How do electric vehicles compare to conventional vehicles? How much more efficient are they compared to conventional and hybrid vehicles?

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1 Introduction

In today's world, the presence of Electric Vehicles (EVs) is increasingly significant, representing a transformative shift in the automotive industry and a critical step toward reducing global carbon emissions and achieving sustainability goals.

This project is not carried out for the purpose of deciding whether it is more sustainable or not to have an EV. Instead, it focuses on the physics behind the efficiency and work performed by Internal Combustion Engines (ICEs) vehicles, EVs and hybrids.

This project seeks to explore and quantify how electric vehicles compare to conventional and hybrid vehicles in terms of efficiency. Rather than addressing the broader question of overall sustainability, the focus lies in the physics of energy conversion and fuel consumption. To evaluate the performance of each drivetrain type under realistic conditions, two standardized drive cycles are used: the WLTC, representing everyday driving behavior, and the US06, which simulates more aggressive acceleration and higher speeds. In addition to differentiating vehicles by engine type (electric, combustion, or hybrid), the analysis also accounts for variations in body type and drivetrain configuration such as front-wheel drive (FWD), rear-wheel drive (RWD), and all-wheel drive (AWD). By examining how these factors influence vehicle behavior across different scenarios, the project aims to provide a clearer picture of their efficiencies and the key physical principles that drive them.

2 Theoretical Model

Mechanics is a discipline that analyzes and simplifies physical systems to solve a wide range of problems, from everyday challenges to complex engineering applications. Assumptions are not bad, but they have to be plausible!

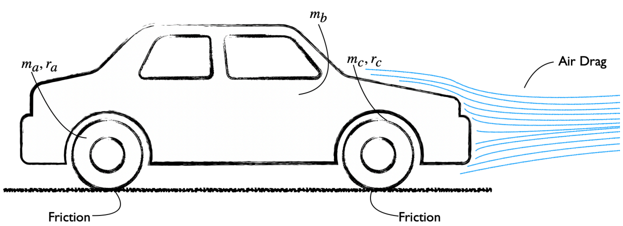

Figure 1: Simplified Car Dynamics Model with Resistive Forces

Figure 1 shows the system of a car ready to start the testing. There is the main body, two wheels (for now indexed as wheel a and c) and dissipative forces, i.e. the drag resistance and friction, slowing the vehicle down. We omit the spring and damper in the vehicle dynamics model, as we focus solely on longitudinal behavior and assume a rigid body.

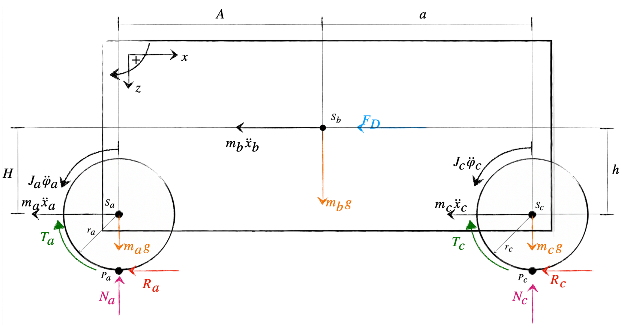

Figure 2: Forces Acting on the Vehicle (d'Alembert's Principle)

Figure 2 depicts a 2D model of a simplified car dynamics system. The objective is to derive a differential equation of motion for the vehicle, from which the Tractive Force can be expressed in the form of:

$$F(t) = A + B\dot{x} + C\dot{x}^2 + D\ddot{x}.$$

In this section, we focus on the most critical components contributing to the vehicle's motion: *Tractive Force*, *Rolling Resistance*, *Aerodynamic Drag* and *Types of Wheel Drives*. The complete derivation of the equations is included in 6 Appendix.

Tractive Force

The tractive force F_T is the force that propels a vehicle forward by generating motion at the tireground interface. It is related to the torque at the wheel T through:

$$T = F_T \cdot r,$$

where r is the effective rolling radius of the tire. This relation assumes an idealized system without drivetrain losses; efficiency factors and gear ratios are incorporated in later sections.

Rolling Resistance

The rolling resistance force R arises from the interaction between the tire and the ground, primarily due to the deformation of both the tire and the surface. When the engine applies torque to the wheels, resulting in a tractive force at the contact patch, rolling resistance is present. It is commonly modeled as

$$R = c_R N,$$

where c_R is the rolling resistance coefficient and N the normal force. For our analysis, we adopt the value for the coefficient of 0.12, as the findings of [8] indicated this value as the most recurrent for motor vehicles with pneumatic tires on asphalt/concrete surfaces.

$$c_R = 0.12$$

Aerodynamic Drag

The drag force air-resistance is given by:

$$F_D(v) = \frac{1}{2}\rho_a c_D A_F v^2,$$

where ρ_a is the specific air density, c_D is the drag coefficient, A_F is the effective frontal area A_F and v is the relative velocity. The Drag Coefficient c_D and Frontal Area A_F depend on the shape and aerodynamic properties of the vehicle.

The air density ρ_A depends on the ambient conditions and can be approximated by

$$\rho_a = \frac{0.0348p}{T},$$

where p is the atmosphere pressure and T - the temperature. For standard conditions ($p = 1$ bar and $T = 15°C = 288.15K$), this yields an air density of $1.225 kg/m^3$ [4, p. 135].

Since velocity is the time derivative of position, i.e. $v = \dot{x}$, the drag force can also be expressed as:

$$F_D = \frac{1}{2}\rho_a c_D A_F \dot{x}^2.$$

Wheel Drive Types

Vehicles can be equipped with either all-wheel drive (AWD) or two-wheel drive (TWD) systems, the latter being subdivided into front-wheel drive (FWD) and rear-wheel drive (RWD). Our model assumes an AWD configuration. Why is this important? Because the number and position of driven wheels directly influence the distribution of tractive force and frictional load across the tires.

In TWD systems, only two wheels receive torque. In FWD vehicles, the front tires are responsible for both steering and propulsion, which can lead to understeering behavior under heavy acceleration. In contrast, RWD vehicles transmit torque through the rear wheels, often offering better weight distribution during acceleration but less traction on slippery surfaces.

From a modeling perspective, non-driven wheels do not contribute to propulsion and thus experience no tractive friction. They primarily support the vehicle's weight and may generate rolling resistance. In AWD systems, torque is distributed across all wheels, which changes how forcesparticularly tractive and rolling resistancesare shared among the tires. This impacts the overall force balance and must be accounted for in the dynamics.

Differential Equation of Motion

Each of the AWD, RWD and FWD have different equations of motion.

Differential equation of motion for RWD vehicles:

$$F_{T,RWD} = \frac{5 \cdot \frac{2m_a + m_b}{2 + \frac{h}{a}c_R} c_R g}{2 + \frac{5c_R r_a}{2a + hc_R}} + \frac{3\rho_a c_D A_F}{4 + \frac{10c_R r_a}{2a + hc_R}}\dot{x}^2 + \frac{3m_b - 5 \cdot \frac{m_c + m_a}{2a + hc_R} c_R h}{2 + \frac{5c_R r_a}{2a + hc_R}}\ddot{x}$$

Differential equation of motion for FWD vehicles:

$$F_{T,FWD} = \frac{5 \cdot \frac{2m_c + m_b}{2 - \frac{h}{a}c_R} c_R g}{2 - \frac{5c_R r_c}{2a - hc_R}} + \frac{3\rho_a c_D A_F}{4 - \frac{10c_R r_c}{2a - hc_R}}\dot{x}^2 + \frac{3m_b + 5 \cdot \frac{m_c + m_a}{2a - hc_R} c_R h}{2 - 5 \cdot \frac{c_R r_c}{2a - hc_R}}\ddot{x}$$

Differential equation of motion for AWD vehicles:

$$F_{T,AWD} = \frac{5}{4}c_R mg + \frac{3}{8}\rho_a c_D A_F \dot{x}^2 + \frac{3}{4}m_b \ddot{x}$$

3 Data Preparation

We use the data from CarAPI, [2]. It contains respectable amount of data for conventional, electric and hybrid vehicles.

