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RESEARCH ARTICLE

Battery Electric Vehicle Lightweighting Strategies: Addressing Energy Consumption and Range Anxiety

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ABSTRACT – In general, an internal combustion engine vehicle is still the convention in personal and commercial transport, but due to its high use stage CO_2 emission, a shift is occurring in propulsion methods, and the use of battery electric vehicles (BEV) will become the new norm. BEV's curb weight is, in general, greater than that of a conventional fuelled vehicle (CFV) for equivalent classes. Consequently, it is questionable that the level of BEV's energy consumption is acceptable. The aim of this paper is to compare the mass induced energy consumption of CFV and BEV. The expectation is that the comparative study of energy consumption between CFV and BEV will provide insight for proposing a strategy to determine the extent to which lightweighting can be introduced to a BEV. Encouragingly, less exhaustive energy consumption can help by reducing range anxiety by increasing BEV range, resolving one issue facing a BEV. With a typical road condition for hilly and flat roads, various drive cycles are also taken into consideration, and the energy consumption profiles for CFV and BEV can be determined. The vehicle model involved using the MATLAB/Simulink software underpinned by longitudinal vehicle dynamic methods. The idea is to determine the amount of lightweighting of various components of a BEV through an iterative process based on energy consumption profiles. As a function of mass reduction, for comparative energy expenditure, the results showed that a range of 28 to 36% reduction in BEV mass was achieved, which in turn can increase the driving range by 36.4 to 46.8%.

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1. INTRODUCTION

Automobiles are no doubt a sizable contributor to harmful global emissions from personal and commercial use. Besides moving from less conventional power trains, lightweighting is an unquestionable strategy to help lower the entire range of use stage gases [1-2]. The Internal Combustion Engine Vehicle (ICEV) is still the most widely used propulsion source for an automobile [3], however its use of fossil fuels and the production of greenhouse gases (GHG) means its time may be limited [4]. Considering a conventional automobile, its environmental impact can be attributed to the operational stage. In this stage of its life, about 85% of its GWP (Global Warming Potential) is realised [5]. Furthermore, the operational stage of the vehicle is directly dependent on the amount of fuel it consumes of which around 33% is weight induced [6]. With more government focus concerning the reduction of GHG's in the transport sector, it has in turn sparked interest in finding alternative methods of propulsion [7].

Given current trends and the ever-growing concern from environmental groups, the switch from conventionally fuelled vehicles (CFV) to Alternatively Fuelled Vehicle (AFV), like BEV's, means they will become a new norm in the transport sector [8-10]. Subsequently, it is recognised by the UK's committee on climate change that the electrification of the private vehicle fleets is key to solving its contribution to climate change and states that by 2035 all new cars and vans sold in the UK will be electric [11]. The implementation of the BEV power train can unquestionably decarbonise the use stage of a passenger vehicle, however they have several issues in comparability to CFV, notably price, limited range, and size of the vehicle [12], with the lengthy charging times, unaffordability and poor charge point infrastructure being prospective barriers for potential BEV owners [13,14]. BEV range and the associated range anxiety is defined as the fear of running out of electricity before reaching a suitable or available charging point. The perception of range anxiety can be challenged in two ways, either by improving charge point infrastructure or increasing BEV driving range [15], with around 70% of drivers feeling that a BEV would need around a 300-mile range before they would consider ownership [16].

Reductions in vehicle resistance and increasing powertrain efficiency offer benefits in reducing energy consumption. However, a more important option to reduce the energy consumption of a BEV is through replacing conventional materials with lighter ones. Hence, lightweighting can reduce cost through the implantation of smaller batteries and drivetrains for constant range, or offer increased range at constant performance [17]. It is still implied that the lightweighting of BEVs will still be a focus as the industry switches from CFVs. The challenge BEVs pose concerns weight, as in general, a BEV drivetrain is 125% heavier than its conventionally fuelled counterpart, thus a reduction in mass is essential to increase the driving range per battery charge, with a 10% reduction in weight returning an approximate 13% increase in range. The

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lightweighting of an automobile can be facilitated in various ways. This area alone encompasses a vast amount of research, however Czerwinski's review on the current lightweighting trend is insightful. The main areas involve either topological changes, using stress analysis to optimise a part or component, or material substitution, using ferrous and nonferrous metals like aluminium and high strength steel, HSS. Also, Czerwinski's review explores the use of composite, honeycomb sandwich laminates and aluminium lattices, which are being adopted for BEV chassis and motor components [18].

There are other factors that also contribute to vehicle energy usage like aerodynamic efficiency and rolling resistance. Reducing energy as a function of mass reduction certainly helps, but in certain circumstances, other vehicle attributes make a considerable contribution to energy consumption. Stabile et al. review and break down the energy usage of aerodynamic drag and rolling resistance and, in the most extreme cases, find that 29% and 24% of a vehicle's total energy consumption is owed to them, respectively. It highlights the importance of aerodynamic efficiency in reducing energy consumption [19]. He and Yi [20] conduct interesting work around an active rear wing on both a computational fluid dynamic (CFD) model and scale size wind tunnel model. They find that with the application of different rear wing positions and attitudes, the drag coefficient can easily be reduced, hence lowering energy consumption via an increase aerodynamic efficiency through passive flow manipulation. Stabile et al. and He and Yi work iterates that significant energy reductions can be obtained when the holistic physical properties are broken down and understood.

Making an automobile more energy efficient is one way to contextualise lightweighting. In general, for a CFV 0.3 litres of fuel is saved per 100km for every 100kg of weight reduction. However, even though lightweighting can increase energy efficiency, it raises more questions, such as economics and what the reasonable impact should be for the end consumer. Lightweight manufacturing has also already been undertaken by some large automakers like Honda, Jaguar, and Audi. They realise the potential of multi-material design in systems like BIW for greater weight reduction potential. Furthermore, some BMW concept designs include Carbon reinforced plastics and aluminium chassis components to construct passenger safety cells. Due to the added weight of batteries, lightweighting is critical to answer problems like range anxiety, but other considerations need to be made, like driver safety, driving performance, and how cost effective the material is [21]. The benefits of BEV lightweighting are important due to the high cost of the energy source, namely the battery.

Nicoletti et al. explores such topics of BEV energy consumption as a function of mass reduction using the WLTP drive cycle. It has been pointed out that with a 100kg reduction in mass, the typical battery size can be reduced by 3.27 kWh, which leads to economic benefits in reducing battery sizes for fixed ranges [22]. Even though BEVs offer zero tailpipe emission, they are not environmentally benign, and a better way to review their associated impacts is by considering life cycle assessment (LCA) [23]. Lightweighting via material substitution is a keyway to lower energy consumption. However, it is essential to understand the wider energy offsets of lightweight materials as their production, i.e., materials like magnesium, aluminium and carbon composites, are generally more energy intensive to produce [24]. Mayyas et al. reviews the life cycle CO_2 emissions produced for a BEV for substituted material in BIW. He reports that with the correct electricity mix, material substitution can, for aluminium intensive BIW, produce less CO_2 overall than its conventionally produced counterpart, around 4293.18 kg CO_2 and 4329.25 kg $CO_{2,}$ respectively [25].

