Rapid Decision-Making Tool for Powertrain Sizing

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***Abstract*— In the early stages of electric vehicle design, the decision-making process concerns the component sizing and trade-offs between various configurations to achieve or update initial target specifications. Motorcycle performance and range are more sensitive to added mass due to configuration selection. Hence, there is a need to quantify the high-level implications of different powertrain configurations and component selection, affecting the total vehicle mass, vehicle range, vehicle acceleration performance. An Excel spreadsheet-based model is described in this paper to aid decision-makers at the early stages of vehicle design. The tool is capable of sizing battery pack, inverter, traction, motor and gearbox, and making performance estimations of a powertrain configuration and component selection. The tool is validated against the listed ranges of two motorcycles and predicts energy usage with an error of 5% for low-speed drive cycles.**

Keywords—modelling, component sizing, electric vehicles, range estimation

I. Introduction

At the beginning of a typical electric vehicle design process, the high-level vehicle requirements are usually influenced by market studies, target customer profile and competitor vehicles. The early stages of the vehicle design are followed by the decision-making process concerning the component sizing and trade-offs between various configurations that can satisfy the high-level vehicle requirements. The decisions at the early stages of the vehicle design impact the entire vehicle lifetime and so are critical to the success of the entire vehicle programme.

Motorcycles are more sensitive to added mass due to their comparatively lower kerb mass than most vehicle categories. Moreover, in most cases, performance is critical to motorcycle target customers [1, 2]. Hence, it is critical to understand and quantify the high-level implications of different powertrain configurations and components selection in motorcycle design, which may affect the vehicle specifications such as total vehicle mass, vehicle range, vehicle acceleration performance, and top speed [3]. Simulation is one of the most common ways of making such an assessment.

There are many possible methods to achieve a sophisticated and detailed model of the vehicle. However, the development of a high-fidelity model is time-consuming. Also, due to the lack of available data at the necessary fidelity at the early stages of a development project, the confidence level between a high-fidelity and a low-fidelity model may not be significant. As a result, to aid the rapid decision-making process of the early-stage vehicle design, there is a need for an accessible, easy to use tool for a range of stakeholders from vehicle concept designers through component suppliers to vehicle product owners.

In this paper, a tool developed for electric motorcycle early-stage design in Excel is presented. The tool presented in this paper is a further development of the tool presented in [4]. Since the mass and performance is more critical for motorcycles, in addition to the battery sizing and pack configuration optimisation available in [4], this new tool performs component sizing for all powertrain components. Also, the sensitivity analysis in [4] is developed further for powertrain configuration performance assessment. The work presented in [5] has a similar approach to the tool presented in this paper, as that also concerns ease-of-access to the tool and ease-of-usability at an early design stage. Depending on the information available in [5], it is deduced that lumped efficiencies are used for the motor, inverter and battery in the tool in [5]. In addition to the capability of using lumped efficiencies, the tool presented in this paper is capable of dynamic efficiency calculation of motor and inverter based on efficiency maps and dynamic calculations from the battery considering Open Circuit Voltage (OCV) vs State of Charge (SoC) and DC-Internal Resistance (DC-IR) vs SoC profiles.

II. Aims and Methodology Proposition

The tool in [4] is a rapid optimisation tool for battery pack configuration based on a vehicle specification and a drive cycle. In addition to the battery sizing and battery pack configuration optimisation, the tool presented in this current paper is also aimed to identify motor and inverter sizing requirements. In addition, the tool can make the acceleration and top speed performance evaluation of selected components and configurations. Moreover, similar to the sensitivity analysis tool presented in [4], the tool quantifies the impact of variance in vehicle and cell specifications on vehicle range and performance to aid critical design decisions.

A. Component Sizing

Typically, at the beginning of the conceptual design phase, a requirements list is generated with regards to the potential market and preferences of the target customer. The component sizing feature of the tool is designed to generate a breakdown of the vehicle level requirements at the component level, which are gearbox, motor, inverter and battery.