Vehicles Data

We begin by dividing the dataset into four subgroups: electric, hybrid, gasoline, and diesel vehicles. For each subgroup, we assign the necessary columns relevant to the vehicle type.

For conventional vehicles, the total range R is commonly used as an indicator of the vehicles current energy state. However, we require the fuel energy capacity of each vehicle. This can be calculated by multiplying the fuel tank volume by the respective energy density of the fuel. Specifically, gasoline (used in both gasoline-powered and hybrid vehicles) has an energy density of 33.526 MJ/L, while diesel has an energy density of 38.290 MJ/L. These values are sourced from the Bureau of Transportation Statistics [6].

$$\text{Fuel Energy} = \text{Tank Capacity} \times \text{Energy Density}$$

Before assigning vehicle names, we first allocate values for center of gravity height, hybrid battery capacity, drag coefficient and frontal area based on each vehicles body type. These reference values were provided by ChatGPT, s. [5], and tailored to each vehicle's body style and hybrid category. Using ChatGPT allowed us to distinguish more clearly between body types and provided a more reliable foundation than relying on arbitrary estimates. All units are converted to the SI system for consistency. Additionally, we include a column with the vehicle name, remove duplicate entries based on this name, rename and regroup the datasets.

Old Name	New Name	Symbol
'Body Curb Weight'	'M'	M
'Body Wheel Base'	'2a'	$2a$
'Drag Coefficient'	'c_D'	c_D
'Frontal Area'	'A_F'	A_F
'Height of Center of Gravity'	'CoG'	CoG
'Body Type'	'Body'	–
'Engine Type'	'Engine'	–
'Engine Drive Type'	'Drive'	–
'Fuel Energy'	'E_F'	E_f
'Mileage Battery Capacity Electric'	'E_b'	E_b

Table 1: Parameter Renaming and Symbol Definitions for Vehicle Dataset

The total vehicle mass is denoted as 'M', representing the sum of the masses of the front and rear tires and the bodywork.

$$M = m_a + m_b + m_c$$

The wheelbase is renamed to '2a', reflecting its definition as twice the distance a from the vehicles center to one axle, a. We then save each subgroup as a separate dataset.

This leaves us with 19 electric vehicles, 406 gasoline vehicles, 34 diesel vehicles, and 37 hybrid vehicles all of which are plug-in hybrids.

Drive Cycles

We load the WLTC and US06 drive cycles for further analysis. The WLTC (Worldwide harmonized Light vehicles Test Cycle) is designed to represent typical driving behavior across different regions globally, while the US06 cycle captures more aggressive driving patterns, including higher speeds and acceleration, and is used in U.S. emissions testing.

The data is processed by converting all values to SI units, ensuring that each cycle ends with zero velocity and zero acceleration. The total distance covered is calculated using the relation:

$$\frac{ds}{dt} = v \qquad \Rightarrow \qquad s = \int v dt$$

The visualizations of both cycles are shown below.

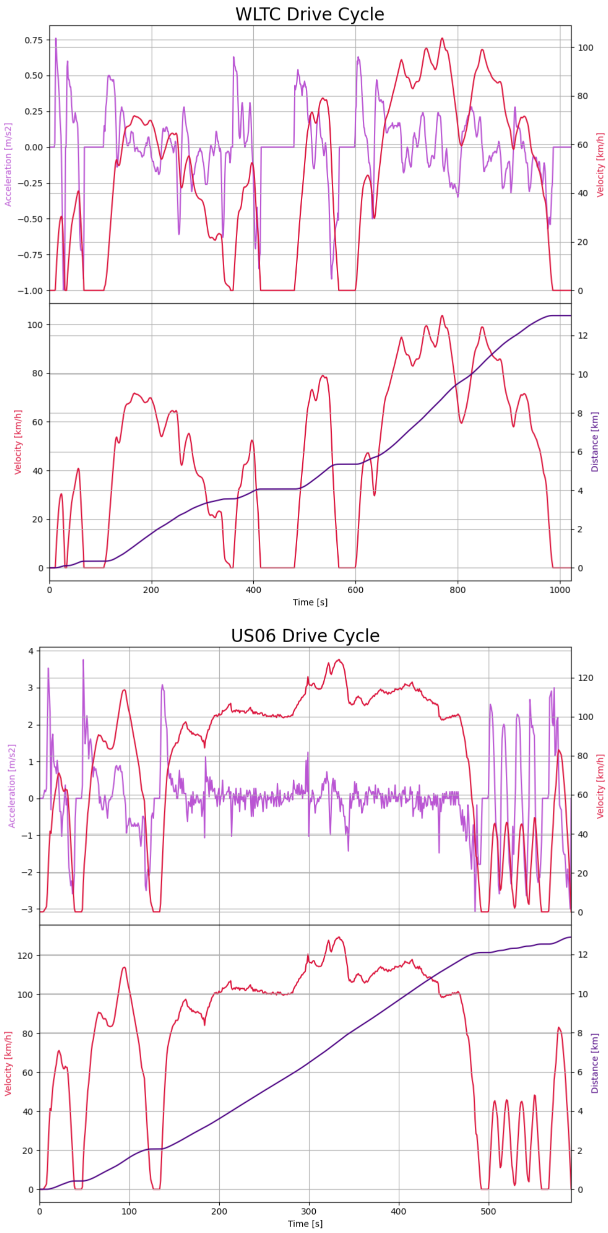

Figure 3: Acceleration, Velocity and Distance Profiles

The images above show the WLTC and US06 Drive

Cycles. As seen in the table below, WLTC reflects a calmer driving style compared to US06, with lower maximum velocity and acceleration, as well as a significantly lower average speed.

Physical Variable	WTLC	US06
Duration T	1022 s	592 s
Max. Acceleration	0.76 m/s^2	3.76 m/s^2
Max. Velocity	103.6 km/h	129.24 km/h
Avg. Velocity	45.82 km/h	78.23 km/h
Distance S	13.021 km	12.887 km

Table 2: Drive Cycles' Data

4 Modeling

Before moving on to the Modeling section, we first define the tire parameters. We assume both tires have an equal weight of 9 kg. The radius of the rear tire, denoted as a, is 0.33 m, and the radius of the front tire, denoted as c, is also 0.33 m. Using these values, we can calculate the height h. As previously mentioned, the values of H and h can be considered equal.

$$h = CoG - r_a \approx CoG - r_c = H$$

Since all of the variables are known, we can proceed to calculate the values of A, B, C and D (s. 2 Theoretical Model) for each drive type. In our model value B is negligible, as there's no corresponding values. This steams from the simplicity of the model.

