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Alternative Propulsion Systems

Kinetic Energy Recovery

ACHA5010

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1 Introduction and Vehicle choice

The vehicle chosen for this assignment is a 2nd generation Toyota Prius (2003-2009). This vehicle was chosen due to its well documented history and widely available data that is easy to publicly find from reliable sources. Due to the Prius being an extensively researched vehicle, it reduces uncertainty in the data's reliability.



Figure 1 2nd generation Toyota Prius. Image Via RAC

The Toyota Prius is designed around efficiency and regenerative braking, making it a very suitable choice for this type of research. The Prius has been used in many academic research papers in the past. Due to it being widely studied in literature, both academic and technical, this means that the aerodynamic profile, mass and rolling resistance data is well established and more reliable.

2 Vehicle dynamic characteristics

Kerb mass is used as the baseline vehicle weight. Test mass is the WLTP standard used for energy modelling. C_d is the aerodynamic drag coefficient. C_{rr} is the rolling resistance which

- Kerb mass: 1325kg (Toyota Motor Corporation, 2004; Parkers, 2024)
- Test mass (assumed): 1425kg. this mass includes 100kg for the WLTP standard add-on, assumed driver and luggage weight (European Union, 2017)
- Vehicle power output: 82 kW combined engine and electric motor system (Toyota Motor Corporation, 2004)
- Aerodynamic drag coefficient of vehicle: $C_d = 0.26$ (Toyota Motor Corporation, 2004; Hucho and Sovran, 2013)
- Frontal Area: $A = 2.16\text{m}^2$ (Kim, Kim and Choi, 2011)
- Rolling resistance coefficient: $C_{rr} = 0.008\text{-}0.009$ (Ehsani, Gao and Emadi, 2010; Li and Wang, 2016)
- Tyre dimensions: 185/65 R15 (Toyota Motor Corporation, 2004)

3 WLTP Selection

WLTP (Worldwide harmonised Light vehicles Test Procedure) is a standardised test for measuring the CO₂ emissions, fuel consumption and electric range of new cars. The WLTP test replaced the NEDC test in September 2017 as it provides more reliable and realistic data than the old tests due to the longer test time, longer test distance and higher average speed among many other factors. (Mazda UK, no date)

The WLTP has 3 vehicle classes, Class 1, Class 2 and Class 3. Class 1 includes vehicles that have a power to weight ratio (PWR) of less than or equal to 22kW/kg. Class 2 includes vehicle in the range of more than 22 kW/kg and less than or equal to 34kW/kg. Class 3 includes vehicles that have a PWR of more than 34kW/kg. Most common road going vehicles are class 3, with class 1 and 2 mostly consisting of small city cars, microcars, mopeds and underpowered passenger cars. Class 3 is the most common class as it most modern vehicles have a PWR of more than 34kW/kg. (TransportPolicy, no date)

The Prius' Power to weight ratio = Power output / Test mass (assumed)

$$= 82\text{kW} = 82,000 \text{ W} / 1425 \text{ kg} = 57.54 \text{ W/kg}$$

This calculation puts the 2nd generation Toyota Prius in the 3rd class for WLTP testing.

The WLTP procedure consists of 4 different stages of driving, the Low speed urban phase, the Medium speed suburban phase, the high speed phase on rural and A roads and Extra high speed phase on motorways. (DieselNet, no date).

The first Low speed phase lasts for approximately 589 seconds with an average speed of 11.75 mph and a maximum speed of 35.1 mph. This phase includes a lot of traffic and start stop driving in cities/town centres. This phase has the most accelerating and braking so it is very important for the test data.

The second phase takes approximately 433 seconds. The average and top speeds of this phase are approximately 24.5 mph and 47.6 mph respectively. This phase usually centres around suburban driving including neighbourhoods and small towns which follows a smoother driving pattern with moderate accelerations and higher speeds than the first phase.

The high speed phase lasts for approximately 455 seconds on rural and A roads that have flowing corners and fewer stops. The average speed is around 35.2 mph and the maximum speed is 60.5 mph. These types of roads include a lot of accelerating and braking due to the windy conditions of the roads.