Material substitution then seems like it can be viable to reduce energy consumption, but other impacts, such as economical ones, need also be considered. Burd et al. has an interesting perspective on future BEV lightweighting economics and how advances in battery technology may influence material selection. The author projects that the use of expensive lightweight material may not be needed, and advanced high strength steel (AHSS) may be used as the high price gap between using aluminium grows as the respective material advantages diminish in battery and motor resizing [26]. Also, Ou et al. explores the knowledge in quantitively linking the cost effectiveness of lightweight technologies. The authors find that the perceived cost of ownership (PCO) for BEVs for range extension is most influenced by daily ranges and lightweighting technology cost and is the most cost effective for those with higher driving intensities and daily driving [27]. An automobile's mass composition can be categorised into different systems, which can be equated to the main subsystems of the glider, which quantifies the portion of the vehicle's mass, including the body, chassis, and interior components. Powertrain is the portion of mass regarding the engine for a CFV or a motor/generator for a BEV. Suspension, the potion of mass owing to the structural support of the vehicle, which is of more importance in BEVs. Finally, the mass of the energy systems, which are for a BEV, its batteries, and for a CFV, its fuel tank and fuel [28].

While numerous studies have recommended a specific reduction value for the overall weight of a vehicle [29-31], there remains a significant knowledge gap regarding the breakdown of mass composition for various vehicle components in term of weight reduction while considering empirical drive cycle data reflecting actual driving behaviour. The remainder of this paper is organised as follows. Section 2 discusses the method used to generate and evaluate comparative energy consumption profiles. Section 2.1 details driver behaviour and the method used for its simulation. Section 2.2 discusses road conditions and the method of evaluation used. Section 2.3 outlines the governing equation used for the generation of energy consumption profiles. In Section 2.4 the Simulink model and its creation using the MATLAB software environment are highlighted. Section 2.5 elaborates on the iterative approach that was adopted to achieve comparative energy consumption. Section 2.6 gives more insight into the mass composition of a BEV. Section 3 contains all results and discusses the finding in which a range for the lightweighting of a BEV is expressed. A conclusion is also made in section 4, and the significant findings are expressed, as well as what it means for the BEV driving range. Consequently, the aim of this paper is to propose a range of mass reduction for various components of a BEV based on the study of comparative energy consumption. Using the scope of relative curbweight, the key contribution of the lightweighting breakdown is to offer a clear understanding of how much weight reduction can be achieved in vehicle components, thereby reducing the energy consumption of BEVs and significantly increasing their range.

2. METHOD

Overview of the System

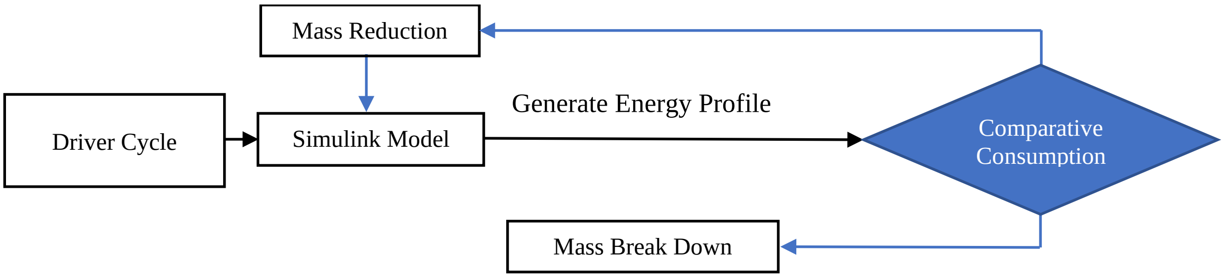
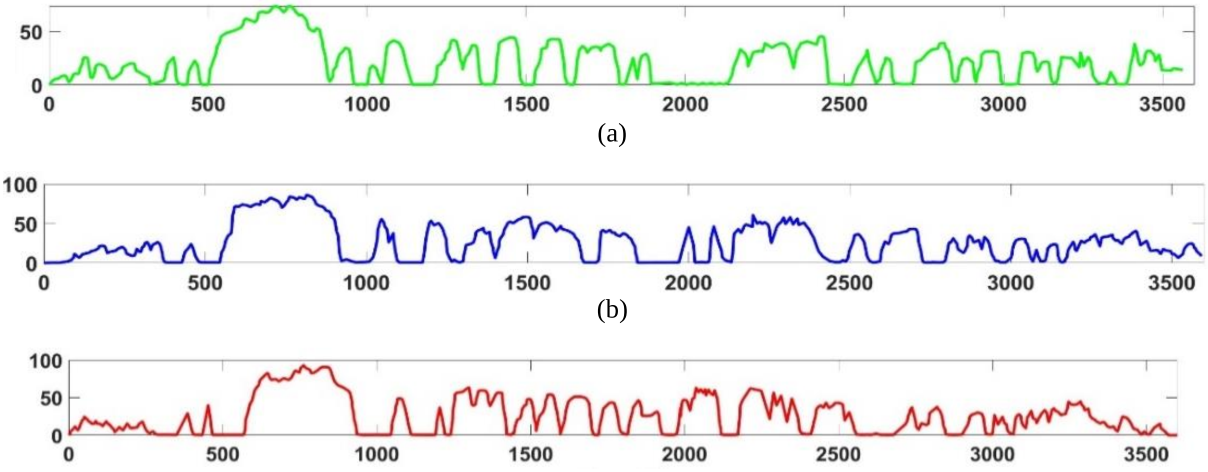


Figure 1. Iterative algorithm for comparative energy consumption evaluation

Figure 1 illustrates the systematic procedure used to determine the percentage reduction in mass needed for a BEV to have a comparative energy consumption. The data inputs for this system include driver behaviour and road conditions. Driver behaviour is characterised by time-dependent velocity profiles that quantify different levels of driver ability and confidence. The road conditions are quantified as hilly and flat, which are represented through time dependent angle magnitudes measured in degrees. The details of these two inputs are discussed in sections 2.1 and 2.2, respectively. A Simulink model was used to output energy profiles based on the driver behaviour and road condition data. The calculation is governed by the longitudinal vehicle dynamic method, as discussed in section 2.3. The details of the Simulink model are further explained in section 2.4. Each generated profile is used to provide insight into the mass reduction that needs to be applied to BEV compared with energy consumption from the CFV counterpart. The process of mass reduction is carried iteratively, which is explained in section 2.5. The percentage of mass reduction is further broken down using knowledge of the percentage composition of a BEV subsystem, as seen in section 2.6. Using the breakdown, a percentage range for the application of lightweighting to a BEV can be determined.

