cycles with more stop and higher acceleration rates will have a higher kinetic intensity value. The authors of the kinetic intensity study also state that vehicles which are used on higher kinetic intensity driving cycles are more suited to electrification and hybridization as they will achieve the most fuel economy and efficiency benefits [4]. In our research paper, the kinetic intensity is divided into its component parts in order to develop a metric that reflects the effect of aerodynamic drag in relation to vehicle energy consumption.

3 Method

3.1 Vehicle Simulation and Models

ADVISOR 2003 is a Matlab/Simulink modeling and simulation plugin developed by the United States National Renewable Energy Laboratory (NREL) [5, 6]. The package is used for the analysis of performance, fuel economy, and emissions of conventional, electric, hybrid electric, and fuel cell vehicles. ADVISOR was used for this study to determine the energy used by the vehicle during each driving cycle as well as the component of the energy due to aerodynamic drag.

The ADVISOR model setups used in this study use the default vehicle block diagrams for conventional and electric vehicles as well as a specific hybrid model developed by NREL (included in ADVISOR) for the Toyota Prius. The block diagram includes all the components for each vehicle as well as the mechanical links between them and a control strategy for the vehicles. The BEV block diagram is shown as an example in Fig. 6.

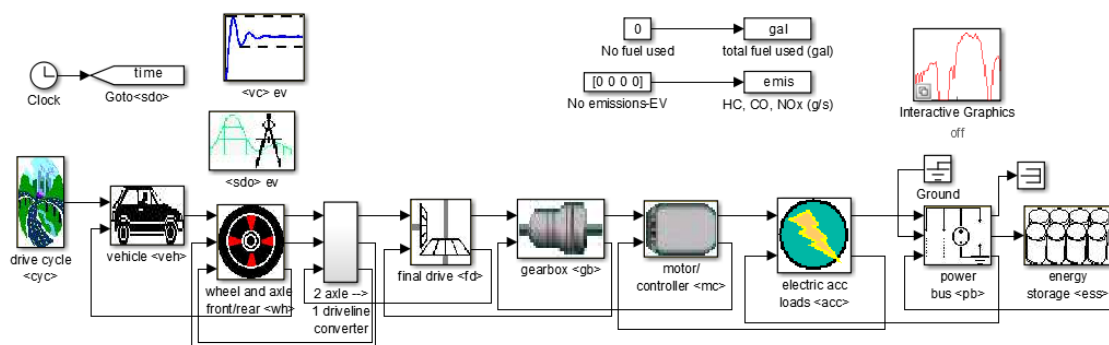


Figure 6: ADVISOR 2003 battery electric vehicle block diagram

Various vehicles were selected for this study in order to compare the aerodynamic coefficient with different vehicle types and sizes, including ICE vehicles, BEVs, and one HEV. The simulation vehicle parameters are shown in Table 1. The internal combustion vehicles are the "conventional defaults", "small car", "sport utility" and the "heavy truck" models that are included with ADVISOR.

The BEV models include the "EV defaults" and the "Purolator 2 1SPD BEV". The EV defaults model is a small electric passenger vehicle included with ADVISOR, while the Purolator 2 BEV is a model of a Class 4 delivery vehicle that was used in previous studies by the Automotive Partnerships Canada team at McGill University. These vehicles use single electric motors with a single-speed reduction gear to reduce speed and increase torque at the wheels. The motor model included with the Purolator 2 BEV is a permanent magnet synchronous motor created by the motor team at McGill. Additionally, a model of the 2013 Nissan Leaf was created using manufacturer data for this vehicle and was tested with and without regenerative braking active. The Leaf is also a BEV with a single-speed reduction gearbox and a permanent magnet electric motor.

The Prius HEV model was created by NREL and is included with ADVISOR. It models the workings of a 1997 Japanese version of the Prius, which includes two electric motors, a small gas engine, and a planetary gear set, along with complex controls in order to improve fuel economy when compared to a similarly sized conventional vehicle. Both the PARALLEL and SERIES HEV defaults vehicles are included in ADVISOR.