The final phase is focused on motorway driving. The average speed of this phase is 58.4 mph and the maximum speed is 81.6 mph. The final phase lasts for 323 seconds and includes the highest speeds of the WLTP test where the drag forces are at the highest and the aerodynamic efficiency is pushed, therefore the vehicles power demand is at its highest. (DieselNet, no date).

4 Spreadsheet of Vehicle data and calculations

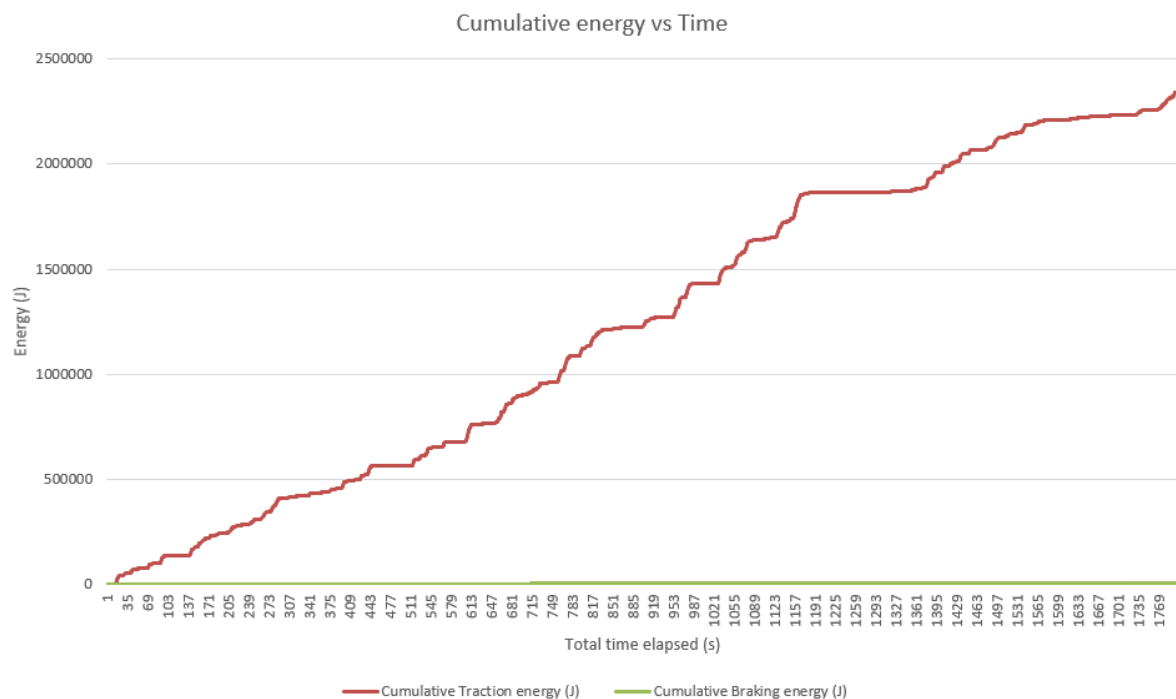


Figure 2 Graph showing the change in Cumulative energy as time increases. R Jones 2025

4.1 Interpretation of results

The graph above shows the change in the two Cumulative energy values as time passes. The Cumulative traction energy rises to 2,340,431.36J, or 2.34MJ, while the Cumulative Braking energy only rises to 8415.46J, or 8.4kJ.

The WLTP Class 3 test consists of mainly medium to higher speed driving with relatively few sharp decelerations. Due to this, most reductions in speed must have occurred through natural deceleration caused by rolling resistance and air resistance, rather than significant braking forces. This would explain why the Traction energy rises to 2.34MJ while the braking energy only rises to 8.4kJ.

4.2 Force calculations

The WLTP Class 3 speed profile was used to determine the main forces acting on the 2nd generation Toyota Prius and how the forces changed throughout the test cycle. The acceleration forces were calculated using the vehicle acceleration in m/s^2 multiplied by the test mass of the prius, following the $F = m \cdot a$ equation. The rolling resistance was calculated as a constant value based on the test mass of the vehicle multiplied by the value of gravity and the rolling resistance coefficient of 0.0085. The equation for calculating the rolling resistance is $F_{rr} = C_{rr} \cdot m \cdot g$. Aerodynamic drag was calculated using the coefficient of drag, multiplied by 0.5, the frontal area and the air density of 1.225 kg/m^3 all multiplied by the vehicle velocity in m/s , squared. The equation for this is Aerodynamic resistance = $\frac{1}{2} \rho C_d A v^2$. The power output from the Prius was then calculated using $P = F \cdot v$.