2.1 Drive Cycles Simulating Driver Behavior

Different driving behaviour can have a significant effect on energy consumption. The use of standardised drive cycle protocol may not fully reflect the impact of on-road vehicles by not providing provisions for driving habits, environmental, and traffic conditions [32-33]. Using an adapted NEDC Drive cycle, Alvarez [16] evaluates such behaviours to ascertain the effect on the driving range of a BEV. A correlation between a decrease in driving range and an increase in driver aggression was found. Consequently, with approximately the same state of charge at the end of the cycle, the less aggressive style had a significant increase in the driving range of 34%. Shahariar [34] evaluates driving behaviour through generated drive cycles via recording of instantaneous velocities of 30 different real-world drivers. The profiles incorporate different portions of driving environment and time periods, e.g., urban roads, motorways, school and hospital zones, residential and city driving and peak and off-peak traffic periods. The cycles were classified into different driving styles through the estimation of relative positive acceleration (RPA), with RPA ≤ 0.15 m/s^2 reflective of a timid driver, 0.16 <= RPA less than 0.2 m/s^2 indicative of normal driving and RPA ≥ 0.2 m/s^2 more in line with an aggressive driving style.

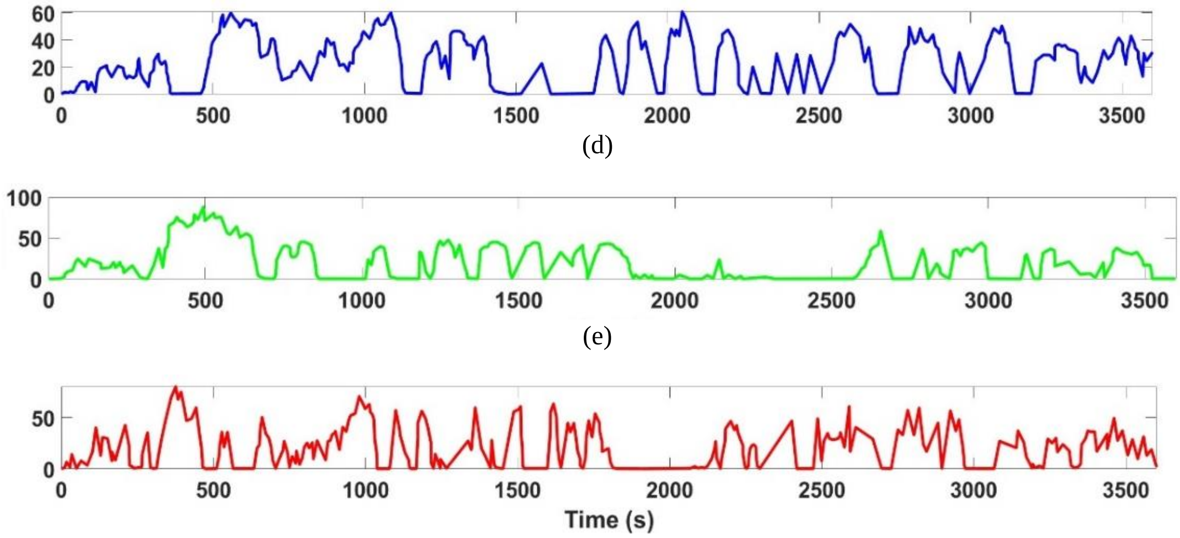


(a)

(b)

(c)

Figure 2. Off Peak drive cycles simulating driver behaviour, (a) timid, (b) normal, (c) aggressive;



(d)

(e)

(f)

Figure 2. (cont.) (d) peak drive cycles simulating driver behaviour timid, (e) normal and (f) aggressive

The term timid driver refers to one who is not as confident and, in general, has lower relative average speed and lower rates of acceleration, whereas a normal driver displays more confidence and has good control over the vehicle. An aggressive driver still displays good control of the vehicle, however, they also drive in a more frantic or sporty way, hence have high levels of acceleration. The six drive cycles in Figure 2 were used to evaluate differing driving styles of timid, normal, and aggressive drivers, along with reflecting different traffic and road conditions [32].

2.2 Road Conditions

When evaluating road conditions, there is a gap in understanding the wider impacts of road gradients, and this is sometimes neglected in the literature [35]. In this context, most evaluations focus on understanding the contribution of road grade to greenhouse gas emissions (GHG) [36]. Zhang [37] estimates energy consumption for uphill and downhill conditions, and it is found that with a greater degree of uphill slope, energy consumption can increase up to 3-fold. Subsequently, in downhill sections, the opposite is observed, in which fuel consumption significantly decreases [35]. Boriboonsomsin [38] also investigates uphill and downhill energy consumption through route selection. Two alternate routes where chosen, one with a completely flat route and one with uphill and downhill gradients of +6% and -6% for each half of the route, respectively. Boriboonsomsin concludes that road grade has a significant impact on a vehicle energy consumption. On downhill sections, Boriboonsomsin records an approximate 70% reduction in energy consumption, as illustrated in Figure 3. Hence, a baseline of 30% was adopted for the subsequent estimation of energy consumption of downhill sections of gradient profiles.

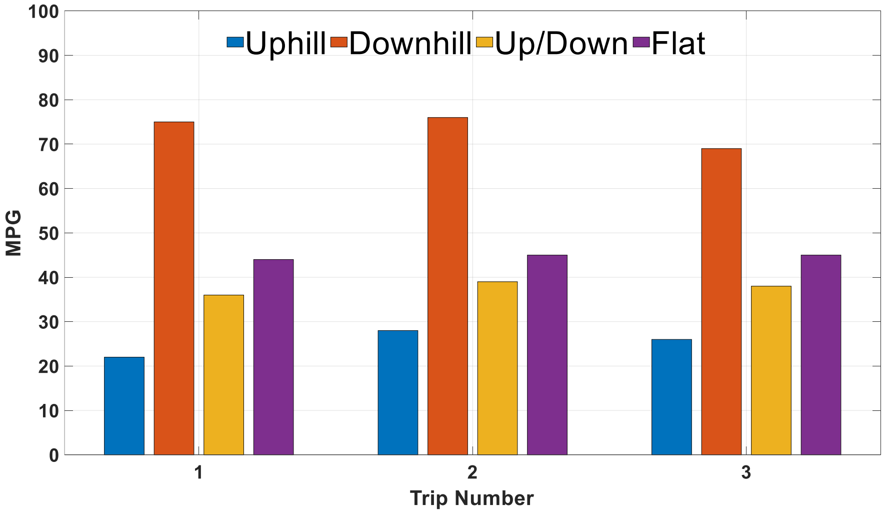


Figure 3. Fuel consumption for uphill and downhill road conditions

Two different road slope profiles were used for the evaluation of a hilly and flat road, captured from elevation data seen in Figure 4. The hilly and flat profile replicates uphill and downhill conditions with slope angles varying from positive to negative. Figure 4 dashed line depicts a hilly road with a more aggressive profile in relation to the slope angle variation than that of the flat road seen in Figure 4 solid line, with the angles varying from 15° to -15° and a 4° to -4° for the hilly and flat road respectively [36].