Table 1: Simulation Vehicle Parameters

Vehicle Type	Mass kg	C_D -	A_F m^2	r_{wheel} m	C_{rr0} -	C_{rr1} s/m
Heavy Truck	7373	0.700	8.55	0.500	9.38×10^{-3}	0
Small Car	1171	0.335	2.00	0.282	9.00×10^{-3}	0
Sport Utility	1924	0.440	2.66	0.343	1.20×10^{-2}	0
Series Defaults	1373	0.335	2.00	0.282	9.00×10^{-3}	0
Parallel Defaults	1350	0.335	2.00	0.282	9.00×10^{-3}	0
Nissan Leaf	1622	0.290	2.27	0.307	9.66×10^{-3}	7.56×10^{-5}
Purolator BEV	6373	0.700	7.02	0.393	7.00×10^{-3}	1.20×10^{-4}
EV Defaults	1144	0.335	2.00	0.282	9.00×10^{-3}	0
Conventional Defaults	984	0.335	2.00	0.282	9.00×10^{-3}	0
Prius Japan	1368	0.300	1.75	0.287	9.00×10^{-3}	0

3.2 Percentage Aerodynamic Energy

The percentage aerodynamic energy use ($E_{aero}\%$) was calculated for the comparison of different cycles and vehicles in this study. The $E_{aero}\%$ was simply defined as the ratio of aerodynamic energy loss over total energy use for the cycle, as shown in Equation 4.

$$E_{aero}\% = \frac{E_{aero}}{E_{used}} \cdot 100 = \frac{E_{aero}}{(E_{fuel} + E_{battery} - E_{regen})} \cdot 100 \quad (4)$$

Note that for an ICE vehicle, the battery energy and regen energy will be zero, whereas for a BEV the fuel energy will be zero. For the HEV in this test, the driving cycles were run with a zero-delta state of charge (SoC) requirement, meaning that the battery SoC at the end of the test had to be the same as the SoC at the beginning within a small tolerance band. This means that for the HEV, $E_{battery}$ was essentially equal to E_{regen} , removing those terms from the equation like for an ICE vehicle.

3.3 Driving Cycle Metrics

As previously mentioned, a driving cycle is a trace of the desired vehicle speed over time. This driving cycle is broken down into small steps by the simulation program. For example, all driving cycles were broken down into time steps of 0.25 seconds in this study. Therefore, when calculating some driving cycle metrics, a summation is required over each discrete point. This method is used in the calculation of metrics such as kinetic intensity. Kinetic intensity was created to analyze driving cycles with respect to their potential for energy savings when switching from conventional vehicles to hybrid or electric vehicles [4]. Based on the work of Michael O’Keefe et al who created the kinetic intensity factor [4] an aerodynamic component of the metric can be broken out. The component of the kinetic intensity which deals with aerodynamics and velocity is called the *aerodynamic speed*. Equation 5 shows the aerodynamic speed as it is used in the kinetic intensity formula [4]. The reason for the square in the aerodynamic speed is likely due to the fact that speed is squared in the vehicle forces equation, Equation 3.

$$v_{aero}^2 = \frac{\sum_{j=1}^{N-1} (v_{j+1}^3 + v_{j+1}^2 \cdot v_j + v_{j+1} \cdot v_j^2 + v_j^3) / 4 \cdot \Delta t_{j,j+1}}{D} \quad (5)$$

In this formula, v_{aero}^2 is the aerodynamic speed, v_j is the speed at the current time step, v_{j+1} is the speed at the next time step, $\Delta t_{j,j+1}$ is the time step, and D is the total distance of the cycle.

Table 2 shows basic and calculated cycle metrics for a few of the selected metrics for this study. A general overview of cycle types (city, highway, and mixed) is shown with several tested cycles omitted due to space constraints. The table contains the cycle name, the total running time of the cycle (including idle time), the distance completed when the cycle is followed exactly, and the average driving speed. Note that idle time is not included in the calculation of the average driving speed. The average acceleration rate is calculated for the time that the vehicle is accelerating, and the same is true for the average deceleration rate using the decelerations. The number of stops is shown but note that this is dependent on the length of the cycle as well as the type, so when comparing cycles it may be more relevant to divide this by the cycle distance to get the number of stops per km. The last three metrics in the table can be calculated based on the previously mentioned formulas. The aerodynamic speed, v_{aero} , is simply the square root of v_{aero}^2 .