Tractive Power & Power

The tractive force is the force produced by the vehicle's propulsion system to initiate and sustain its motion. Force, on its own, does not provide any meaningful information about the energy or work performed by the system. Hence, we need to introduce Tractive Power:

$$P_T(t) = F_T(t) \cdot \dot{x} = \left(A + B\dot{x} + C\dot{x}^2 + D\ddot{x}\right) \cdot \dot{x}.$$

The tractive power, just like the tractive force, only considers the power required to propel the vehicle forward, while other components need to be accounted for as well. P_{HVAC} represents the power consumed by the heating, ventilation, and air conditioning system, which we estimate to be around 1.5 kW. We assume

$$P(t) = \left(A + B\dot{x} + C\dot{x}^2 + D\ddot{x}\right) \cdot \dot{x} + P_{\text{HVAC}}$$

We assume the engine remains active during standby, so P_{HVAC} is included. The zero-velocity periods are too brief to suggest the vehicle is off. The figures below show the Tractive Force and Power profiles for each drive cycle.

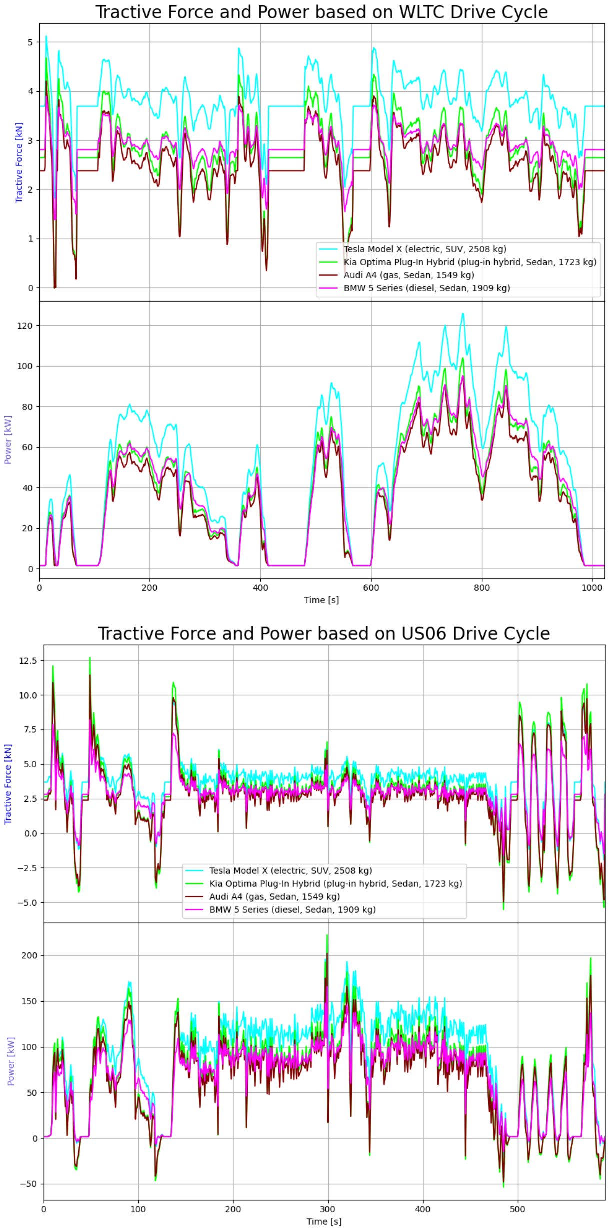

Figure 4: Tractive Force and Power Profiles

Efficiency & Energy

Energy losses due to friction and electrical components are inevitable, so we use efficiency ratios to quantify these losses. These ratios compare the actual state with the ideal state. Key efficiencies are:

$$\begin{aligned} \text{Regenerative Braking:} \quad & \eta_{\text{reg}} = \frac{P_{\text{reg}}}{P_{\text{brake}}} = \frac{P_{\text{reg}}}{P_T}, \\ \text{Powertrain:} \quad & \eta_{\text{pt}} = \frac{P}{P_{\text{motor}}} = \frac{P}{P_b}, \\ \text{Fuel-to-Wheel:} \quad & \eta_{\text{F-W}} = \frac{P_T}{P_{\text{F-W}}}. \end{aligned}$$

The Regenerative Braking Efficiency η_{reg} compares the power recovered during braking P_{reg} to the tractive power P_T, as the energy recovery occurs through the same propulsion system.

Powertrain efficiency η_{pt} compares the Total Power P to the power drawn from the battery P_b. It reflects the efficiency of components transmitting energy from the battery to the wheels, considering both propulsion and auxiliary systems. Hence, the total power P is used. Since P_{motor} equals P_b, both terms are interchangeable.

For many modeling purposes, tank-to-wheel efficiency is commonly approximated as a constant. However, this efficiency depends on a range of operational characteristics and is not inherently fixed. In this study, we adopt the value utility parameter $p = 0.2$, which represents the average proportion of the engines maximum work capacity utilized throughout the drive cycle. This value is derived from simulated data and taken from Figure 4 of the cited paper. Based on this, we assume fuel-to-wheel efficiencies of 27% for gasoline and 30% for diesel vehicles, and a powertrain efficiency of 75%. [3]

For the Mitsubishi i-MiEV, data has shown that the regenerative braking system (RBS) can recover up to 62% of the available kinetic energy under ideal conditions, such as at a speed of 120 km/h over a short interval. However, regenerative performance varies significantly depending on the drive cycle and vehicle settings. Based on typical cycle characteristics and findings from comparable studies, we assume a regenerative braking efficiency of 45% for the WLTC drive cycle, which includes a balanced mix of urban and highway segments, and 35% for the US06 drive cycle, which features more aggressive acceleration and braking. These values reflect realistic average efficiencies for electric vehicles operating under these respective conditions. [7, p. 1423]

The total power P can be divided into Motoring Power P_{motor}, which draws energy from the battery (P_b), and Braking Power P_{brake}. Braking occurs when acceleration and velocity are in opposite directions, while motoring occurs when they are in the same direction.

$$P(t) = \begin{cases} P_{motor}, & \dot{x} \cdot \ddot{x} \geq 0 \\ P_{brake}, & \dot{x} \cdot \ddot{x} < 0 \end{cases}$$

To propel the vehicle, motoring energy W_{motor} must be supplied. During braking, electric and hybrid vehicles recover energy W_{brake}, while conventional vehicles do not.

$$W_b = \int P_b dt = \int \frac{P}{\eta_{\text{pt}}} dt = \int P_{\text{motor}} dt = W_{\text{motor}}$$

$$W_{\text{reg}} = \int P_{\text{reg}} dt = \eta_{\text{reg}} \int P_T dt = \eta_{\text{reg}} W_{\text{brake}}$$

Hybrid Vehicles

Electric and conventional vehicles rely solely on electric motors and internal combustion engines, respectively. Hybrid vehiclesq, on the other hand, alternate between both power sources.

Hybrid vehicles typically use their electric motor during vehicle launch (below 16 km/h), light acceleration (assumed less than 2m/s^2), and regenerative braking (mild deceleration). The combustion engine engages at cruising speeds above 50 km/h, under strong acceleration, or when the batterys state of charge is low (below 20%). [1]

The algorithms developed to determine the engine mode condition and compute the energy consumption for hybrid vehicles are provided in 6 Appendix as Algorithm 1 and Algorithm 2, respectively.