B. Performance evaluation

After the component requirements are determined by the tool, the second stage is to identify and select the appropriate components for the application. At that stage, the performance

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evaluation feature of the tool is required to evaluate whether the selected components fulfil the target requirements. Alternatively, due to a particular design constraint, a particular component may be required to be selected. As a result of that initial selection of components, the vehicle requirements may be shaped by the constraints that the selected component introduces. By using the performance evaluation tool, the vehicle performance limitations due to that particular component can be understood, and vehicle requirements can be revised at an early stage and trade-off studies performed.

C. Sensitivity analysis

At the early stages of vehicle development, vehicle parameters such as vehicle mass, frontal area and drag coefficient are subject to change. Also, in addition to the differences due to manufacturing, the cell characteristics may vary with respect to temperature, internal resistance and ageing compared to the manufacturer's specifications. Variance in both vehicle parameters and cell parameters at a later product development stage may impact the component sizing. The sensitivity analysis is purposed to identify how variance in those parameters changes vehicle performance estimations at this early stage in design.

III. Model Development

The Vehicle Spreadsheet Model (VSM) was developed as a powertrain component sizing tool. It was developed as a spreadsheet model in Excel intending to give flexibility to users to run the model on any computer with only limited background knowledge of modelling and simulation. In addition to its powertrain component sizing feature, the VSM was improved by the addition of powertrain configuration performance estimation and model parameter sensitivity analysis features, which are 1) A powertrain component sizing tool for given performance requirements, which sizes components to achieve specified range and acceleration requirements, 2) A powertrain configuration performance estimation tool for a given component configuration, which evaluates the range and acceleration performance of some selected (i.e. off-the-shelf) components, and 3) A parameter sensitivity analysis tool.

A. Powertrain Component Sizing Tool

The powertrain component sizing tool within the VSM estimates the battery pack energy and power requirements, the motor torque, speed and power requirements, and the inverter power, current and voltage requirements to achieve given performance and range criteria. The component sizing tool can estimate the component sizes based on several range requirements over different drive-cycles and 0-100kph minimum acceleration requirements.

The component sizing tool is a backwards-facing model (BFM), which calculates the road-loads to trace a given drive-cycle. Then the road-loads are used for calculating the torque and speed demand from the motor, the power demand from the inverter, and the battery and the total energy demand. The structure of the BFM is shown in the model flow diagram in Fig. 1.

There are ten drive-cycles preloaded in the tool, including certification drive-cycles such as World Motorcycle Test Cycle (WMTC) and Worldwide-harmonised Light vehicles Test Cycle (WLTC) [6], and some real-world drive-cycles logged by Warwick Manufacturing Group (WMG). The tool was designed to allow the usage of any drive-cycle in any time-step in the model. The BFM is used to identify the maximum possible range on a drive-cycle for a given powertrain configuration by tracing the battery usable SoC from 100% to 0%. In addition to identifying the power and energy requirements for the battery pack, the tool makes a pack arrangement suggestion for a given cell specification and pack voltage selection as presented in [4].

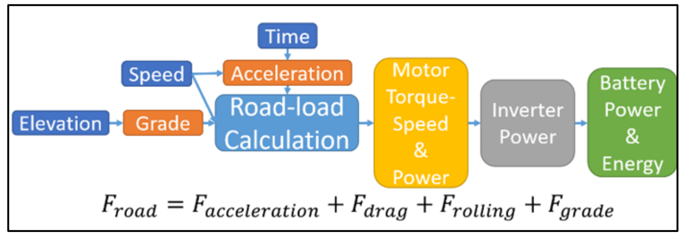

Fig. 1. Backwards-facing Model Flow Diagram

B. Powertrain Configuration Performance Estimation Tool

The powertrain configuration performance estimation tool within the VSM uses a forward-facing model (FFM) and the BFM of the component sizing tool. The FFM calculates the vehicle's acceleration and speed during Wide-Open-Throttle (WOT) acceleration for a selected powertrain configuration and identifies the minimum time for 0-100kph. The FFM considers the maximum no-slip traction torque, the gear selection, the maximum torque that the motor can deliver for a given speed, the motor power requirement, and the maximum power that the battery can deliver at a specific State of Charge (SoC). As a result of the consideration, the FFM decides the maximum torque delivered to the wheels. The decision-making logic of the FFM is shown in the diagram in Fig. 2.

