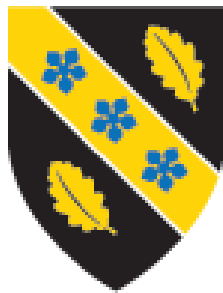


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Alternative Propulsion Systems

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1.0 Introduction

The increasing demand for reduced vehicle fuel consumption and lower emissions has driven significant interest in energy recovery systems within the automotive industry. During typical driving, particularly in urban conditions, a substantial proportion of the vehicle's kinetic energy is dissipated as heat through friction braking. Kinetic Energy Recovery Systems (KERS) aim to capture part of this energy and store it for later use, thereby reducing overall fuel consumption and improving powertrain efficiency. While hybrid passenger cars typically employ battery based regenerative braking, high-power devices such as supercapacitors appear as an attractive alternative due to their rapid charge-acceptance and cycle life characteristics.

This study evaluates the feasibility and potential benefits of introducing a supercapacitor based KERS to a 1997 Toyota Starlet Glanza V. The analysis is performed using the Worldwide harmonised Light-duty Test Procedure (WLTP) Class 3 drive cycle, which reflects the performance capability of this lightweight, turbocharged vehicle. A detailed spreadsheet model is developed to calculate tractive forces, power demand, braking energy availability and the possible energy recovery within specific KERS limitations. The results are used to estimate system power requirements, storage capacity, and the overall impact on vehicle operation and fuel consumption.

2.0 Vehicle Selection & Data

An appropriate vehicle was selected in accordance with the brief: A 1997 Toyota Starlet Glanza V (EP91), a lightweight front-wheel-drive hatchback with a 1.3-litre turbocharged engine. It was chosen due to its relatively low mass, frequent acceleration/deceleration behaviour, and suitability for a more performance-oriented KERS application.

The dynamic characteristics required for drive-cycle modelling were obtained from both published specifications and justified assumptions where direct data is not available. The parameters are as follows:

- Kerb mass: 950kg (Carfolio.com)
- Test mass: 1150kg
- Frontal area: 1.9m²
- Drag Coefficient: 0.33
- Rolling resistant coefficient: 0.012
- Air density: 1.2kg/m³
- Gravity: 9.81

These parameters directly influence the aerodynamic drag, rolling resistance and inertial forces acting on the vehicle. Their selection and justification demonstrate appropriate engagement with engineering judgement as required by the assessment criteria.

3.0 WLTP Class Selection

To ensure the analysis reflects realistic real-world driving, the WLTP Class 3 drive cycle was selected. WLTP assigns vehicles to classes depending on their specific power (rated power divided by kerb mass). The Glanza V develops approximately 99 kW and has a kerb mass of 950 kg, giving:

$$\frac{P}{m} = \frac{99,000}{950} = 104 \text{ W/kg}$$

This exceeds the WLTP Class 3 threshold of 34 W/kg. Class 3 includes low, medium, high and extra high speed phases, allowing the cycle to reflect the performance potential of the vehicle. The provided WLTP data was used in spreadsheet form, ensuring consistency with the assessment specification.

4.0 Methodology

A spreadsheet model was developed to compute the tractive forces and power demands for each 1-second timestep of the WLTP cycle. The following physical relationships were applied:

$$\begin{aligned} \text{Rolling resistance (} F_{rr} \text{)} &= mgC_{rr} \\ \text{Aerodynamic drag (} F_d \text{)} &= \frac{1}{2} \rho C_d A v^2 \\ \text{Inertial Force (} F_{in} \text{)} &= ma \\ \text{Total Tractive Force (} F_{trac} \text{)} &= F_{rr} + F_d + F_{in} \end{aligned}$$

Positive tractive power corresponds to propulsion and negative tractive power indicates braking. Energy flows were obtained by integrating power over each timestep:

$$\begin{aligned} \Delta \text{Energy}_{trac} &= \max(\text{Power}_{trac}, 0) \Delta t \\ \Delta \text{Energy}_{brake} &= \max(-\text{Power}_{trac}, 0) \Delta t \end{aligned}$$

Cumulative sums of tractive and braking energy were plotted to reveal the total energy demand and braking opportunities.