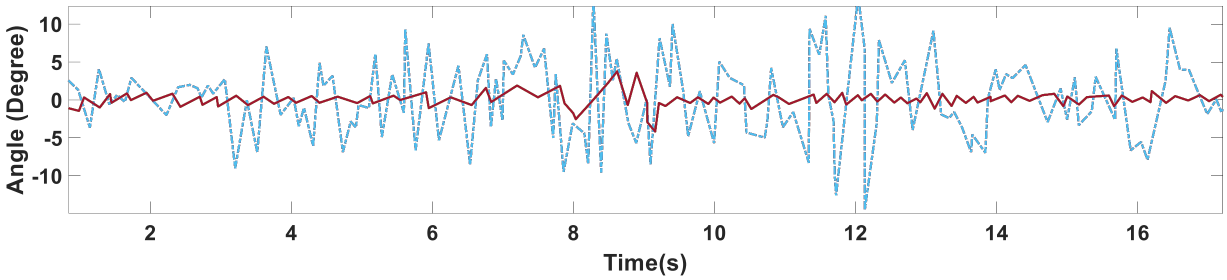


Figure 4. Gradient profiles used for the simulation of hilly and flat road. Solid line represents a flat road and the dashed is depict a hilly road

2.3 Governing Equations During Driving

A vehicle must overcome a set of longitudinal forces to propel it forward. These consist of

$$F_D = F_a + F_r + F_T + F_g + F_i \tag{1}$$

where aerodynamic drag (F_a), rolling resistance (F_r), transmission resistance (F_T), gradient resistance, and inertial resistance (F_i) which are calculated as such.

$$F_a = 0.5 C_d A \rho v^2 \tag{2}$$

$$F_r = C_r cos(|a|) \tag{3}$$

$$F_T = (F_t)\frac{1 - \eta_T}{\eta_T} \tag{4}$$

$$F_g = mg\, sin(|a|) \tag{5}$$

$$F_i = m\left(\frac{dv}{dt}\right) \tag{6}$$

where C_d is the drag coefficient, C_r is the coefficient of rolling resistance, a is the angle in degree, g is the gravitational constant, m is the mass of the vehicle v is velocity, A is the vehicle projected frontal area, ρ is the air density and η_T is the drive train efficiency, the total force required to drive the vehicle is estimated using (7).

$$F_{tD} = mg\left(C_r cos(|a|) + sin(|a|) + \frac{1}{g}\left(\frac{dv}{dt}\right)\right) + 0.5 C_d A \rho v^2 + (F_t)\frac{1 - \eta_T}{\eta_T}\ (N) \tag{7}$$

With this, the mechanical work required to move a lumped mass a defined distance can be obtained by using the work integral measured in joules (J) .

$$W = \int F_{tD}\, ds = Total\ Mechanical\ work\ (J) \tag{8}$$

When a mathematical function is more complex and can't expressed simply, the evaluation of energy consumption can be obtained via the summation of all instantaneous work increments, hence, the total energy required to complete the drive cycle is expressed as equation (9) [6].

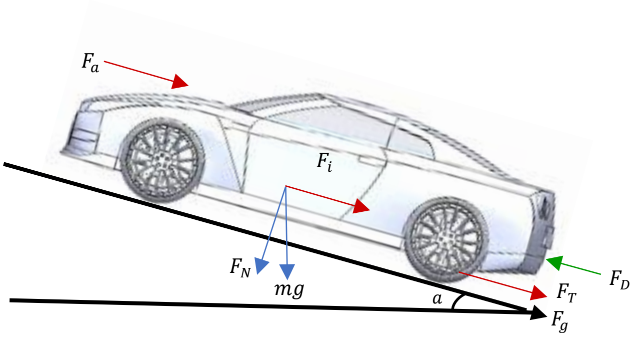


Figure 5. Free body diagram of automobile

$$\sum_{i=1}^{n} F_{tD}\, \Delta s_i = \sum_{i=1}^{n} mg\left(|a|(C_r cos + sin) + \frac{1}{g}\left(\frac{dv}{dt}\right)\right)\Delta s_i + \sum_{i=1}^{n} 0.5 C_d A \rho v^2\, \Delta s_i + \sum_{i=1}^{n} (F_t)\frac{1 - \eta_T}{\eta_T}\, \Delta s_i \tag{9}$$

Using the statistical method, the assumption is made that downhill increments are 70% more efficient; hence, only a 30% portion of the energy consumption is taken for the downhill sections [38]. Using the constants in Table 1, the total energy consumption can be calculated.

$$Energy\ consumption_{total} = \beta \sum_{i=1}^{n} F_{tD}\ \Delta s_i \begin{cases} \beta = 0.3 & Downhill \\ \beta = 1 & Uphill \end{cases} \tag{10}$$

Finally, the total energy consumption is calculated and expressed as equation (11).

$$\frac{kWh}{100} = \frac{100km}{S}\left(\frac{\sum_{i=1}^{n} F_{tD}\ \Delta s_i}{3.6x10^6}\right) \tag{11}$$

Table 1. Vehicle parameters

Vehicle data			
	CFV	BEV	
Vehicle mass (m)	1331	1769	kg
Frontal Area (A)	2		m^2
Drivetrain Efficiency (%)	0.98		
C_r	0.01		
C_d	0.3		
Gravity (g)	9.81		m/s
Air density (**ρ**)	1.255		Kg/m^3

2.4 Simulink Model

Using the MATLAB Simulink software environment, a model was created underpinned by the governing longitudinal vehicle dynamics method seen in Figure 6. Driven by the velocity profile, the corresponding resistance force was calculated using constant blocks for each of the vehicle parameters, as a product of the derivative output block, the energy was estimated for each instance of a 3600 second simulation. Using an integrator block, the summation of energies to complete each full drive could be estimated. For the evaluation of the different road slopes, the simulation was split into two sections: uphill, or positive gradient and, downhill, negative gradient. Using a logical output, the velocity for the corresponding road slope, either negative or positive, was output through the simulation. Based on the literature, the approximation of downhill energy consumption is 70% less than when travelling uphill hence, a coefficient of total downhill energy of 30% was used, taking the absolute angle in degrees. Also, due to the uneven spacing of the data, a saturation block was used to limit acceleration spikes.