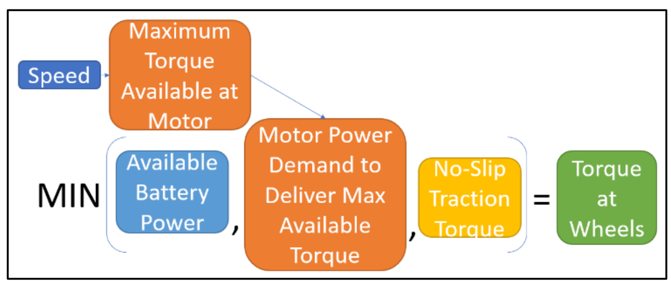

Fig. 2. Forward-facing Model Flow Diagram

C. Model Parameters Sensitivity Analysis Tool

Due to the limited information at the early stage of the project, several assumptions were made to run the model. These assumptions include but are not limited to vehicle mass, vehicle drag coefficient, frontal area, cell capacity, cell maximum discharge C-rate, cell DC-IR, mechanical efficiency of the drivetrain, and inverter efficiency. Those assumptions directly influence the component sizing suggestions or powertrain performance estimations. As a result, it is essential to identify how much a variation in those assumptions leads to a significant change in performance estimations or sizing suggestions.

The model parameters sensitivity analysis tool runs the model for a specified window of parameters and identifies how the model results change compared to the initial assumptions. The sensitivity analysis allows us to understand how much deviation from initial assumptions would lead to an oversized or undersized battery.

There are two different approaches to sensitivity analysis. The first one seeks to answer how much the vehicle or cell parameters should vary to require an additional string or remove a string to meet vehicle requirements. The second approach seeks to answer the impact of vehicle or cell parameter variance on the range and performance of the vehicle with the same battery pack configuration as done in [4].

IV. Configurations Considered

Powertrain configurations consist of several parameters, as summarised in Table I. The parameters considered and the configuration scenarios investigated as part of the study are discussed in the following section.

TABLE I. Powertrain Configuration Parameters

Battery Pack	Gearbox	Motor
s-p Arrangements	Number of speeds	Torque-speed Profile
Cell Specifications	Efficiency	Efficiency Map
Cell OCV Profile	Gear ratios	Max Operation Point
Cell DC-IR Profile		

A. *Battery Pack Configuration Options*

This analysis aims to quantify the performance and total mass of different series (s) and parallel (p) cell configurations and the deviation from the initial vehicle high-level requirements. The pack configuration is suggested based on a cell selection. There are preloaded cell specifications in the tool that the user can make selections among. The obtained s-p configuration performance estimation data is compared to the initial vehicle requirements, including 0-100kph acceleration time, certification drive-cycle range and top speed, and performance requirements of real-world drive-cycles.

DC fast charging conforming to the CCS protocol [7] requires the minimum battery pack voltage to be higher than 250V. Where DC fast charging is a requirement, the s-p configuration options are limited to the cells in series interval where the minimum pack voltage is higher than 250V. This analysis covers the s-p pack configuration and identifies the mass reduction potential against performance compromise.

B. *Motor and Gearbox Configuration Options*

There are preloaded motor specifications in the tool. Also, the user can add a custom motor specification. The motor specifications for peak and continuous torque and the motor efficiency map indicates a trade-off concerning the acceleration targets, motor operation points and vehicle kerb mass. This analysis aims to quantify the impact of single-speed and 2-speed gearboxes on the vehicle kerb mass and acceleration performance.

V. Parameters and Assumptions

In this section, the model parameters and assumptions are presented for the proof of concept. The demonstration parameters that are used to generate the result sets are based on a Harley-Davidson Livewire electric motorcycle. The parameters shown in the following tables are obtained from [8, 9]. The certification drive-cycle is used as WMTC [6].