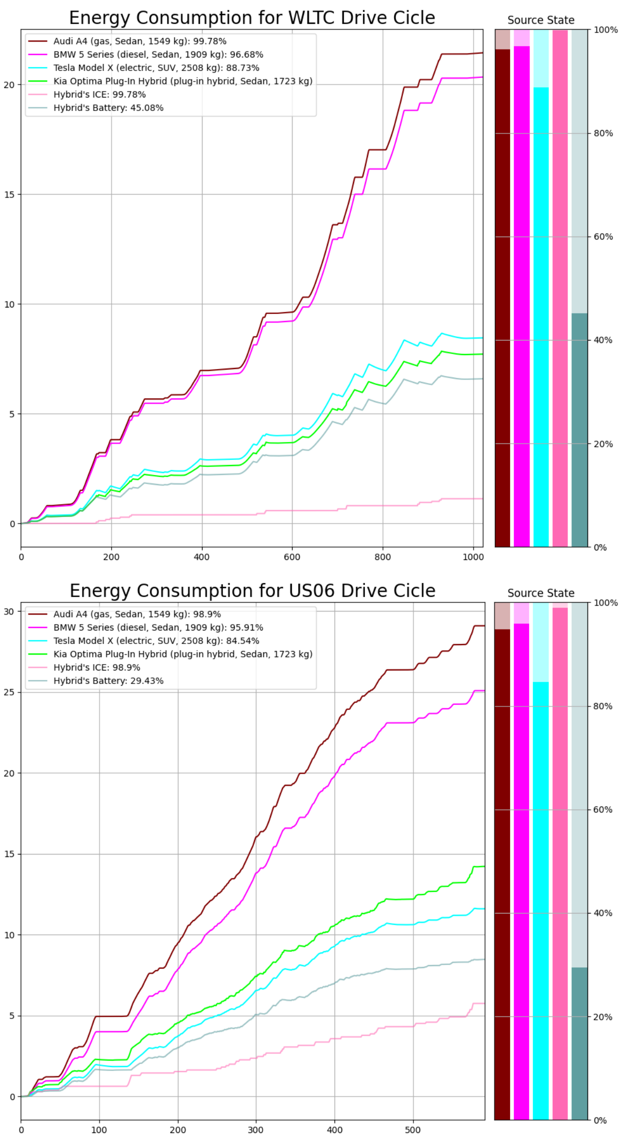

Figure 5: Energy Consumption Across Drive Cycles for Different Powertrains

Fuel Consumption

Fuel consumption refers to the amount of fuel a vehicle uses to travel a specific distance, commonly expressed in liters per 100 kilometers or miles per gallon. It reflects the vehicles energy efficiency and is influenced by factors such as driving behavior, engine type, vehicle load, and environmental conditions. To allow for consistent comparison across internal combustion engine vehicles, hybrids, and electric vehicles, all fuel consumption values in this study are converted and expressed in kilowatt-hours per kilometer (kWh/km).

$$FC = \frac{W_{\text{drive}}}{S} = \frac{P_{\text{drive}}}{\dot{x}}$$

Body	Hatchback	Hatchback	Hatchback	Hatchback	Sedan	Sedan	Sedan	Sedan
Engine	diesel	electric	gas	plug-in hybrid	diesel	electric	gas	plug-in hybrid
FC US06	1.917004	0.688301	1.964537	1.003624	2.005238	0.802561	2.228575	1.131156
FC WLTC	1.392743	0.426079	1.442597	0.507682	1.528688	0.518212	1.673927	0.586951

Body	Coupe	Coupe	Wagon	Wagon	Wagon	Wagon
Engine	gas	plug-in hybrid	diesel	electric	gas	plug-in hybrid
FC US06	2.108834	0.976307	1.965671	0.728156	2.208677	0.874123
FC WLTC	1.578243	0.530098	1.428193	0.447484	1.679698	0.489600

Body	SUV	SUV	SUV	SUV
Engine	diesel	electric	gas	plug-in hybrid
FC US06	2.150523	0.889010	2.442687	1.103319
FC WLTC	1.704287	0.566658	1.861112	0.607724

Figure 6: Fuel Consumption's Mean by Body and Engine Type

Figure 6 shows the average fuel consumption, categorized by body and engine type. For each entry, the fuel consumption is higher for the US06 drive cycle, which is consistent with its characteristic: higher average speeds result in greater fuel consumption, as visible in Table 2. What about overall representation?

Figure 7 presents the distribution of fuel consumption across all engine types, grouped by vehicle body type. This classification enables a more balanced comparison between vehicles with similar mass distribution and dynamic characteristics. Its worth noting that data is limited for certain body types, particularly Wagons and Coupes, which are represented by only a few samples or even just two vehicles.

Despite this, clear clustering patterns emerge within each body type based on engine type. Both drive cycles reveal consistently lower fuel consumption for hybrid and electric vehicles across all categories. Notably, none of the electric or hybrid vehicles exceed 1 kWh/km in the WLTC cycle. In contrast, conventional vehicles tend to cluster just below 2 kWh/km.

Under the demanding US06 drive cycle, the differences become even more pronounced. Fuel consumption for conventional SUVs and sedans peaks slightly above 3.5 kWh/km. In comparison, the highest-consuming hybrid remains below 1.5 kWh/km, while electric vehicles top out at just 1 kWh/km.

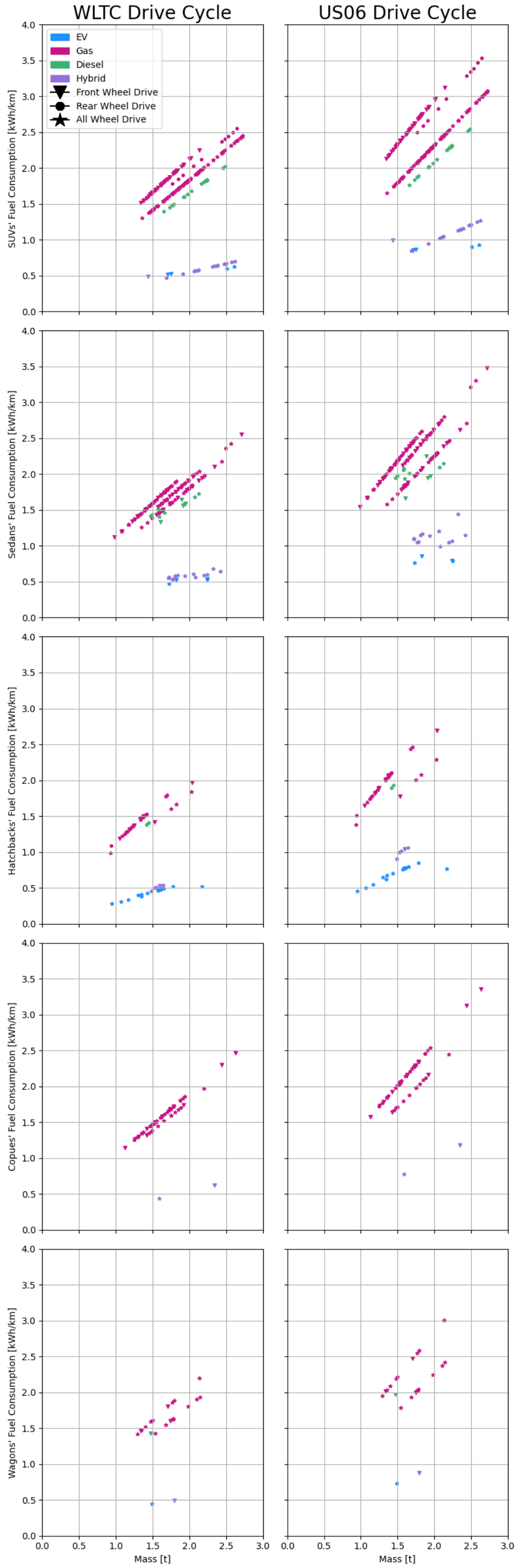

Figure 7: Fuel Consumption by vehicles

Let's compute the percentage difference between electric vehicles and the other engine types. We start by sorting the grouped values to identify the maximum and minimum fuel consumption within each category. Then, we calculate the relative efficiency gain of electric vehicles compared to the others. Figure 8 highlights the minimum and maximum fuel consumption values across all configurations, while Figure 9 illustrates how much lower the consumption of electric vehicles is compared to other engine types.