5.0 KERS Specification

A high-power electric KERS using supercapacitors was selected due to their favourable characteristics for short braking events. Supercapacitors offer high power density, rapid charge acceptance, and long cycle life, making them attractive for repeated braking phases in WLTP.

5.1 Maximum KERS Regen Power

Peak braking power observed in the cycle was ~27.8 kW. A KERS, as shown in Figure 1, regen power limit of 25 kW was selected to remain within realistic inverter and motor-generator capabilities, while still capturing most of the available braking energy.

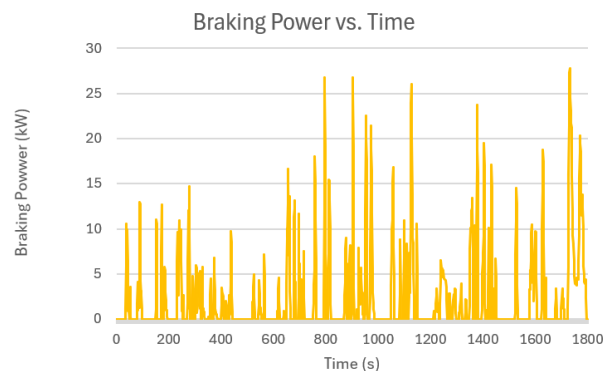


Figure 1 - Braking Power vs. Time

5.2 Recovered Energy

A high electrical efficiency of 90% was used for the supercapacitor storage phase, this was based off findings that supercapacitors can and do exceed 95% efficiency (Harnyss, 2025). However, as this is at the supercapacitor and not the wheels of the vehicle the efficiency has been reduced to account for full system losses.

5.3 Largest Braking Event & Supercapacitor Sizing

During the WLTP Class 3 cycle, braking does not occur as a single continuous event but as a series of short and long braking periods. To determine the supercapacitor energy storage requirement, each braking event must be isolated and evaluated individually. A helper column was implemented within the spreadsheet to assign a unique Event ID to each continuous period of braking, identified through non-zero values of recovered energy per second. These Event IDs were then used within a PivotTable to sum the recovered energy for every event.

The analysis showed that braking events vary widely in magnitude, with many small events recovering less than 5 kJ. However, one markedly larger event was identified, recovering approximately 688 kJ of energy. This represents the largest single braking pulse that the KERS must be capable of absorbing without saturating its storage device. This event therefore forms the primary basis for sizing the supercapacitor pack.

Supercapacitors store energy according to the electrostatic relationship

$$E = \frac{1}{2} CV^2$$

Rearranging for capacitance and substituting $E = 688,000 \text{ J}$ and a selected DC bus voltage of $V = 250 \text{ V}$ gives:

$$C = \frac{2E}{V^2} = \frac{2 * 688,000}{250^2} = 22.02 \text{ F}$$

This value represents the minimum total effective capacitance required across the entire supercapacitor bank to safely store the largest braking event energy.

The peak current associated with the chosen KERS regen limit of 25 kW is:

$$I_{peak} = \frac{P_{regen,max}}{V} = \frac{25,000}{250} = 100 \text{ A}$$

Both the required capacitance and the peak current lie within the specifications of commercially available cylindrical and pouch-type supercapacitor modules, confirming the technical feasibility of the system. (Eaton, 2024)

