Independent, not-for-profit, low emission vehicle and energy for transport experts

Real-World Scooter Performance Study

A Cenex technical paper on understanding and modelling the performance of scooters under real-world inner-city drive cycles.

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Contents

Table of abbreviations

CH_4	Methane
CO	Carbon monoxide
CO_2e	Carbon dioxide equivalent
CVT	Continuously Variable Transmission
DEFRA	Department for Environment, Food and Rural Affairs
EU	European Union
EV	Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
kW	Kilowatt
kWh	Kilowatt-hours
MJ	Mega-Joule
MPG	Miles per gallon
NMC	Nickel Manganese Cobalt
NOx	Oxides of nitrogen
PM	Particulate matter
THC	Total hydrocarbons
ULEZ	Ultra Low Emission Zone
UN	United Nations
WHO	World Health Organisation
WMTC	World Motorcycle Test Cycle
WTW	Well-to-Wheel

1 Executive Summary

This document reports on the process and learnings of a research programme undertaken by Cenex which aimed to:

- Develop scooter drive cycles from real-world driving data
- Test energy consumption and emissions from electric and petrol scooters
- Develop and calibrate scooter simulation models
- Assess the emissions from scooters under different fuel supply scenarios

The use of urban 2-wheeled vehicles is expected to increase as cities become more congested and restrictions are placed on the type of vehicles able to operate within inner city boundaries. In common with all vehicles, pressure is likely to increase on lowering the emissions of 2-wheeled vehicles, and the London Ultra Low Emission Zone (ULEZ) already has a minimum requirement of Euro 3 for motorcycles. A literature review conducted by Cenex showed very little data available in the public domain on the real-world duty cycles, energy consumption and emissions performance of 2-wheeled vehicles. Therefore, this report provides a first of a kind evidence base for the performance of scooters in the real-world.

As part of its research work, Cenex has tested scooters for energy consumption and emissions over regulated and real-world driving cycles. Two scooters were tested: an electric E-Fun Puma and a petrol comparator Yamaha X-Max 250. The tests were performed in an emissions testing laboratory equipped with a chassis dynamometer. Three drive cycles were tested: the World Motorcycle Test Cycle (WMTC), which is the legislative cycle, plus two drive cycles representative of urban and extra urban driving environments in cities created by Cenex from a large dataset of scooter telemetry data. Several parameters were measured including fuel/electricity consumption, CO_2 and NOx emissions.

The study found that the **total hydrocarbons (THC), CO and NOx emissions from the petrol scooter were 71%, 34% and 58% lower than the Euro 4 regulatory limits (to which the scooter complies) in WMTC part 2**, which is the legislation cycle for motorcycles. Figure 1 below shows the comparison between the tested NOx emissions of the petrol scooter, the Euro 4 limits (introduced in 2017) and the Euro 5 limits (to be introduced in 2020).

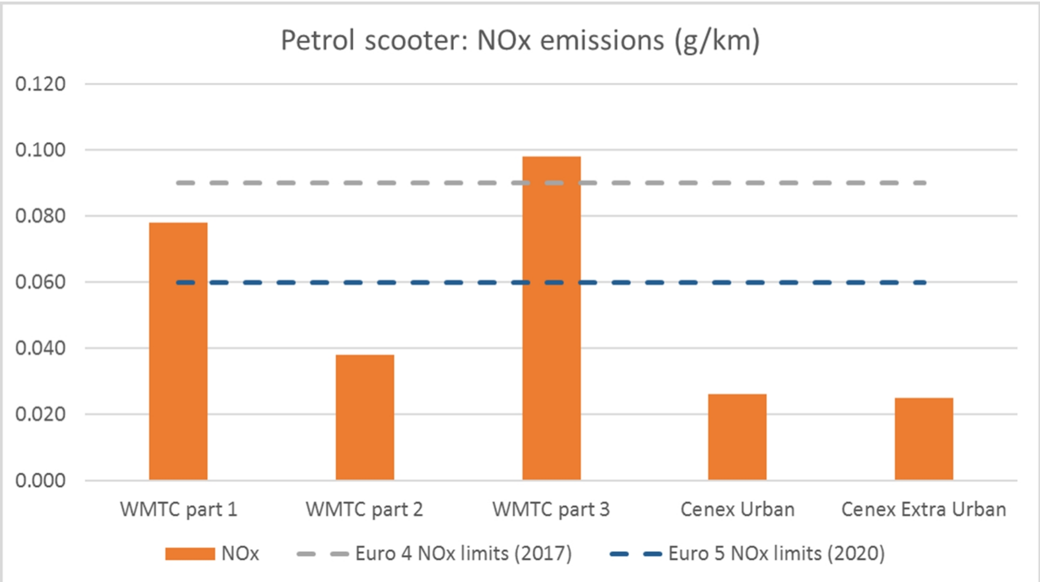

Figure 1: Tested NOx emissions vs regulatory limits

The petrol scooter performed very well in terms of NOx in the real-world urban and extra urban cycles created by Cenex, with a reduction of 71% against the Euro 4 limits. The petrol scooter was tested under a cold start for every cycle to simulate real-world conditions. The effect of a cold start can be observed in the THC, CO and NOx emission traces as it took between 4 and 5 minutes for the catalytic converter to reach the effective operating temperature. **Even though this cold start phase only represented 16% of the test duration, between 73 and 88% of the THC, CO and NOx emissions from the Cenex urban cycle were produced solely in this phase.**

The charging efficiency in the electric scooter was measured as 85%, while the measured usable battery capacity was 29% less than the quoted value, yielding a range of 92 km compared to the quoted 134 km.