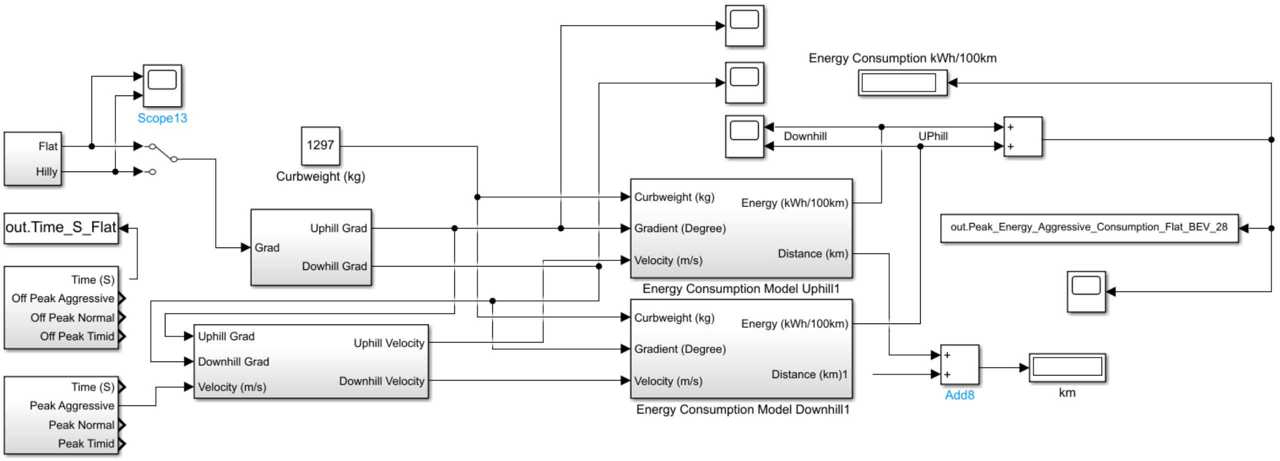


Figure 6. Simulink model

2.5 Iterative Process

When applying the iterative process, the maximum and minimum energy profiles were selected. The energy profiles were categorised by road conditions for the respective timid, normal, and aggressive drive cycles for both peak and off-peak time periods. Employing the system in Figure 1 and using the conditions that achieve the maximum energy consumption, the minimum was approached as a function of mass reduction. Increments of 5% were used and fine-tuned until comparative energy consumption was achieved for the road conditions seen in Figure 7.

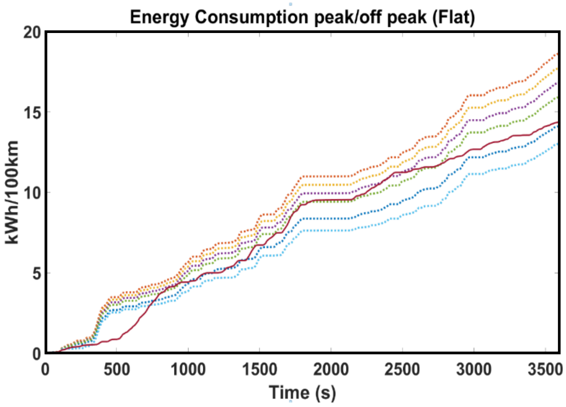


Figure 7. Energy consumption profile as a function of mass reduction

2.6 Mass Breakdown

The overall mass or curbweight of a passenger vehicle can be broken down into several systems. In general, the mass breakdown can be characterised as the sum of 4 main subsystems expressed as equation (12)

$$m_v = m_{pt} + m_{es} + m_{gl} + m_{sup} \tag{12}$$

of which m_v is the overall curbweight of the vehicle, m_{pt} is the mass of the power train, m_{es} is energy system mass, m_{gl} is the glider mass and m_{sup} is the portion of curb weight owed to suspension [28].