A. *Vehicle Parameters*

The vehicle parameters as presented in Tables II-VI are used in the model. The reference for each parameter is shown in those tables. Since one of the objectives of the configuration trade-off study is to identify any mass reduction potential, the kerb mass of the vehicle is calculated based on (1). The battery pack mass is assumed to be 1.5 times the total cell mass. The kerb mass changes depending on the gearbox configuration, battery pack arrangement, and motor and inverter selection.

$$M_{Total} = M_{Motor} + M_{Inverter} + (M_{Cells} \times 1.5) + M_{Gearbox} + M_{Rider} \quad (1)$$

The gear shift speed for 0-100kph acceleration can be varied. For the drive-cycle gear shifting strategy, it was assumed that the bike always operates with the gear that leads to the most efficient motor operation. This approach is not practical since gear shifting might happen at every instant of time; however, since the development of a gear shifting strategy is out of the model's scope, this approach is used.

TABLE II. Vehicle Parameters and General Assumptions Used in the Model

Vehicle Parameters	Value	Reference
Total Kerb Mass [kg]	250	[8]
Battery Pack Mass [kg]	100	Assumption
Motor and inverter mass [kg]	30	Assumption
Chassis and body systems mass [kg]	120	Assumption
Rider mass [kg]	75	Based on [6]
2-speed gearbox mass [kg]	4	Assumption
Rolling friction coefficient	0.02	Assumption
Drag coefficient	0.7	Assumption
Frontal area [m^2]	0.74	Assumption

TABLE III. Gearing Parameters and Assumptions Used in the Model

Gearing Parameters	Value	Reference
Rolling Wheel Radius [m]	0.315	[9]
Motor-to-Wheel (Single-speed)	10	[9]
Motor-to-Wheel 1st Gear (2-speed)	12	Assumption
Motor-to-Wheel 2nd Gear (2-speed)	8	Assumption
0-100kph Acceleration Gear Shift Speed [kph]	100	Assumption
WMTC Gear Shifting Strategy	Maximum motor efficiency	Assumption

The traction parameters are used for calculating the load transfer between the front and rear wheel at an event of acceleration and deceleration. The load transfer calculation allows the model to identify no-slip tractive force during acceleration and the maximum possible no-slip regenerative braking force during deceleration.

TABLE IV. Vehicle Parameters Related to Traction Calculations

Traction Parameters	Value	Reference
CoG height [m]	0.585	Assumption
Wheelbase [m]	1.49	[9]
Static mass distribution on rear-axle	49%	Assumption
Friction coefficient (Tire-Road)	0.95	Assumption

B. *Mechanical and Electrical Efficiency Parameters*

The mechanical lumped efficiency parameters are generated based on the assumption that a single gear pair is 98% efficient and the overall efficiency from the gearbox output to the wheel is assumed to be 92%.

TABLE V. MECHANICAL AND ELECTRICAL EFFICIENCY PARAMETERS USED IN THE MODEL

Efficiency Parameters	Value	Reference
Efficiency of a single gear pair	98%	Assumption
Gearbox-to-wheel Efficiency	92%	Assumption
Motor-to-wheel Efficiency (2-speed gearbox)	90.25%	Assumption
Motor-to-wheel Efficiency (single-speed - 1 gear pair)	90.25%	Assumption
Inverter	95% lumped inverter efficiency	Assumption
Motor Efficiency	Efficiency Map	Manually generated from Fig. 6 in [10]
Battery DC-IR Based Efficiency	DC-IR based	The DC-IR curve in [11]
Regenerated Energy Fraction	20%	Assumption

The mechanical and electrical efficiencies used in the model are summarised in Table V. An efficiency map is generated for the motor. A cell specification list is generated and used in the model based on [12]. A lumped efficiency is assumed for the inverter.

C. Cell Specifications

The OCV profile is generated based on [12]and the DC-IR curve is from [11].

TABLE VI. CELL SPECIFICATIONS

Cell Specifications	Value	Reference
Capacity [Ah]	4.8	[12]
Nominal voltage [V]	3.6	[12]
Charge Cut-off Voltage [V]	4.2	[12]
Maximum Discharge C-rate [1/h]	10C	[12]
Mass [g]	68	[12]

VI. MODEL VALIDATION

The model was validated with the data available from the Harley-Davidson Livewire and Zero SR/F. The model is validated based on the listed range of Livewire and Zero S/RF by setting the model up with bike parameters. Table VI shows the specifications of HD Livewire and Zero S/RF that are considered in the model with references. The rider mass is taken as the minimum rider mass that is specified in [6].