Body	Engine	FC US06	FC WLTC
Hatchback	diesel	1.899099	1.379371
Hatchback	electric	0.458338	0.279708
Hatchback	gas	1.376667	0.983681
Hatchback	plug-in hybrid	0.906684	0.457468
SUV	diesel	1.769217	1.397165
SUV	electric	0.853951	0.516230
SUV	gas	1.655217	1.302250
SUV	plug-in hybrid	0.850272	0.470778
Sedan	diesel	1.663093	1.334033
Sedan	electric	0.764011	0.470124
Sedan	gas	1.548527	1.119027
Sedan	plug-in hybrid	0.998311	0.532579
Wagon	diesel	1.965671	1.428193
Wagon	electric	0.728156	0.447484
Wagon	gas	1.786361	1.415156
Wagon	plug-in hybrid	0.874123	0.489600

Body	Engine	FC US06	FC WLTC
Hatchback	diesel	1.934909	1.406115
Hatchback	electric	0.847136	0.521464
Hatchback	gas	2.697094	1.965598
Hatchback	plug-in hybrid	1.064043	0.538655
SUV	diesel	2.543440	2.020762
SUV	electric	0.933256	0.623623
SUV	gas	3.539450	2.555588
SUV	plug-in hybrid	1.267633	0.702506
Sedan	diesel	2.253545	1.725283
Sedan	electric	0.861325	0.536218
Sedan	gas	3.477235	2.550135
Sedan	plug-in hybrid	1.445457	0.682728
Wagon	diesel	1.965671	1.428193
Wagon	electric	0.728156	0.447484
Wagon	gas	3.007202	2.199900
Wagon	plug-in hybrid	0.874123	0.489600

Figure 8: Minimum (left) and Maximum (right) Values of Fuel Consumption grouped by Body and Engine Type

The percentage gain has been calculated by using the following formula:

$$\text{Gain} = \frac{\text{FC}_{\text{other}} - \text{FC}_{\text{EV}}}{\text{FC}_{\text{other}}} \cdot 100\%$$

	Body	Engine	WLTC %	US06 %
0	Hatchback	diesel	79.72	75.87
1	Hatchback	gas	71.57	66.71
2	Hatchback	plug-in hybrid	38.86	49.45
3	SUV	diesel	63.05	51.73
4	SUV	gas	60.36	48.41
5	SUV	plug-in hybrid	-9.65	-0.43
6	Sedan	diesel	64.76	54.06
7	Sedan	gas	57.99	50.66
8	Sedan	plug-in hybrid	11.73	23.47
9	Wagon	diesel	68.67	62.96
10	Wagon	gas	68.38	59.24
11	Wagon	plug-in hybrid	8.60	16.70

	Body	Engine	WLTC %	US06 %
0	Hatchback	diesel	62.91	56.22
1	Hatchback	gas	73.47	68.59
2	Hatchback	plug-in hybrid	3.19	20.39
3	SUV	diesel	69.14	63.31
4	SUV	gas	75.60	73.63
5	SUV	plug-in hybrid	11.23	26.38
6	Sedan	diesel	68.92	61.78
7	Sedan	gas	78.97	75.23
8	Sedan	plug-in hybrid	21.46	40.41
9	Wagon	diesel	68.67	62.96
10	Wagon	gas	79.66	75.79
11	Wagon	plug-in hybrid	8.60	16.70

Figure 9: Minimum (left) and Maximum (right) Percentage Gain of Fuel Consumption grouped by Body and Engine Type

As shown in Figure 9, electric vehicles are approximately 63.01% to 77.63% more efficient than diesel-powered vehicles, and 57.99% to 79.66% more efficient than gasoline-powered vehicles in the WLTC cycle. For hybrid vehicles, the maximum efficiency gain compared to EVs reaches 32.54%, while the lowest value is -9.65%indicating that one hybrid vehicle is actually 9.65% more efficient than its electric counterpart under the WLTC cycle.

Electric vehicles are approximately 51.73% to 73.40% more efficient than diesel-powered vehicles, and 48.41% to 75.79% more efficient than gasoline-powered vehicles under the US06 drive cycle. In comparison, hybrid vehicles show a maximum efficiency gain of 44.29% relative to EVs, while the minimum value is -0.43% - indicating that one hybrid vehicle is slightly more efficient than an electric vehicle in this particular cycle.

5 Conclusion

The analysis highlights clear distinctions in fuel consumption across different engine, body and drive types, particularly under varying drive cycle conditions. Grouping vehicles by body type allowed for more equitable comparisons by accounting for differences in mass and dynamics.

Hybrid and electric vehicles consistently demonstrate superior efficiency, with none exceeding 1 kWh/km under the WLTC cycle, and maintaining significant advantages even under the more demanding US06 cycle. In contrast, conventional vehicles not only consume more energy on average but also exhibit greater variability, especially in high-load conditions. These findings underscore the fuel efficiency benefits of electrified powertrains and their potential for reducing energy consumption across a wide range of vehicle classes.

Additionally, Figure 7 offers valuable insight into how drivetrain configuration influences vehicle behavior and efficiency. It becomes evident that front-wheel-drive vehicles typically require more energy to operate compared to rear-wheel and especially all-wheel-drive configurations. Vehicles with rear or all-wheel drive appear to hold an advantage in both efficiency and dynamic performance, highlighting the significant role of drivetrain layout in overall energy consumption.

Across all body types and drivetrain configurations, electric vehicles consistently demonstrate superior efficiency compared to conventional vehicles. Their higher energy conversion rates and minimal heat lossesunlike internal combustion enginesgrant them a clear advantage. However, their main limitations remain battery storage capacity and charging infrastructure.

Hybrid vehicles emerge as a compelling middle ground. They offer notable efficiency improvements over gasoline and diesel engines while enabling longer driving ranges. Its important to note, however, that our analysis is based on energy consumption over a single drive cycle. Over extended periods-particularly after the hybrid battery is depleted-fuel consumption may rise to levels comparable to conventional vehicles.

In the WLTC cycle, electric vehicles were between 9.65% less efficient and 32.54% more efficient than hybrid vehicles, showing that under calm driving conditions, some hybrids can nearly match or even slightly outperform EVs in isolated cases. In contrast, under the more aggressive US06 drive cycle, the gap widened considerably, with EVs showing up to 44.29% greater efficiency compared to hybrids. The lowest value was -0.43%, a very marginal advantage for the hybrid vehicle. This highlights how hybrid performance tends to degrade more under demanding conditions, where electric drivetrains maintain a stronger advantage.

Looking ahead, the key challenge will be improving battery storage and charging solutions for electric vehicles, while continuing to explore and invest in hybrid technologies. Perhaps the optimal solution lies somewhere in between-balancing the strengths of both electric and hybrid systems.