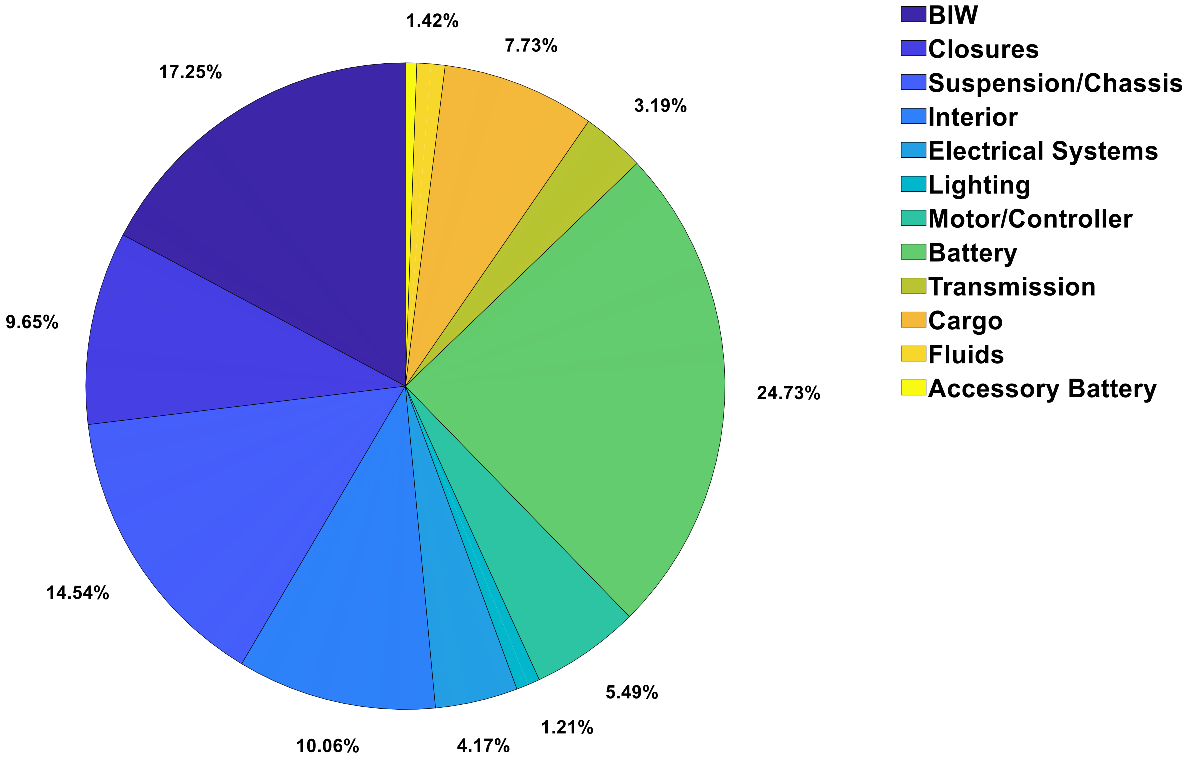
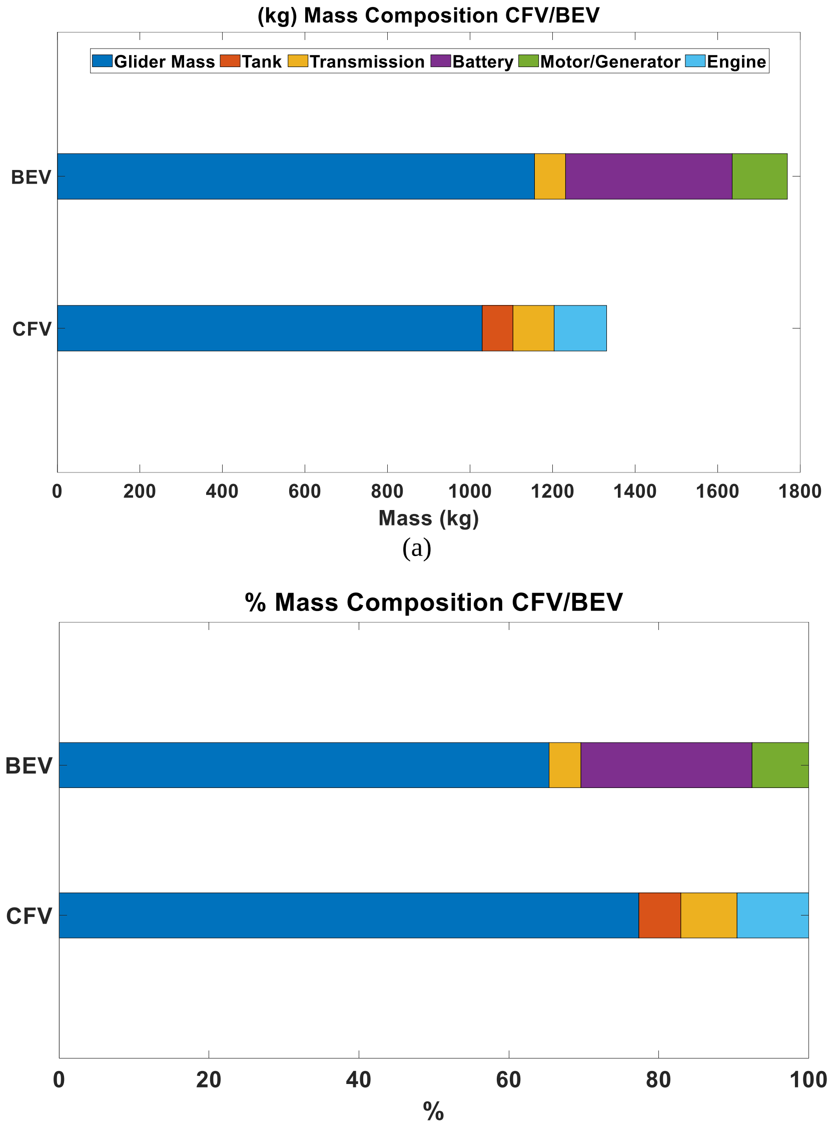


Figure 8. BEV breakdown

The word glider is broad and can encompass other subsystems of a vehicle; hence, it is more often used to include all parts of the vehicle other than the drivetrain itself. A breakdown of the glider can contain systems such as Body in White (BIW), Closures, Interior, Electrical Systems, Suspension/Chassis, and lighting [39-40]. Figure 8 illustrates a further breakdown of the glider based on literature. Hence, m_{gl} is equal to equation (13).

$$m_{gl} = BIW + Closures + Interior + Lighting + Electrical\ Systems \tag{13}$$



(a)

(b)

Figure 9. Mass composition of a BEV and CFV (a) % b (b) kg

Figure 9 shows the percentage composition, of which the BEV powertrain components share a greater percentage of the mass breakdown. However, the mass of the glider still contributes the most when considering both vehicles, to the tune of 64% and 76% for the BEV and CFV, respectively [41]. Two curb weights were chosen that reflect the curbweight of a CFV and BEV [42] (Table 1). These curb weights were further broken down into the subsystems of the glider, drivetrain and miscellaneous. Based on the breakdowns presented by Palencia [42] and Del Pero [7], a further breakdown was developed for the whole vehicle as detailed breakdowns where available for the various subsystems. The relative curbweight for each subsystem was calculated as a percentage using equation (14).

$$Percent\ Compostion = \frac{100}{Curbweight}\ .\ Subsytem\ Weight \tag{14}$$

3. RESULTS AND DISCUSSION

Energy consumption was estimated based on the evaluation of six different drive cycles and two varying road profiles, reflecting the following conditions.

- A mixture of urban, residential and city driving conditions
- Differing driving style
- Driving periods both peak and off peak
- Road conditions, both hilly and flat
- The mass induced energy consumption of CFV and BEV

Table 2 displays the accumulated energy consumption for each profile illustrated in Figure 10. The aggressive driving style generated the highest energy consumption for both peak and off-peak driving periods for both flat and hilly road conditions. Interestingly, the timid driver did not always consume the least energy in all circumstances. The normal driver has a 13.15% and 13.44% reduction in energy consumption over the timid driver for the peak driving period, for the flat and hilly roads respectively, potentially due to less aggressive acceleration events. Also notable was the variation in trend for the timid profile for the peak driving period. At around 1500 to 2750 seconds, the trend is significantly different to other generated profiles. This is primarily due to the low velocities and negligible gradients at these points in the simulation. For the rest of the accumulated energy profiles, the recorded responses reflect that the aggressive driver has the highest energy consumption, with the timid driver having the least energy consumption for the rest of the categories for the CFV. For hilly and flat road conditions, a significant increase in baseline energy consumption is seen across the board. For the CFV, the increase in energy consumption is in the range of 39.17% to 43.54%, which is an approximate 2.4-fold increase when evaluating hilly road conditions. These somewhat fit with Alvarez [16] research in which he also finds a more aggressive driver style significantly reduces the vehicle range through higher energy consumption. It is also worth noting the correlation with Zhang [27] in the estimation of hilly and flat road conditions, where a 2.4-fold increase was seen for hilly road conditions in line with the author's evaluation of empirical data.