4 Results

4.1 Percentage Aerodynamic Energy Results

In order to compare several cycle metrics, vehicle simulations were run for different vehicles over many driving cycles. The driving cycle metrics were calculated and the $E_{aero}\%$ was calculated for each of the tests as well. Table 1 lists the vehicles used in the testing along with their basic characteristics and Table 2 shows the cycles along their calculated cycle metrics. The cycles in Table 2 are organized by increasing v_{aero}^2 , which is loosely correlated with average driving speed as well. The cycles with low v_{aero}^2 tend to be city driving cycles and have the highest kinetic intensity. The cycles with the highest average speeds and highest v_{aero}^2 are highway cycles like the HWFET, REP05, and US06 cycles.

Fig. 7 shows the aerodynamic speed versus the characteristic acceleration and shows lines of constant kinetic intensity, similar to the map created in [4]. This map shows the spread of all the tested driving cycles in terms of these variables and also shows that a wide range of kinetic intensities were selected. Next, Fig. 8 plots the simulated $E_{aero}\%$ versus the kinetic intensity, revealing that the kinetic intensity

Table 2: Driving Cycle Metrics for Selected Cycles

Cycle	Time	Dist	Avg Spd	Avg Accel	Avg Decel	Stops	KI	v_{aero}^2
-	s	km	km/h	m/s ²	m/s ²	-	km ⁻¹	m ² /s ²
NYCC	598	1.9	16.8	0.62	-0.61	18	5.15	60
OCC	1909	10.5	24.7	0.45	-0.64	31	2.23	98
ECE	195	1.0	26.5	0.64	-0.75	3	1.45	100
1015	660	4.2	31.1	0.60	-0.67	7	0.98	168
HTUF4	3306	20.1	36.0	0.42	-0.48	27	0.75	186
UDDS	1369	12.0	38.3	0.50	-0.58	17	0.80	219
HTUF4S	1878	13.1	38.8	0.42	-0.48	15	0.62	223
SC03	600	5.8	42.3	0.50	-0.60	6	0.89	233
RUCSBC	1200	12.8	43.6	0.63	-0.74	12	0.96	255
UDDSHDV	1060	8.9	44.6	0.48	-0.58	14	0.38	361
NEDC	1184	10.9	43.7	0.54	-0.79	13	0.31	364
LA92	1435	15.8	46.7	0.67	-0.75	16	0.60	381
EUDC	400	7.0	69.5	0.38	-0.93	1	0.18	515
HWFET	765	16.5	78.1	0.19	-0.22	1	0.14	517
REP05	1400	32.3	85.3	0.44	-0.50	7	0.21	734
US06	600	12.9	82.7	0.67	-0.73	5	0.27	770

seems to be inversely proportional to the % aerodynamic energy for all the vehicles. The Prius has the lowest $E_{aero}\%$ for all cycles, which is unexpected since it is a vehicle designed to use less fuel than a conventional ICE vehicle. This would lead to the idea that it should have a high $E_{aero}\%$ since energy loss from other sources has been minimized. Perhaps the improved aerodynamics of this vehicle (which has a low C_D) means that the air resistance is lower than usual. The BEVs (Nissan Leaf, EV defaults, and Purotorator 2 BEV) have the highest $E_{aero}\%$. This is as expected because of the inherent efficiency of their drivetrains due to their use of electric motors, making aerodynamic drag one of the main contributors to energy use.