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6 Appendix

Derivation of Differential Equation of Motion

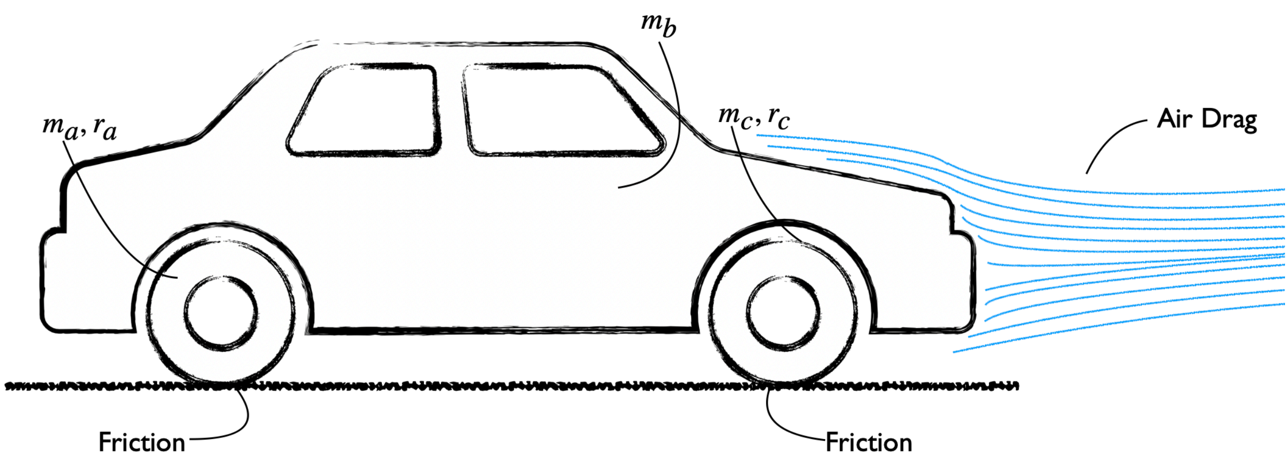

Figure 10: Simplified Car Dynamics Model with Resistive Forces

We will now cut the bodies free according to d'Alembert's principle. We do so to establish the motion equation for the whole system by balancing the forces. If done correctly every force should account to the motion differential equation.

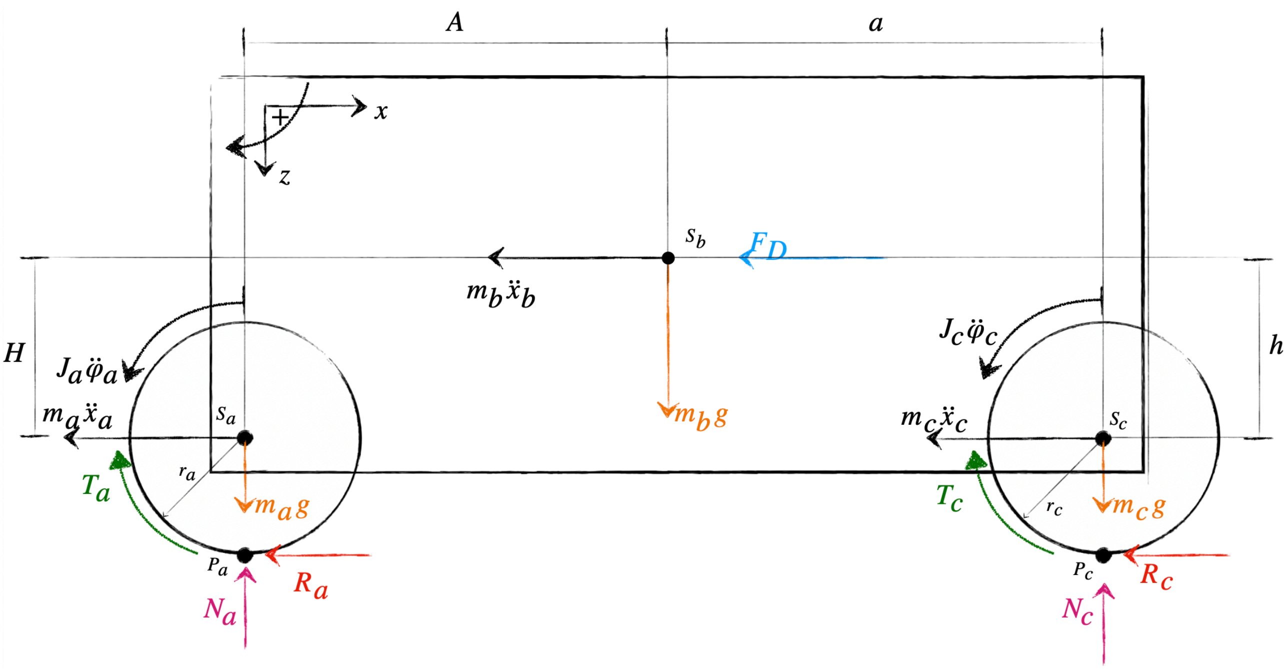

Figure 11: Forces Acting on the Vehicle (d'Alembert's Principle)

Before proceeding further, we should examine the car's kinematics. The wheels and the body are interconnected, meaning they move together as a single system. As a result, they share the same translation vector x with different reference points i.e. $x = x_a = x_b = x_c$. We assume to slip-condition, hence all derivatives of x (e.g., velocity and acceleration) are identical for the wheels and the body. Thus the velocity and accleration of the wheels can be simplified to: $\dot{x} = \dot{\varphi}_a r_a = \dot{\varphi}_c r_c$ and $\ddot{x} = \ddot{\varphi}_a r_a = \ddot{\varphi}_c r_c$.

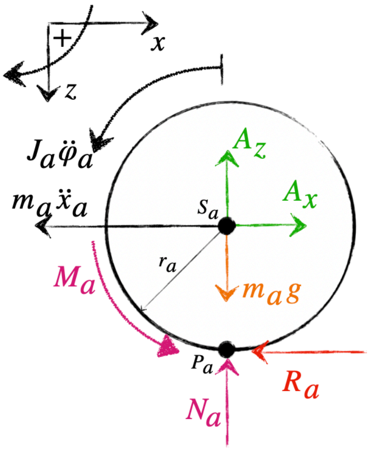

Figure 12: Rear Wheel a

$$\sum F_x : \qquad A_x = m_a\ddot{x} + R_a \tag{1}$$

$$\sum F_z : \qquad A_z = m_a g - N_a \tag{2}$$

$$\sum M^{(P_a)} : \qquad J_a^{P_a}\ddot{\varphi}_a = [A_x - m_a\ddot{x}_a]\, r_a - T_a$$

$$\frac{3}{2} m_a\ddot{x}_a = (A_x - m_a\ddot{x}_a) r_a - T_a \tag{3}$$

With (1) in (3) follows:

$$\frac{2}{3}\left(R_a - \frac{T_a}{r_a}\right) = m_a r_a \ddot{\varphi}_a = m_a\ddot{x} \tag{4}$$

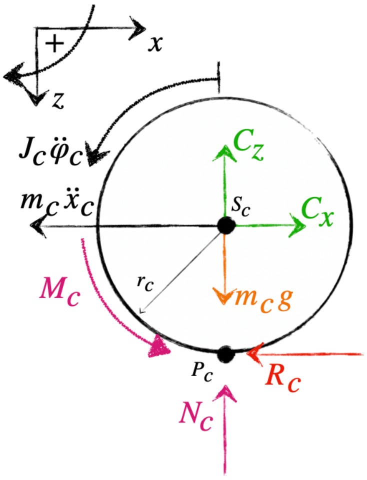

Figure 13: Front Wheel c

$$\sum F_x : \qquad C_x = m_c\ddot{x} + R_c \tag{5}$$

$$\sum F_z : \qquad C_z = m_c g - N_c \tag{6}$$

$$\sum M^{(P_c)} : \qquad J_c^{P_c}\ddot{\varphi}_c = [C_x - m_c\ddot{x}_c]\, r_c - T_c$$

$$\frac{3}{2} m_c\ddot{x}_c = (C_x - m_c\ddot{x}_c) r_c - T_c \tag{7}$$

With (5) in (7) follows:

$$\frac{2}{3}\left(R_c - \frac{T_c}{r_c}\right) = m_c r_c \ddot{\varphi}_c = m_c\ddot{x} \tag{8}$$