6.0 Results

6.1 Tractive & Resistive Forces

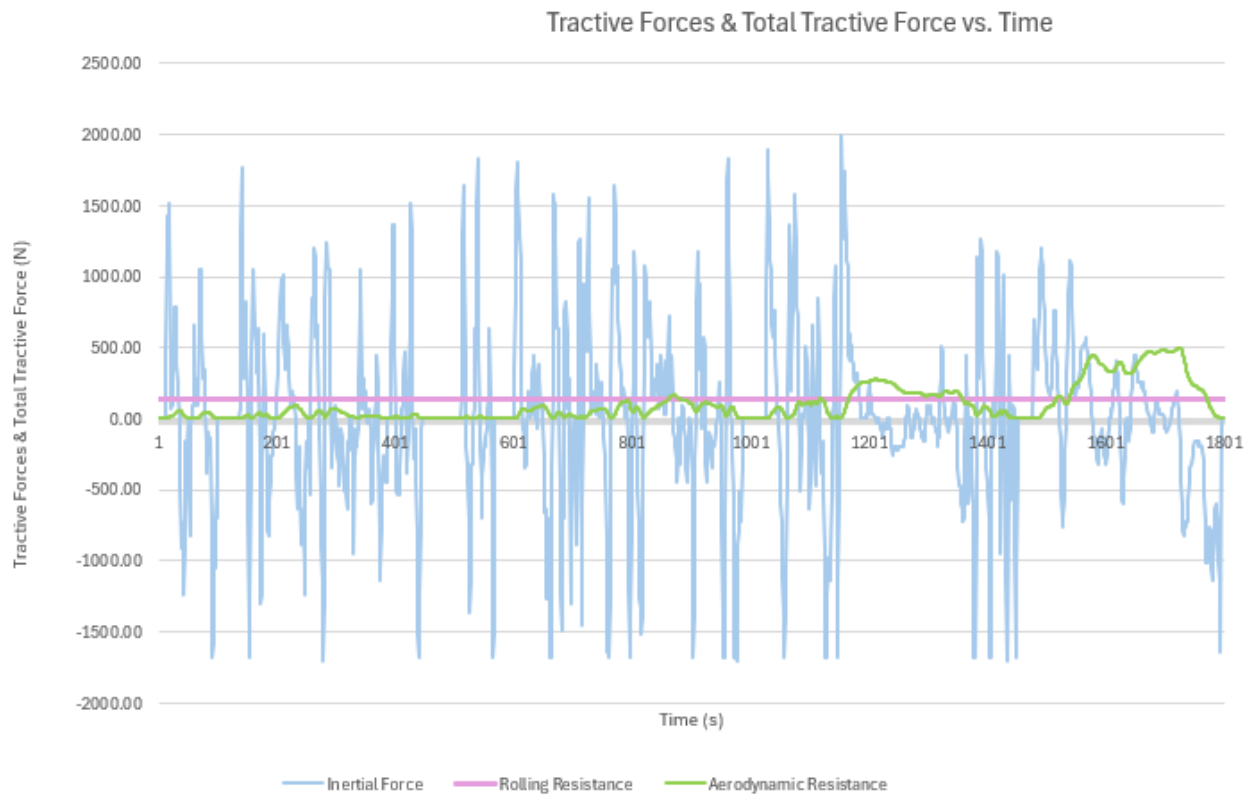


Figure 2 - Tractive Forces vs. Time

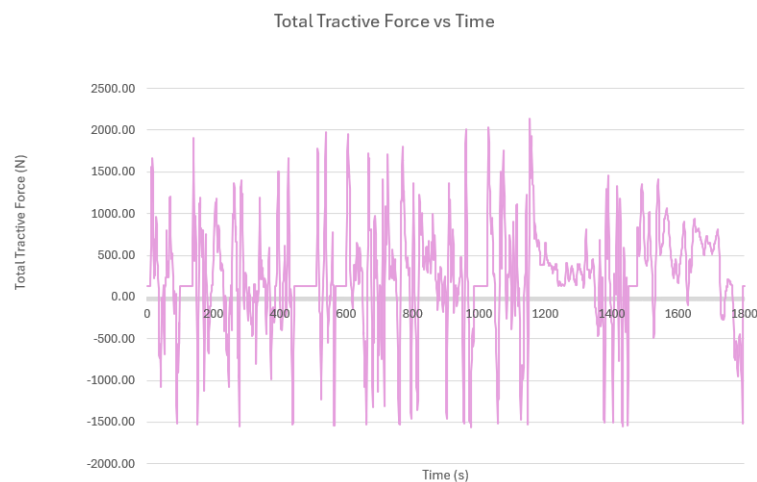


Figure 3 - Total Tractive Force vs. Time

Figure 2 illustrates the varying demands across the WLTP cycle.