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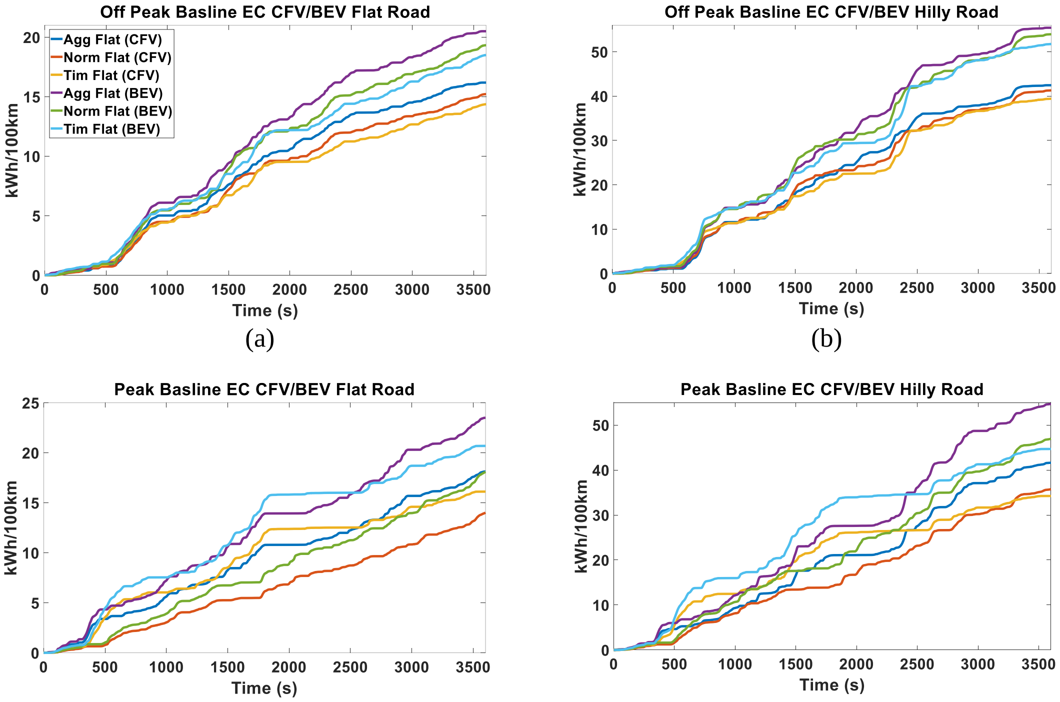
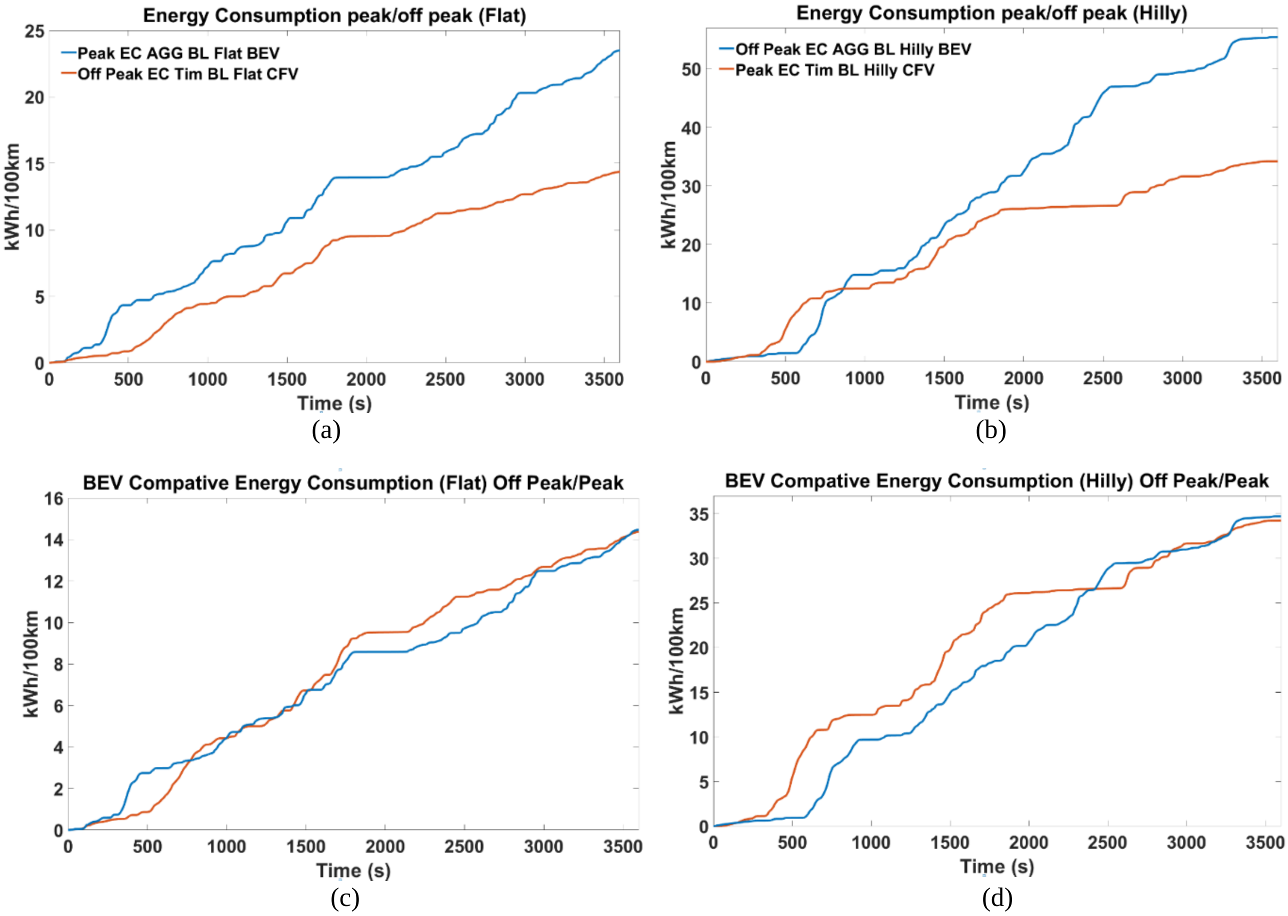


(a) (b)

(c) (d)

Figure 10. All baseline energy consumption profiles based on driver behaviour, time period and road condition (a) off peak flat (b)peak flat (c) off peak hilly (d) peak hilly

With the heavier BEV, a corresponding increase is also observed in the accumulated energy consumption. Both the hilly and flat road conditions display relatively the same increase in energy consumption, which was expected, as the driving forces are mass dependent. The interest lies in finding the comparative energy consumption for the BEV. The maximum energy consumption for the flat road categories was achieved through the evaluation of the aggressive peak driver, with the curbweight relative to BEV. The minimum was achieved by the normal driver with the curbweight respective of a CFV, with a 23.50kWh/100km and a 14kWh/100km energy consumption, respectively. For the hilly section, the energy consumption showed approximately the same 2-fold increase. The maximum was again achieved through the evaluation of the aggressive profile, with the BEV weight influencing the off-peak period, and an energy consumption of 55.42kWh/100km was returned. These results also fall in the same region of energy consumption of Sandrini et al. [43], with the caveat that he used a standardised drive cycle and did not consider the impact of road gradient.