TABLE VII. PARAMETERS OF HD LIVEWIRE AND ZERO S/RF CONSIDERED IN THE MODEL

Parameters	Harley-Davidson Livewire	Zero S/RF	Reference
Kerb Mass [kg]	251	220	[8, 9]
Rider Mass [kg]	75	75	[6]
Maximum Battery Energy Capacity [kWh]	15.5	14.4	[8, 9]
Nominal Battery Energy Capacity [kWh]	13.6	12.6	[9, 13]

It is intended to quantify the energy usage per unit distance in WMTC for HD Livewire and urban and highway range for Zero S/RF with 89 kph and 113 kph steady-state cruise driving as listed in the manufacturer's webpages [8, 13]. The average energy consumption of the bikes over a specific drive-cycle is found by the nominal energy capacity divided by the listed range. Then the average energy consumption estimated by the model for the same drive-cycle is compared with the derived values. Table VIII summarises the simulation results for range prediction and the listed ranges of motorcycles on different drive-cycles.

The results indicate that model performance is around ±5% for low and mid-speed drive-cycles, i.e. WMTC, SAE J2982, 89 kph cruise. As the speed increases, the model results deviate from the energy consumption derived from the listed range of Zero S/RF for cruising at high speed by 26.3%. One of the reasons behind this deviation might be due to the over-estimation of the frontal area or drag coefficient. It is also possible that since operating temperature of the battery is not represented in the model this could have some contribution to the range difference since a hotter battery is able to deliver more energy. As a result, high-speed cruise might be more efficient and that could be another reason behind the deviation in model estimations.

In summary, except for the high-speed cruise estimations, the VSM was considered a reliable tool considering its purpose of aiding the early-stage decision-making process with an error of considerably less than 15% [4]. The sensitivity analysis mitigates the risks of obtaining high-error results for applications at high speeds by allowing comparative results based on input variations.

TABLE VIII. COMPARISON OF THE MODEL RESULTS WITH DERIVED ENERGY CONSUMPTION FROM THE LISTED RANGE

Motorcycle	Drive-Cycle	Listed Range [km]	Nominal Battery Capacity [Wh]	Energy Consumption [Wh/km]	Model Estimation [Wh/km]	Delta [%]
HD Livewire	WMTC	159	13,600	85.5	87.8	1.2%
Zero S/RF	Urban-Range (SAE J2982)	259	12,600	48.7	51.2	5.1%
	Highway (89kph)	159	12,600	79.2	82	3.5%
	Highway (113kph)	132	12,600	95.5	120.67	26.3%

VII. SIMULATION RESULTS

A. Component Sizing

The simulation results are generated as a proof of concept of the presented tool. The assumptions and parameters presented in Tables II-VI are used. Motor output requirements and inverter requirements, and battery requirements generated by the BFM are shown in Fig. 3-5, respectively.

Motor Output Requirements	
Average Power [kW] (Drive-Cycle Req)	20.15
Peak Power [kW] (Acceleration Req)	80.24
Average Torque [Nm]	38.99
Peak Torque [Nm]	94.68
Max. Rotational Speed [RPM]	15,158

Fig. 3. An example of motor requirements identified by the tool

Inverter Output Requirements	
Average DC-Bus Current [A]	58.54
Peak DC-Bus Current [A]	203.57
Maximum DC-Bus Voltage [V]	468.26
Peak Power [kW]	87.62

Fig. 4. An example of inverter requirements identified by the tool

Battery Sizing Requirements	
Required Nominal Battery Energy [kWh]	13.86
Continous Discharge Power [kW]	31.01
Maximum Discharge Power [kW]	92.23
Maximum Charge Power [kW]	13.86
Volume Constraint [L]	50
Mass Constratint [kg]	60
Nominal Voltage [V]	416
Maximum Discharge Current [A]	203.57

Fig. 5. An example of battery requirements identified by the tool

A battery pack configuration is calculated based on the battery pack requirement identified by BFM. The specifications of the battery pack configuration suggested for the application is calculated and compared to target, which is set as the component sizes of real vehicles.