At low vehicle speeds, inertial effects dominate, resulting in sharp positive tractive force spikes during acceleration phases. As vehicle speed increases, aerodynamic drag becomes increasingly significant, particularly in the high and extra-

high WLTP phases, where drag force rises quadratically with velocity. Rolling resistance remains constant throughout the cycle, contributing a baseline load just shy of 135N. Figure 3 follows the sum of these components, exhibiting a highly dynamic profile reflecting the stop-and-go nature of the WLTP drive cycle.

6.2 Tractive & Braking Power

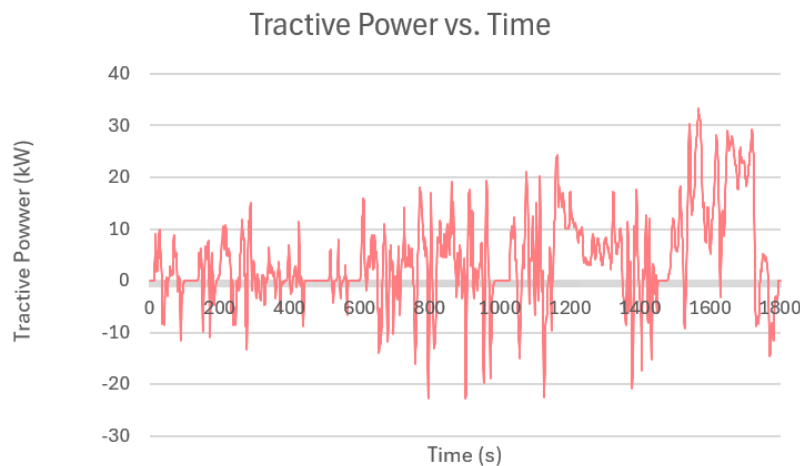


Figure 4 - Tractive Power vs. Time

Figure 4 demonstrates repeated high power acceleration bursts, frequently reaching 15–20 kW, with occasional peaks beyond 25 kW. Negative tractive power corresponds to braking, where several significant braking events particularly in the medium, high, and extra-

high phases offer opportunities for energy recovery. The distribution of braking power is highly intermittent, reinforcing the suitability of supercapacitors, which excel at short-duration high-power charging.

6.3 Cumulative Tractive & Braking Energy

As shown in Figure 5, the cumulative tractive energy curve increases steadily throughout the cycle, reaching several megajoules by the end of the 1800-second test. The cumulative braking energy curve follows a similar shape but always below the tractive energy, as expected. The difference between the two curves represents the theoretical maximum available braking energy that KERS can recover.

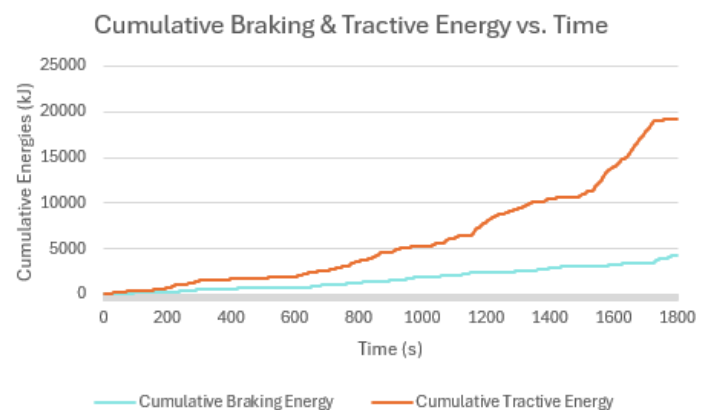


Figure 5 - Cumulative Braking & Tractive Energy vs. Time

6.4 KERS Recovered Energy

Figure 6 displays how cumulative recovered energy increases consistently throughout the WLTP cycle, with sharp rises during medium and high-speed phases where braking is more frequent. The final recovered energy is approximately 3.82 MJ, demonstrating that the 25kW regenerative power limit is well matched to the braking profile of the vehicle. The steepest increases occur