(a) (b)

(c) (d)

Figure 11. Energy difference between flat road (a), hilly road (b) and comparative energy consumption found through iterative approach flat road (c) and hilly road (d)

The minimum energy consumption for the hilly road was achieved through the evaluation of the timid driver, for this simulation, the accumulated energy consumption was 34.23kWh/100km. The energy difference can be seen in Figures 11 (a) and (b). It was found that for the flat road condition, a 28% mass reduction would need to be applied for comparative energy consumption. Subsequently, for the hilly road condition, a mass reduction of 36% would need to be applied to achieve the same comparative energy consumption seen in Figure 11 (d). Therefore, a mass reduction of approximately 28-36% would achieve a comparable mass-induced energy consumption for both hilly and flat terrain. Further extending the breakdown would reflect the values in Table 3, which are estimated using equation (9). Also, a 13% increase per 10% weight reduction would mean a 36.4 to 46.8% increase in a BEV driving range calculated using equation (15).

$$Range\,\% \;=\; \left(\frac{100\%}{Curbweight}\right) * subsystem\ mass * mass\ reduction\ \% \tag{15}$$

$$\begin{aligned} &Driving\ Range\ Increase\ \% \\ &\quad = \left(\frac{mass\ reduction\ \%}{correltion\%}\right) * \%\ increase\ in\ driving\ range\ per\ \%\ mass\ reduction \end{aligned} \tag{16}$$

However, as the proportion of mass is different for the various subsystems, mass reduction based on percentage can have a greater effect. For example, the glider has an approximate 56% share of the BEV's overall curbweight. Based on the upper end of the range and the percentage composition of the glider, it would return an approximate 10kg weight reduction per percent. Consequently, with the drivetrain owing approximately 33% of the overall BEV curbweight again based on the upper end of the range would return an approximate 6kg weight reduction per percent, hence an extra 1% reduction in the glider area could equate to an almost 2% reduction in the drive train area.

Table 2. Accumulated energy consumptions for a given velocity profile and road condition

Peak Energy Consumption kWh/100km				Off Peak Energy Consumption kWh/100km			
CFV	Aggressive	Normal	Timid	CFV	Aggressive	Normal	Timid
Hilly	41.61	35.74	34.23	Hilly	42.46	41.29	41.18
Flat	18.12	14.00	16.12	Flat	16.18	15.22	14.37
BEV				BEV			
Hilly	54.66	46.96	44.67	Hilly	55.42	53.96	51.77
EC/kg (Wh/100km)/kg	30.90	26.55	25.25		31.32	30.5	29.26
Flat	23.50	18.09	20.68	Flat	20.50	19.33	18.51
EC/kg (Wh/100km)/kg	13.28	10.23	11.70		11.59	10.93	10.46

Table 3. Mass breakdown and reduction ranges and driving range increase

	Mass Composition (%)	Subsystem Mass Composition (%)	Mass (kg)	Reduction Range (%)		Driving Range Increase (%)	
Glider	56.59	100.00	1001.0	15.84	20.37	20.60	26.40
BIW	17.16	30.32	303.5	4.80	6.18	6.24	8.00
Closures	9.6	16.99	170.0	2.70	3.46	3.52	4.56
Suspension/Chassis	14.47	25.56	255.9	4.10	5.20	5.33	6.75
Interior	10.01	17.68	177.0	2.80	3.60	3.64	4.68
Electrical Systems	4.15	7.33	73.4	1.14	1.49	1.48	1.93
Lighting	1.2	2.12	21.2	0.30	0.43	0.39	0.56
Drivetrain	33.75	100.00	597.0	9.45	12.16	12.28	15.80
Motor/Controller	5.46	16.41	98.0	1.65	1.99	2.18	2.59
Battery	24.6	74.05	442.0	6.90	8.90	8.97	11.56
Transmission	3.17	9.54	57.0	0.90	1.27	1.17	1.65
Miscellaneous	9.66	100.00	171.0	2.71	3.47		
Cargo Fluids Accessory load (Batt)	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Even though it seems almost common sense to apply mass reduction to the heavier parts of the vehicle, the finding somewhat corroborates the assumption. From the findings, it seems that to achieve a comparative mass included energy consumption. It would almost certainly be better to concentrate the application of lightweighting on parts of the vehicle that share greater portions of the overall curbweight. It seems that the glider and its systems have the greatest potential for realising a comparative energy consumption based on the composition and percentage weight reduction and should be the area for further study.

4. CONCLUSION

The evaluation of 6 different drive cycles covering two different time periods under two road conditions was performed. For the consideration of the range of mass reduction needed to be applied to a BEV, the energy consumptions were categorised as hilly and flat. From the evaluation, it was found that the range of mass reduction would need to be in the region of 28 to 36% to achieve comparable energy consumption. Further breaking down the mass reduction needed for each of the respective subsystems of the BEV, around a 20.6 to 26.48% and 12.28 to 15.8 % reduction would be needed for the glider and drivetrain respectively. Based on the extended breakdown of the BEV, the range of mass reduction would need to be in the region of 6.24 to 8%, 3.52 to 4.56%, 5.35 to 6.75%, 3.64 to 4.68%, 1.48 to 1.93% and 0.39 to 0.56% for the BIW, closures, suspension/chassis, interior, electrical and lighting systems respectively. Based on the mass induced energy consumption, for a comparative consumption on the flat road considering all driving styles and time periods, a

9.5kWh/100km reduction in energy consumption would achieve a comparable energy consumption to that of a CFV. Likewise, for the hilly road for both time periods and all driver styles, the mass induced energy saving would need to be 21.19kWh/100km for comparability to the CFV, which is somewhat in line with the findings of Sandrini's estimation on the mass induced energy consumption of a compact BEV. Based on the value reductions calculated of 28% and 36%, the increase in BEV driving range based on the 13% range increase per 10% reduction in mass would mean an increase of driving range of 36.4 to 46.8%. The glider gives the greatest increase in driving range for mass reduction based on the glider's upper limit, would return a 26.48% increase in driving range, for the average driving range of 115 km for the reduction in the glider alone would achieve an approximate 30km increase in driving range. The benefits of the proposed mass reduction will also bring BEV more in line with consumer expectations of driving range and reduce the range anxiety problem. Nevertheless, the proposed strategy for mass reduction is only limited to the scope of the consumer use phase. For future research, the scope should be expanded so that the raw material extraction, manufacturing, and disposal phases are considered.

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The author expresses that there is no conflict of interest, intentionally or otherwise.

DATA AVAILABILITY STATEMENT

This statement is to provide clarity on data availability, and iterates, that should a reasonable request be made for the raw data or any supporting methods, it will be made available at the earliest convenience.

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