Battery Pack Actual Size	Value
Actual Nominal Pack Energy [kWh]	13.98
Actual Maximum Pack Energy [kWh]	15.73
Actual Pack Voltage [V]	416.10
Actual Pack Power (DisC) [kW]	117.75
Actual Power (Chrg) [kW]	13.98
Battery Pack Max. Continous Discharge Current [A]	74.52
Cell Max Continous C-Rate in Pack (DisC) [1/h]	2.22
Cell Max Continous C-Rate in Pack (Chg) [1/h]	0.99
Cell Max Peak C-Rate in Pack (DisC) [1/h]	6.60
Cell Current for Peak Discharge at Low SoC [A]	41.28
C-rate for Peak Discharge at Low SoC [1/h]	8.60
Peak Power at Low SoC [kW]	107.25

Fig. 6. An example of actual pack specification compared to target requirements

B. *Performance Estimation*

As a result of the components sizing suggestion made by the tool, the user can select an appropriate component among the preloaded motor and inverter or enter a custom motor or inverter specifications. As the second stage, the tool makes a performance estimation with the selected configuration of gearbox, motor, inverter, cell and pack configuration. The tool quantifies the trade-off between performance, kerb mass. The tool allows decision makers to understand the effects of mass in particular on vehicle performance and range – and therefore set a mass reduction priority based on component or base chassis mass. An example results set from the FFM is shown in Fig. 7.

Also, an example trade-off study considering different gearbox types and battery pack configurations is shown in Table IX based on the assumed parameters of Harley-Davidson Livewire.

Forward Facing Model Results	
Cells in Series	114
Number of Strings in Parallel	7
Actual Energy Capacity [kWh]	13.98096
Gearbox Configuration	Single-Speed
Maximum Motor Torque Curve	Nm
Expected WMTC Range [km]	**160.99**
Expected Acceleration Time [s]	**4.30**
Expected Continuous Top Speed [min]	**16.13**
Expected Acceleration Time at 30%SoC [s]	**4.30**
Total Kerb Mass [kg] (without rider)	250.00
Max Discharge C-rate [1/h]	5.70
Average Discharge C-rate [1/h]	3.65
30% SoC WOT Discharge C-rate [1/h]	6.67
Max Temp [C]	90.17

Fig. 7. An example of powertrain configuration performance results

VIII. Sensitivity Analysis Results

The purpose of the sensitivity analysis is to understand how much variation in range and acceleration should be expected due to a variation in a parameter. The sensitivity analysis was done for two datasets: the vehicle parameters and cell specification parameters. The vehicle parameters that the sensitivity analysis was conducted on were the total kerb mass the drag coefficient and the overall motor-to-wheel mechanical efficiency (motor efficiency is excluded). The cell specifications that were subject to sensitivity analysis were the cell capacity and the cell DC-IR.

A. *Vehicle Parameters Sensitivity Analysis*

The results for the change of range and 0-100 kph acceleration time with respect to vehicle kerb mass is shown in Fig. 8. A 5% reduction in the kerb mass leads to 1.2% extension in range and no change in 0-100 kph acceleration time due to the no-slip tractive force being lower than available traction force at the rear wheel. The top speed cruise duration was only changed by 1.8% with a 5% reduction in kerb mass.

TABLE IX. Configuration Trade-Off Analysis Results

Gearbox Type	**2-Speed**	**2-Speed**	**Single-Speed**	**Single-Speed**
Torque Profile	***Peak - 116Nm***	***Peak - 116Nm***	***Peak - 116Nm***	***Peak - 116Nm***
Kerb Mass [kg]	255	240	251	236
Cells in series [ea]	114	114	114	114
Cells in parallel [ea]	7	6	7	6
Total Number of Cells [ea]	798	684	798	684
Expected WMTC Range [km]	158	137	165	141
Expected Real-world Range (Commute) [km]	170	147	178	155
Expected Real-world Range (Commute at 2pm) [km]	169	153	182	158
Expected Real-world Range (Commute at 5pm) [km]	178	156	189	161
Expected Real-world Range (Highway Cruise) [km]	128	111	134	116
Expected Actual Acceleration Time [s]	4.3	4.3	4.3	4.3
Expected Actual Continuous Top Speed [min]	15.6	13.4	16.3	14.05
Average Total Efficiency (WMTC) [%] (Battery-to-Wheel)	79%	79%	82%	82%
Max Discharge C-rate [1/h]	5.7	6.7	5.7	6.6
Average Discharge C-rate [1/h]	3.8	4.4	3.6	4.2
30% SoC WOT Discharge C-rate [1/h]	6.7	7.8	6.7	7.8