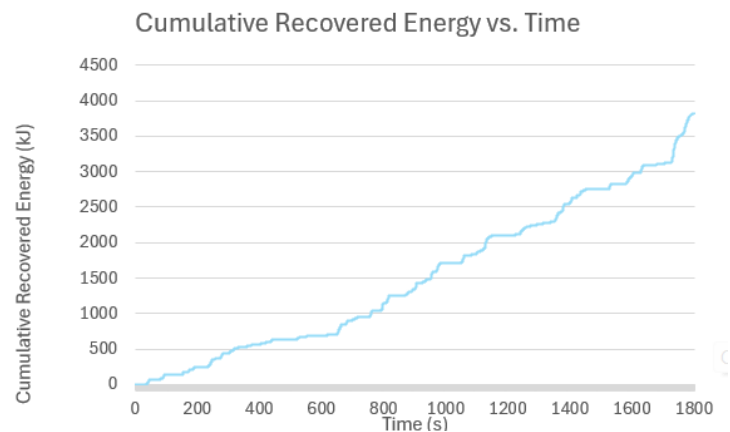


Figure 6 - Cumulative Recovered Energy vs. Time

during heavier deceleration periods, confirming that the KERS is most effective during higher energy braking events. The smooth overall trend validates the accuracy of the energy integration and shows the impactful contribution of larger braking pulses to total recovery. By comparing the 3.82MJ recovered with the total braking energy of approximately 6MJ, the KERS captures around 63% of all braking energy available during the WLTP cycle. This indicates that the system is highly effective across most deceleration events, with energy loss occurring primarily during the heaviest braking where the regeneration ceiling is reached. The shape of the curve further reinforces that the KERS is power limited rather than energy limited, as recovery increases rapidly during strong braking but becomes constrained whenever the regen power cap is exceeded.

6.5 Largest Braking Event Analysis

To determine the maximum energy storage requirement for the KERS, each braking event within the WLTP Class 3 cycle was identified and evaluated individually. Braking does not occur as a single continuous process; instead, it consists of numerous short and long events with varying magnitude. Identifying the largest of these events is essential, as it defines the peak energy that the supercapacitor must be capable of absorbing without saturating. To do this, a helper column was introduced in the spreadsheet to assign a unique 'Braking Event ID' to each continuous period of braking. This was achieved by detecting non-zero values of recovered energy per second. Whenever recovered energy transitioned from zero to a positive value, a new Braking Event ID was generated, representing the start of a new braking event. This allowed all braking periods to be isolated and analysed independently.

A PivotTable was then used to sum the recovered energy per second (J) for every Braking Event ID. Smaller braking events typically recovered less than 5kJ, while medium-sized events reached 20–80kJ depending on vehicle speed and deceleration magnitude. One event, however, was significantly larger than the rest. The PivotTable identified the largest braking event as recovering approximately 688kJ, making it the best choice to analyse. This event defines the peak energy the supercapacitor must safely store in a single braking pulse. Using the largest event ensures that the KERS is sized conservatively and can operate effectively across the full range of real driving conditions present in the WLTP cycle. The following section uses this value to calculate the required system capacitance and peak electrical current.

6.6 Supercapacitor Sizing Results

The largest braking event identified in Section 6.5 recovered approximately 688kJ, representing the maximum energy the KERS must absorb in a single deceleration phase. This value forms the basis for sizing the supercapacitor bank, which must safely store this energy without exceeding its voltage or thermal limits.