Bodywork:

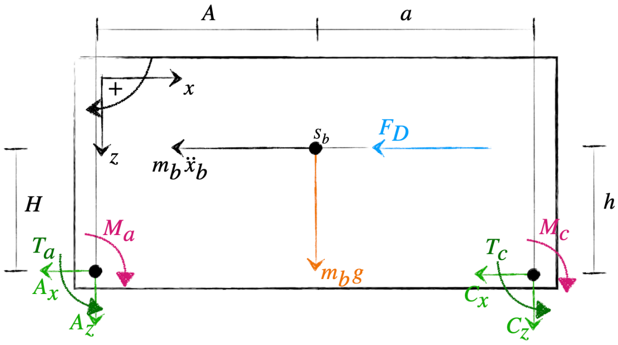

Figure 14: Bodywork

$$\sum F_x : \qquad m_b\ddot{x} = -A_x - C_x - F_D \tag{9}$$

$$\sum F_z : \qquad m_b g + A_Z + C_z = 0 \tag{10}$$

(1), (5), (2) and (6) into (9) and (10):

$$(m_a + m_b + m_c)\,\ddot{x} = -R_a - R_c - F_D \tag{11}$$

$$\underbrace{(m_a + m_b + m_c)}_{=m} g = mg = N_a + N_c \tag{12}$$

(4), (8) into (11):

$$m_b\ddot{x} = -\frac{5}{3}\,(R_a + R_c) + \frac{2}{3}\left(\frac{T_a}{r_a} + \frac{T_c}{r_c}\right) - F_D \tag{13}$$

$$\sum M^{(S_b)} : \qquad C_x h + A_x H + C_z a + T_a + T_c - A_z a = 0 \tag{14}$$

(1), (5), (2) and (6) into (14):

$$h(m_c\ddot{x} + R_c) + H(m_a\ddot{x} + R_a) + (m_c g - N_c)a - (m_a g - N_a)a + T_a + T_c = 0 \tag{15}$$

We will assume that the distance from the center of mass is equal and the difference in heights are negligible, hence $A = a$ and $H \approx h$. The eq. (15) takes the form:

$$N_c - N_a - \frac{h}{a}(R_a + R_c) = (m_a - m_c)g + \frac{T_a + T_c}{a} + \frac{h}{a}(m_c + m_a)\ddot{x} \tag{16}$$

The tractive force F_T is the force that propels a vehicle forward by generating motion at the tireground interface. It is related to the torque at the wheel T through:

$$T = F_T \cdot r,$$

where r is the effective rolling radius of the tire. This relation assumes an idealized system without drivetrain losses; efficiency factors and gear ratios are incorporated in later sections.

$$N_c - N_a - \frac{h}{a}(R_a + R_c) = (m_a - m_c)g + \frac{F_T r_a + F_T r_c}{a} + \frac{h}{a}(m_c + m_a)\ddot{x} \tag{17}$$

The rolling resistance force R arises from the interaction between the tire and the ground, primarily due to the deformation of both the tire and the surface. When the engine applies torque to the wheels, resulting in a tractive force at the contact patch, rolling resistance is present. It is commonly modeled as

$$R = c_R N,$$

where c_R is the rolling resistance coefficient and N the normal force. For our analysis, we adopt the value for the coefficient of 0.12, as the findings of [8] indicated this value as the most recurrent for motor vehicles with pneumatic tires on asphalt/concrete surfaces.

$$c_R = 0.12$$

The drag force air-resistance is given by:

$$F_D(v) = \frac{1}{2}\rho_a c_D A_F v^2,$$

where ρ_a is the specific air density, c_D is the drag coefficient, A_F is the effective frontal area A_F and v is the relative velocity. The Drag Coefficient c_D depends on the shape of and aerodynamic properties of the vehicle. A typical value for the frontal area A_F is approximately 2m^2.

The air density ρ_A depends on the ambient conditions and can be approximated by

$$\rho_a = \frac{0.0348p}{T},$$

where p is the atmosphere pressure and T - the temperature. For standard conditions ($p = 1$ bar and $T = 15°C = 288.15K$), this yields an air density of $1.225kg/m^3$ [4, p. 135].

Since velocity is the time derivative of position, i.e. $v = \dot{x}$, the drag force can also be expressed as:

$$F_D = \frac{1}{2}\rho_a c_D A_F \dot{x}^2.$$

Vehicles can be equipped with either all-wheel drive (AWD) or two-wheel drive (TWD) systems, the latter being subdivided into front-wheel drive (FWD) and rear-wheel drive (RWD). Our model assumes an AWD configuration. Why is this important? Because the number and position of driven wheels directly influence the distribution of tractive force and frictional load across the tires.

In TWD systems, only two wheels receive torque. In FWD vehicles, the front tires are responsible for both steering and propulsion, which can lead to understeering behavior under heavy acceleration. In contrast, RWD vehicles transmit torque through the rear wheels, often offering better weight distribution during acceleration but less traction on slippery surfaces.

From a modeling perspective, non-driven wheels do not contribute to propulsion and thus experience no tractive friction. They primarily support the vehicle's weight and may generate rolling resistance. In AWD systems, torque is distributed across all wheels, which changes how forcesparticularly tractive and rolling resistancesare shared among the tires. This impacts the overall force balance and must be accounted for in the dynamics.

We proceed to the distinction between them using the eq. (12) and (17).

1. RWD: $R_c, W_c, M_c = 0$ and $R_a = c_R N_a$

$$\begin{aligned} N_c &= mg - N_a \\ N_a &= \frac{(2m_a + m_b)g - \frac{F_T r_a}{a} - (m_c + m_a)\frac{h}{a}\ddot{x}}{2 + \frac{h}{a}c_R} \end{aligned} \tag{18}$$

2. FWD: $R_a, m_a, W_a = 0$ and $R_c = c_R N_c$

$$\begin{aligned} N_a &= mg - N_c \\ N_c &= \frac{(2m_a + m_b)g + \frac{F_T r_c}{a} + (m_c + m_a)\frac{h}{a}\ddot{x}}{2 - \frac{h}{a}c_R} \end{aligned} \tag{19}$$

3. AWD: $R_a = c_R N_a$ and $R_c = c_R N_c$

$$N_a + N_c = mg \tag{20}$$

The differential equation of motion for each Drive type takes up the following forms:
Rear-Wheel Drive:

$$\left(m_b - \frac{5}{3}\cdot\frac{m_c + m_a}{2a + hc_R}c_R h\right)\ddot{x} = -\frac{5}{3}\cdot\frac{2m_a + m_b}{2 + \frac{h}{a}c_R}c_R g + \left(\frac{2}{3} + \frac{5}{3}\cdot\frac{c_R r_a}{2a + hc_R}\right)F_T - \frac{1}{2}\rho_a c_D A_F \dot{x}^2 \tag{21}$$