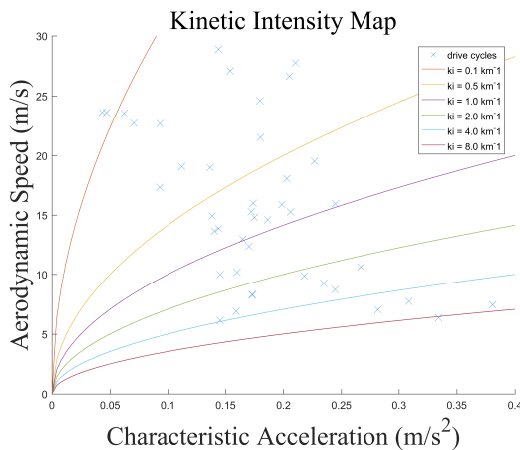


Figure 7: aerodynamic speed vs characteristic acceleration of all cycles, showing lines of constant KI

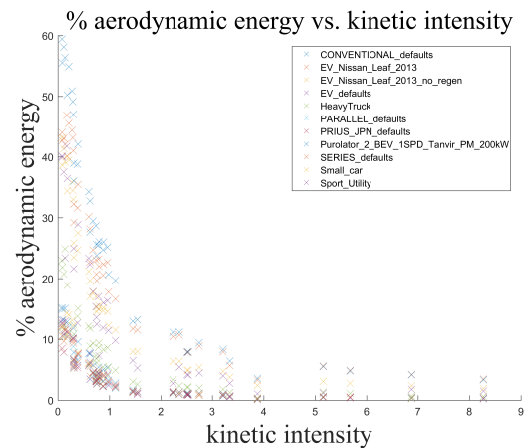
Figure 8: $E_{aero}\%$ versus kinetic intensity

Fig. 9 shows the $E_{aero}\%$ plotted against the average driving speed of all cycles. There is an obvious correlation between the driving speed and the aerodynamic energy percentage, however there is some variation between the results and they end up being dispersed in some cases. For example, at a similar

average driving speed, the $E_{aero}\%$ can vary significantly.

Fig. 10 show the $E_{aero}\%$ compared to the aerodynamic speed. Notice that using the aerodynamic speed rather than the average driving speed leads to a visible reduction in the variation for the $E_{aero}\%$. The points for each different vehicle appear to be more distinct within each particular vehicle.

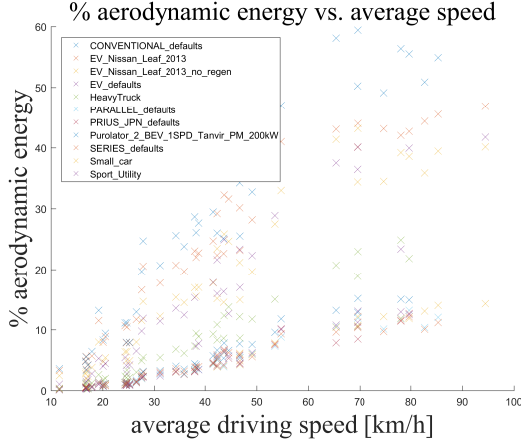


Figure 9: $E_{aero}\%$ versus average driving speed

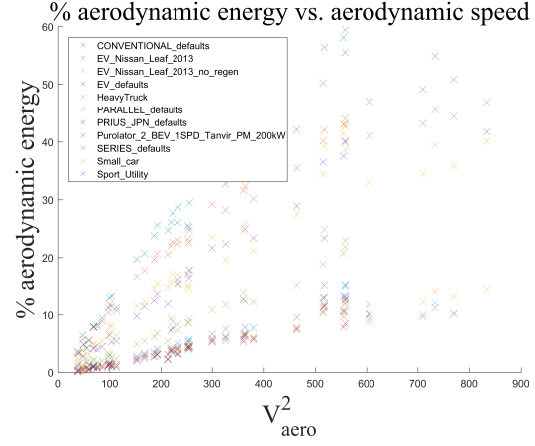


Figure 10: $E_{aero}\%$ versus aerodynamic speed

4.2 Normalization of Percentage Aerodynamic Energy

A further modification to these calculations and graphics is to normalize the $E_{aero}\%$ using some of the vehicle constants shown in Table 1. Since these constants are used in the calculation of aerodynamic energy use, normalizing the $E_{aero}\%$ by a combination of these constants could lead to a standardized relationship between aerodynamic speed and $E_{aero}\%$ for each of the different types of vehicle (ICE, HEV, BEV). The normalization used in this case is