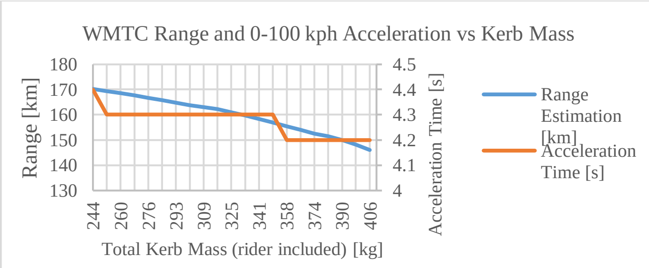

Fig. 8. The change of 0-100kph acceleration time and WMTC range with respect to change in total kerb mass (including the rider)

The results for the change of range and 0-100 kph acceleration time with respect to vehicle drag coefficient are shown in Fig. 9. A 10% reduction in the drag coefficient leads to 4.3% extension in range and 2.3% decrease in 0-100 kph acceleration time. The top speed cruise duration is the most sensitive to drag coefficient which changed by 9.7% with a 5% reduction in drag coefficient.

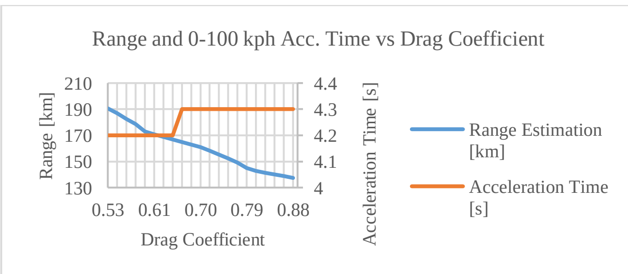

Fig. 9. The change of 0-100kph acceleration time and WMTC range with respect to change in drag coefficient

B. *Cell Parameters Sensitivity Analysis and End-of-Life (EoL) Performance Prediction*

In the light of the cell capacity and DC-IR sensitivity analysis, the tool can be used to conduct a high-level battery EoL analysis. It is assumed that at EoL the cell capacity will drop to 80% and cell DC-IR will be doubled [14]. The tool can present some estimations regarding the EoL range of the vehicle, the discharge C-rate required at the EoL to maintain the acceleration target. As a result, decisions-makers would be able to review the EoL targets or initial design decisions at an early-stage of the development.

IX. Conclusion

An Excel Spreadsheet Model has been developed to conduct component sizing, powertrain configuration performance estimation and the analysis for vehicle performance sensitivity to model parameters and assumptions. The model was validated against the listed ranges of two motorcycles. The model shows a maximum error of around 5% on low-speed drive-cycles.

Similar to [4, 5], the tool is developed in Excel and therefore universal in terms of people being able to use it. Compared to the baseline study in [4], a performance calculation and sizing for the rest of the powertrain is added. The tool differentiates from [5] with the capability of dynamic efficiency calculations for components. Moreover, simultaneous sizing over multiple duty cycles and a multi speed gearbox with simple gear change definitions are the capabilities of the VSM.

It is demonstrated that the model presents the opportunity to compare different powertrain configuration and component selection options. The performance of each decision regarding component selection and powertrain configuration can be compared against initial targets and the performance can be estimated against various range and acceleration targets.

The sensitivity analysis is able to aid the early-stage prototype vehicle testing phase as well as aiding the early-decision making process. This tool can be used to provide some relatively detailed initial sizing and sensitivity studies for new products, thus potentially reducing the component sizing phase timescales and risks.

The VSM can be improved by developing a thermal module for cooling system design and considering a broader spectrum of parameters in sensitivity analysis. It is also possible to developing a graphical user interface and preloading vehicle configurations from different sectors, i.e. automotive, off-highway, bus, etc. as in [5].

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