Front-Wheel Drive:

$$\left(m_b + \frac{5}{3}\cdot\frac{m_c + m_a}{2a - hc_R}c_R h\right)\ddot{x} = -\frac{5}{3}\cdot\frac{2m_c + m_b}{2 - \frac{h}{a}c_R}c_R g + \left(\frac{2}{3} - \frac{5}{3}\cdot\frac{c_R r_c}{2a - hc_R}\right)F_T - \frac{1}{2}\rho_a c_D A_F \dot{x}^2 \tag{22}$$

All-Wheel Drive:

$$m_b\ddot{x} = -\frac{5}{3}c_R mg + \frac{4}{3}F_T - \frac{1}{2}\rho_a c_D A_F \dot{x}^2 \tag{23}$$

$$\begin{aligned} F_{T,RWD} &= \frac{\frac{5}{3}\cdot\frac{2m_a+m_b}{2+\frac{h}{a}c_R}c_R g + \frac{1}{2}\rho_a c_D A_F \dot{x}^2 + \left(m_b - \frac{5}{3}\cdot\frac{m_c+m_a}{2a+hc_R}c_R h\right)\ddot{x}}{\frac{2}{3} + \frac{5}{3}\cdot\frac{c_R r_a}{2a+hc_R}} \\ F_{T,FWD} &= \frac{\frac{5}{3}\cdot\frac{2m_c+m_b}{2-\frac{h}{a}c_R}c_R g + \frac{1}{2}\rho_a c_D A_F \dot{x}^2 + \left(m_b + \frac{5}{3}\cdot\frac{m_c+m_a}{2a-hc_R}c_R h\right)\ddot{x}}{\frac{2}{3} - \frac{5}{3}\cdot\frac{c_R r_c}{2a-hc_R}} \\ F_{T,AWD} &= \frac{3}{4}\left(\frac{5}{3}c_R mg + \frac{1}{2}\rho_a c_D A_F \dot{x}^2 + m_b\ddot{x}\right) \end{aligned}$$

Now we express the Forces as in the form of $F(t) = A + B\dot{x} + C\dot{x}^2 + D\ddot{x}$:

$$\begin{aligned} F_{T,RWD} &= \frac{5\cdot\frac{2m_a+m_b}{2+\frac{h}{a}c_R}c_R g}{2 + \frac{5c_R r_a}{2a+hc_R}} + \frac{3\rho_a c_D A_F}{4 + \frac{10c_R r_a}{2a+hc_R}}\dot{x}^2 + \frac{3m_b - 5\cdot\frac{m_c+m_a}{2a+hc_R}c_R h}{2 + \frac{5c_R r_a}{2a+hc_R}}\ddot{x} \\ F_{T,FWD} &= \frac{5\cdot\frac{2m_c+m_b}{2-\frac{h}{a}c_R}c_R g}{2 - \frac{5c_R r_c}{2a-hc_R}} + \frac{3\rho_a c_D A_F}{4 - \frac{10c_R r_c}{2a-hc_R}}\dot{x}^2 + \frac{3m_b + 5\cdot\frac{m_c+m_a}{2a-hc_R}c_R h}{2 - 5\cdot\frac{c_R r_c}{2a-hc_R}}\ddot{x} \\ F_{T,AWD} &= \frac{5}{4}c_R mg + \frac{3}{8}\rho_a c_D A_F \dot{x}^2 + \frac{3}{4}m_b\ddot{x} \end{aligned}$$

Algorithms

Algorithm 1 Engine Mode Determination for Hybrid Vehicles

Require: Acceleration array a, velocity array v
Ensure: Condition array *cond*, where 1: electric engine, -1: combustion engine
for $i = 0$ to $n-1$ **do**
  if $v[i] \cdot 3.6 < 16$ **then**
    $cond[i] \leftarrow 1$
  else if $a[i] < 2$ **then**
    $cond[i] \leftarrow 1$
  else if $a[i] = 0$ **and** $v[i] \cdot 3.6 \leq 50$ **then**
    $cond[i] \leftarrow 1$
  else if $a[i] \cdot v[i] < 0$ **then**
    $cond[i] \leftarrow 1$
  else
    $cond[i] \leftarrow -1$
  end if
end for
return *cond*

Algorithm 2 Hybrid Vehicle Energy Calculation

Require: Time vector t, velocity v, acceleration a, power demand P, total power P_T
Require: Battery capacity E_b, minimum State of Charge SoC, efficiencies $\eta_{\text{pt}}, \eta_{\text{gas}}, \eta_{\text{reg}}$
Ensure: Total energy W, combustion engine energy W_{comb}, battery energy W_{bat}
Compute $\Delta t_i \leftarrow t_{i+1} - t_i$, and set $\Delta t_n \leftarrow \Delta t_{n-1}$
Initialize $bat \leftarrow 0$, $ice \leftarrow 0$
Initialize arrays $W\_bat \leftarrow 0$, $W\_ice \leftarrow 0$
Compute $cond \leftarrow \text{cond\_hyb}(a, v)$
for $i = 0$ to $n-1$ **do**
  $p \leftarrow P[i]$, $pt \leftarrow P_T[i]$
  if $a[i] \cdot v[i] \geq 0$ **then** ▷ Motoring phase
    if $cond[i] = 1$ **and** $bat \leq (1 - S) \cdot E_b$ **then**
      $$bat \leftarrow bat + \frac{p}{\eta_{\text{pt}}} \cdot \frac{\Delta t_i}{3.6 \cdot 10^6}$$
    else
      $$ice \leftarrow ice + \frac{p}{\eta_{\text{gas}}} \cdot \frac{\Delta t_i}{3.6 \cdot 10^6}$$
    end if
  else ▷ Braking phase
    $$bat \leftarrow bat - pt \cdot \eta_{\text{reg}} \cdot \frac{\Delta t_i}{3.6 \cdot 10^6}$$
  end if
  $W\_bat[i] \leftarrow bat$
  $W\_ice[i] \leftarrow ice$
end for
$W \leftarrow W\_bat + W\_ice$
return W, W_ice, W_bat

Fuel Consumption Data Frame

Body	Convertible	Convertible	Coupe	Coupe	Hatchback	Hatchback	Hatchback	Hatchback	SUV
Engine	**diesel**	**gas**	**gas**	**plug-in hybrid**	**diesel**	**electric**	**gas**	**plug-in hybrid**	**diesel**
FC US06	2.069363	2.216192	2.108834	0.976307	1.917004	0.688301	1.964537	1.003624	2.150523
FC WLTC	1.503735	1.627310	1.578243	0.530098	1.392743	0.426079	1.442597	0.507682	1.704287

Body	SUV	SUV	SUV	Sedan	Sedan	Sedan	Sedan	Truck (Crew Cab)	Truck (CrewMax)
Engine	**electric**	**gas**	**plug-in hybrid**	**diesel**	**electric**	**gas**	**plug-in hybrid**	**gas**	**gas**
FC US06	0.889010	2.442687	1.103319	2.005238	0.802561	2.228575	1.131156	2.857232	2.979566
FC WLTC	0.566658	1.861112	0.607724	1.528688	0.518212	1.673927	0.586951	2.181922	2.348045

Body	Truck (Double Cab)	Truck (Extended Cab)	Truck (Quad Cab)	Truck (Quad Cab)	Truck (SuperCab)	Wagon	Wagon	Wagon	Wagon
Engine	**gas**	**gas**	**diesel**	**gas**	**gas**	**diesel**	**electric**	**gas**	**plug-in hybrid**
FC US06	2.897931	2.639396	3.094777	3.156506	2.657212	1.965671	0.728156	2.208677	0.874123
FC WLTC	2.158816	1.850424	2.199894	2.234756	1.973274	1.428193	0.447484	1.679698	0.489600