$$E_{aero,norm}\% = \frac{E_{aero}\% \cdot m}{C_D \cdot A_F} \quad (6)$$

and the result of this is shown in Fig. 11. Note that the $E_{aero}\%$ normalized lines for each different type of vehicles begin to converge together, for example for the ICE vehicles. This relationship was investigated further by plotting only the points for each vehicle type and fitting a line of best fit in Figs. 12 to 14. The equations of the empirically determined lines of best fit for each type of vehicle are as follows:

$$E_{aero,norm,BEV}\% = 29810 \cdot x + 41990 \quad (7)$$

$$E_{aero,norm,HEV}\% = 8502 \cdot x + 9774 \quad (8)$$

$$E_{aero,norm,ICE}\% = 6030 \cdot x + 7257 \quad (9)$$

where

$$x = (v_{aero} - mean)/std \quad (10)$$

Note that the slope of the BEV line is much greater than either the HEV or ICE lines, meaning that BEVs will have a higher $E_{aero,norm}\%$ for the same cycle. This is as expected since the BEV will have less losses in the drivetrain. Also, the HEV $E_{aero,norm}\%$ has a higher slope than that of ICE vehicles. HEVs are designed to be more efficient than ICE vehicles and this confirms this fact. The mean and standard deviation for use with Equation 10 are included in Table 3 for each type of vehicle.