The Cumulative Traction energy (J) was calculated by taking the positive power output values from the vehicle at each second of the WLTP cycle and adding each value over time. The positive values were the only ones included as the negative power is related to braking energy rather than traction energy.

The Cumulative Braking energy (J) was calculated by summing up the magnitude of all the negative power values throughout the WLTP cycle. The braking forces occur when the total traction forces oppose the direction of the vehicles travelling force, meaning the vehicle is slowing down and the brakes are applied. The values were calculated at each one second interval where braking occurred to obtain the final Cumulative Braking energy values.

5 KERS energy storage

5.1 Energy available for storage

The total braking energy available for kinetic energy recovery over the entire Class 3 WLTP cycle is calculated as approximately 8.4kJ, equivalent to 0.00234kWh. This is an extremely small value when compared to the Cumulative Traction energy total of approximately 2.34MJ. The highest negative wheel power value shows the braking power levels that a kinetic energy storage system would need to store. Therefore, the KERS would only need to store a small quantity of energy during the drive cycle.

The negative wheel power values were analysed to identify the largest power input the KERS would need to store. The peak braking power was recorded at -697.46 W during a short braking period. This number shows the maximum power that the KERS would be required to absorb instantaneously. Both the cumulative braking energy (8.4kJ) and the peak braking power rating (0.7kW) are both quite low due to the braking pulses being very short, typically only lasting for 1-3 seconds with only a few braking events being longer. This means that the KERS for this Prius would only need to store a small amount of energy.

5.2 Suitable KERS storage technologies

Given that the amount of recoverable energy and the peak braking power are very low. The main energy storage technologies that can be considered for the KERS are lithium ion batteries, supercapacitors and a mechanical flywheel system.

Lithium ion batteries provide very high energy density but they provide relatively low power storage density, meaning they cannot absorb and store energy as quickly as other energy storage systems during quick bursts of braking. These batteries degrade at a faster rate when exposed to regular rapid charging, even in short bursts. The minimum capacity of a practically sized lithium ion battery would be far above the 8.4kJ available during the WLTP cycle. (U.S. Department of Energy, 2020)

According to (Farnell, no date), Supercapacitors offer a very high power that can absorb and release energy very quickly while keeping an excellent life cycle. The low energy density of supercapacitors is not an issue in this case as the total energy recoverable per braking event is so low it will not hinder the performance of the capacitors. Therefore, a supercapacitor would be well suited for a low energy KERS in sub kilowatt energy levels.

A mechanical flywheel KERS system would provide a very high power capability but would add many more moving mechanical parts, leading to a higher chance of failure and requiring more space in the vehicle. (Amiriyar and Pullen, 2017) These types of systems are more attuned to higher performance driving such as motorsport applications due to the high energy and high power capacities. For low energy and low power braking cycles like the WLTP of the Prius, a flywheel system would be unnecessarily complicated and would add unnecessary weight to the vehicle.

5.3 KERS requirements and Specification

The specifications required for the KERS will be found using the data collected from the WLTP.

Required Energy storage capacity:

- Total braking energy: 8.4kJ
- Largest braking energy burst, lasts for 1-3 seconds: approximately 0.7-1kJ

KERS needs an energy capacity of 8-10kJ to make sure it can store enough braking energy.

Required Power charge rating

- Peak braking power: 0.7kW

The KERS must be able to accept a charging power of at least 1kW of power.

A Supercapacitor would be the most appropriate type of a KERS storage system. Supercapacitors can absorb high levels of energy over short periods of time with excellent efficiency and little degradation to the system. This would work well with the low energy braking energies seen in the data from the WLTP. Supercapacitors offer extremely quick charging and discharging rates, making it well suited to the nature of braking that the Toyota Prius displays during the WLTP test. The discharge power requirement of a Supercapacitor for KERS is able to match the 1kW input and output capability with an energy capacity of 8-10kJ with ease.