Supercapacitors store energy electrostatically, and their storage capacity is defined by the equation:

$$E = \frac{1}{2} CV^2$$

Rearranging for capacitance and substituting the peak braking event energy and the selected DC bus voltage of 250 V:

$$C = \frac{2E}{V^2} = \frac{2 \times 688,000}{250^2} = 22F$$

A total capacitance of approximately 22F is therefore required across the full supercapacitor module. This value is representative of a moderately sized automotive supercapacitor pack and is achievable using commercially available cylindrical or pouch-type cells arranged in series and parallel. The maximum electrical current experienced by the KERS occurs during peak regenerative braking at the system power limit of 25 kW. The corresponding peak current is:

$$I_{peak} = \frac{P}{V} = \frac{25,000}{250} = 100A$$

A peak current of 100A is well within the operational capabilities of modern motor-generators, DC-DC converters, and automotive-grade supercapacitor modules. Commercial data sheets from manufacturers such as (Eaton, 2024) confirm that components with comparable or superior voltage, capacitance, and pulse-current ratings are widely available for these applications. Overall, the calculated capacitance and peak current demonstrate that the proposed KERS is technically feasible, appropriately sized for the Glanza V's braking characteristics, and compatible with realistic component availability.

7.0 Practical Implications & Driver Experience

The introduction of a supercapacitor based KERS influences vehicle behaviour primarily during braking and acceleration. During light and moderate deceleration, the motor generator supplies a significant portion of the braking torque, reducing reliance on the hydraulic friction brake system. This results in a smoother and more progressive initial brake response, as the regenerative system absorbs deceleration forces without requiring immediate engagement of the brake pads. Drivers may perceive a firmer pedal feel during these phases due to reduced hydraulic pressure.

At low vehicle speeds, regenerative braking becomes limited because the generator speed decreases and torque capability falls. In these conditions, the braking system must blend seamlessly into conventional friction braking to maintain consistent stopping performance. During heavy or emergency braking, the 25kW regeneration limit is quickly exceeded, and most of the braking effort is provided by the friction brakes. Consequently, the driver does not experience any reduction in braking capability or delay in stopping response, as the regenerative system supplements rather than replaces the primary brake system.

On the propulsion side, the recovered energy stored in the supercapacitor may be redeployed as torque assist, improving acceleration responsiveness and reducing load on the internal combustion engine. The high power & density of supercapacitors allows this energy to be delivered almost instantaneously, which can be beneficial during short bursts of acceleration typical in urban and extra-urban driving. Overall, the system provides efficiency gains while preserving normal driving behaviour and maintaining safety, comfort, and vehicle stability.

8.0 Conclusion

This study examined the integration of a supercapacitor-based KERS into a 1997 Toyota Starlet Glanza V using the WLTP Class 3 drive cycle. A detailed spreadsheet model was used to quantify tractive forces, power demands, braking profiles and kinetic energy recovery throughout the cycle. The results showed that braking is highly intermittent, with energy distributed across numerous small events and a smaller number of larger pulses.

Using a Braking Event ID method and PivotTable analysis, the largest braking event was found to recover 688kJ, which was later used to define the storage requirement for the supercapacitor. Applying the supercapacitor energy equation with a selected system voltage of 250V, the required system capacitance was calculated as approximately 22F with an associated maximum regenerative current of 100A. These values fall within the capability of commercially available automotive-grade supercapacitor modules, confirming the technical feasibility of the design as previously mentioned.

Across the full 1800s WLTP cycle, the system recovered approximately 3.82MJ of energy, representing a substantial proportion of the available braking energy. This highlights the effectiveness of a 25kW regenerative limit and demonstrates the suitability of supercapacitors for short, high power recovery events typical of this drive cycle. Overall, the proposed KERS offers meaningful improvements in energy efficiency with minimal impact on driver experience, making it a viable enhancement for compact spark-ignition vehicles such as the Glanza V.

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