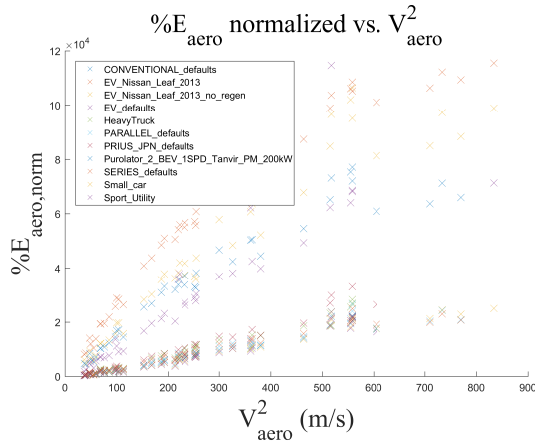


Figure 11: $E_{aero}\%$ normalized versus aerodynamic speed

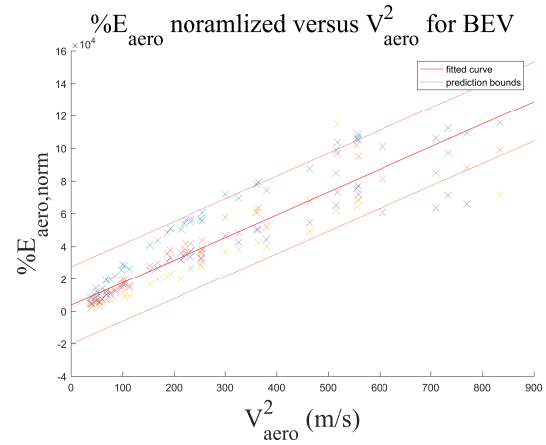


Figure 12: $E_{aero}\%$ normalized versus aerodynamic speed for BEVs

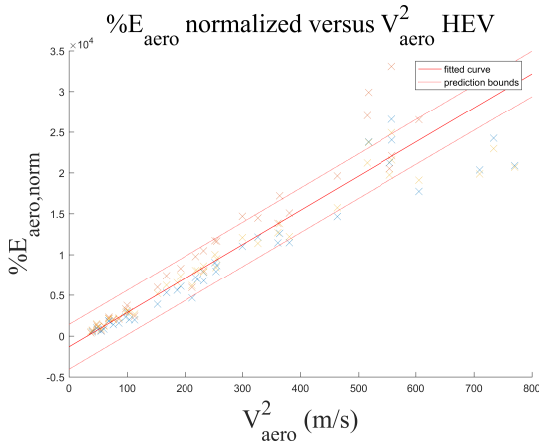


Figure 13: $E_{aero}\%$ normalized versus aerodynamic speed for HEV

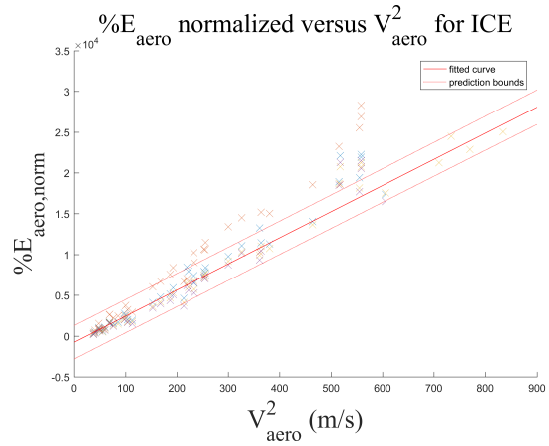


Figure 14: $E_{aero}\%$ normalized versus aerodynamic speed for ICE vehicles

4.3 Normalized Percentage Aerodynamic Energy Estimation Example

The equations of the lines of best fit for each graph of $E_{aero}\%$ normalized versus v_{aero}^2 can be used to approximate the $E_{aero}\%$ normalized for a vehicle of a specific vehicle type. For example, the aerodynamic speed can be calculated for a known cycle, then vehicle specifications can be used to determine the normalized percentage aerodynamic energy. Then, the $E_{aero}\%$ can be estimated using the vehicle constants as in the next section.

A numerical example is demonstrated here with a selected BEV, EV Passenger 1SPD. This vehicle has a mass of 1019 kg, a frontal area of 2.0 m², a coefficient of drag of 0.335, and a first coefficient of rolling resistance of 0.009. Using Equation 7 and the NEDC cycle v_{aero}^2 of 364, the $E_{aero,norm,BEV}\%$ was calculated as 54289. Then, inverting Equation 6 yields

$$E_{aero}\% = \frac{E_{aero,norm}\% \cdot C_D \cdot A_F}{m} = \frac{54289 \cdot 0.335 \cdot 2.0}{1019} = 35.7\% \quad (11)$$

Experimental results show that the $E_{aero}\%$ for this vehicle on this cycle is actually 27.0%, reinforcing that the calculated $E_{aero}\%$ of 35.7% is only an estimate.

Table 3: Mean and Standard Deviation for Calculation of x

Vehicle	Mean	Std
BEV	275.5	214.5
HEV	265.3	203.1
ICE	250.5	188.2

5 Conclusion

All driving cycle metrics showed a close relationship to the aerodynamic percentage contribution to energy losses. This should allow easy comparison between cycles to determine which ones have a high loss due to aerodynamics. Also, if a vehicle's driving cycle is known, the component of aerodynamic loss may be estimated based on vehicle type and class. For example, the Class 4 BEV type of vehicle has the highest $E_{aero}\%$. If the driving cycle has a high aerodynamic speed (over $200 \text{ m}^2/\text{s}^2$ for example), the $E_{aero}\%$ in the tests approached and even exceeded 30% of total losses. In this situation, aerodynamic improvement could lead to a significant reduction in energy use and an improvement in driving range.

Internal combustion vehicles of the same general size as their electric counterparts showed a much lower $E_{aero}\%$ for all driving cycles, due to the fact that much more losses were present in the driveline than in battery electric vehicles. In light of this consideration, it may be useful to remove the driveline losses in another comparison. Also, it can be said that driveline efficiency improvement may be of higher priority in conventional vehicles, for example by hybridizing or electrifying such vehicles, prior to improvements in aerodynamics.

Future areas of study for this topic include testing more vehicles and further normalizing the results to vehicle types such as BEV and ICE vehicles. Normalization of the aerodynamic speed was attempted based on the vehicle specifications such as the coefficient of drag, frontal area, and mass. This led to the convergence of the results into tighter bands with the BEV, HEV, and ICE vehicles grouped together. However, note that the experimental results and the estimates given from the normalized equations are not as precise as could be hoped, but may be adequate for determining where to focus energies when designing new energy efficient vehicles.

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