6 Kinetic Energy Recovered

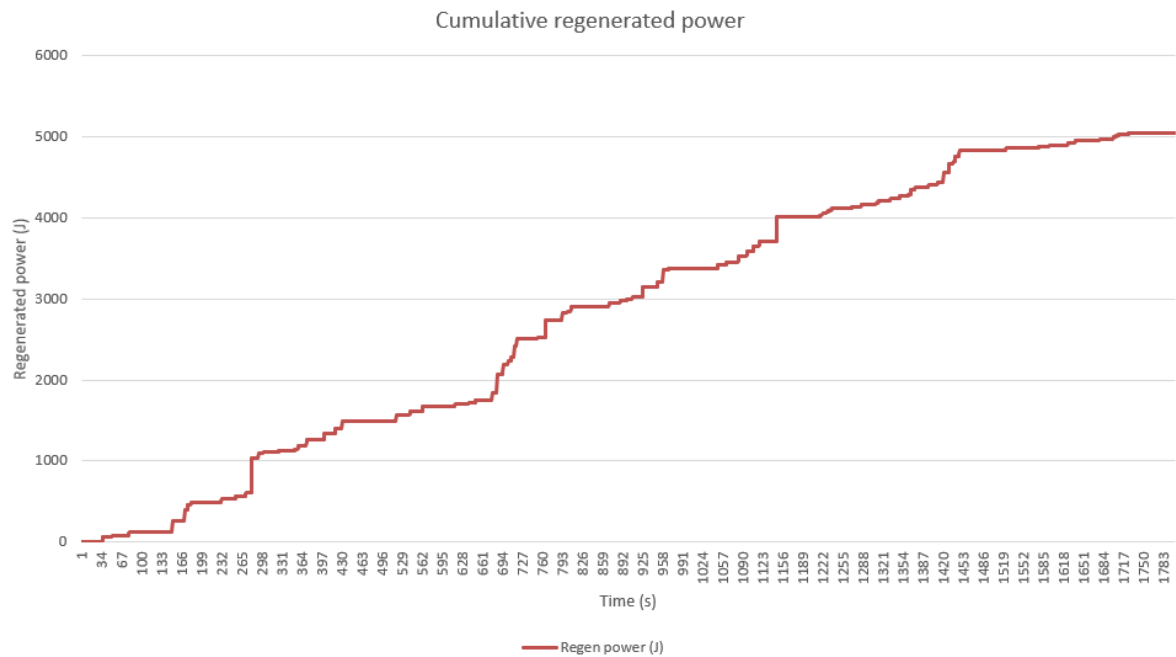


Figure 3 Graph showing Kinetic energy regeneration against time during WLTP test. R Jones 2025

A regeneration efficiency of 60% was assumed for the KERS, meaning the kinetic energy recovered was calculated as 60% of the cumulative braking energy over time.

7 System operation

The selected KERS system operates by capturing energy during vehicle braking and storing it in a small supercapacitor module, then returning this stored energy to the power train next time the vehicle is accelerated. When the driver lifts off the accelerator or applies the brakes, the system detects this and begins to rapidly absorb the short pulses of energy from the brakes identified during the WLTP test.

From the driver's perspective, the system introduces very subtle differences to how the car would drive and perform compared to a conventional ICE vehicle with simple friction brakes and no energy regeneration. Light braking may feel smoother and require less pressure on the pedal as part of the braking process. During acceleration, the driver may feel a slightly improved responsiveness from the accelerator pedal due to the recovered energy instantly available. However, in the case of the Prius, due to the small energy values, these differences would most likely be too small to notice and would not make any noticeable difference in every day driving.

8 References

Figure 1 Toyota Prius 2nd generation. Image available at: [https://www.rac.co.uk/drive/car-reviews/toyota/prius-xw20/prius-\[xw20\]-2003-2009/](https://www.rac.co.uk/drive/car-reviews/toyota/prius-xw20/prius-[xw20]-2003-2009/) (Accessed 15 November 2025)

Figure 2 Graph showing the change in Cumulative energy as time increases. R Jones 2025

Figure 4 Graph showing Kinetic energy regeneration against time during WLTP test. R Jones 2025

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