While typically electric vehicles (EVs) consume 50 to 70% less energy than ICEVs, **the tested energy usage in the electric scooter ranged from 72 to 91% less than the energy consumption from the petrol scooter.** The reason for this discrepancy is that, as discovered during vehicle modelling, the petrol scooter engine is half as efficient as a generic petrol engine in a car, whereas the motor map in the electric scooter has a similar efficiency to the motor in an electric car. The tested WMTC fuel consumption in the petrol scooter was only 0.8% higher than the quoted WMTC value given by the manufacturer. In the case of the electric scooter, the tested WMTC energy usage was 3.3% lower than the quoted WMTC value. **Using the 2018 UK average grid mix, the electric scooter emitted 70 to 90% less greenhouse gas well-to-wheel (WTW) CO_2 equivalent (CO_2e) emissions.**

The results from the tests were used to develop backward facing simulation models of the scooters. In this type of model, the forces required to drive the vehicle are calculated directly from its drive cycle and are translated into a torque that must be provided by the components upstream of the wheels. The three main modules in the modelling process were tractive force, transmission and fuel consumption. **The petrol and electric scooter models were calibrated to the test results within +/- 5% of fuel/electricity consumption.**

Once the electric and petrol models were calibrated, the vehicle specifications were altered to simulate two different scooters: one medium-power electric scooter and its comparator petrol scooter equivalent to a 250cc model. Three different electricity grid mixes were used to calculate the WTW CO_2e emissions in the EV: the current grid mix, a predicted 2030 low carbon intensity (optimistic) scenario and a predicted 2030 high carbon intensity (pessimistic) scenario. **Using the current grid mix, the CO_2e savings ranged from 75% to 88%. Using the 2030 grid mix scenarios, all the CO_2e savings were above 89% even with the pessimistic assumptions, with the optimistic grid mix yielding WTW CO_2e savings of almost 100%.** These results are shown in Figure 2. The energy consumed by the electric scooter was 77 to 89% less than the energy consumed by the petrol scooter due to the low efficiency of the small petrol engine compared to the electric motor.

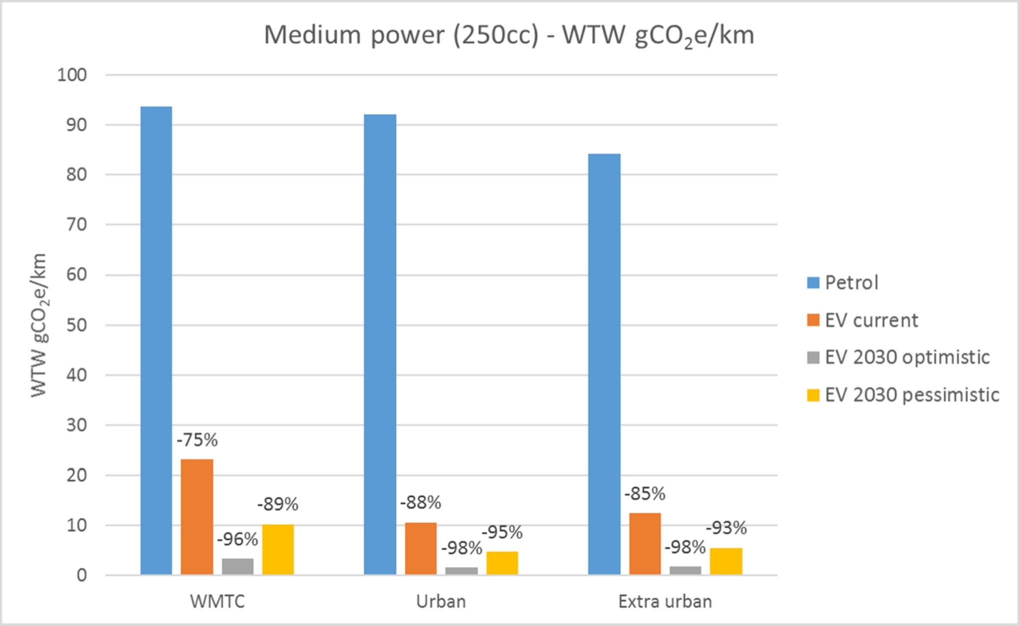

Figure 2: WTW CO2e emissions from simulation models

Whilst this study identified some real-world duty cycle information and emission data from scooters, the author accepts this is from a very limited usage pattern and scooter sample size. This limited testing suggests that the well-publicised large discrepancies observed between real-world and legislative emission performance in cars is not as pronounced in the scooter vehicle segment. It is recommended that this work is further expanded to understand a wider breadth of operating cycles and the real-world emissions and energy consumption of motorcycles and scooters to understand further how lower emission variants of these vehicles can assist air quality improvements in cities and overall GHG reduction.

2 Introduction: motorcycles in cleaner cities

This section introduces environmental issues, clean air zones and the need for providing an evidence base for the emissions and energy performance of scooters.

There is a vast and growing body of scientific evidence showing that climate change is already happening. Global average surface temperatures have risen higher than pre-industrial levels, global sea level has risen by 20 metres from melting ice sheets, and sea ice is decreasing.

Human activity is a significant contributor to the greenhouse gas effect, and the burning of fossil fuels has increased progressively since the industrial revolution, releasing huge quantities of greenhouse gases into the atmosphere. Much of these emissions come from transport and the operation of vehicles driven by internal combustion engines.

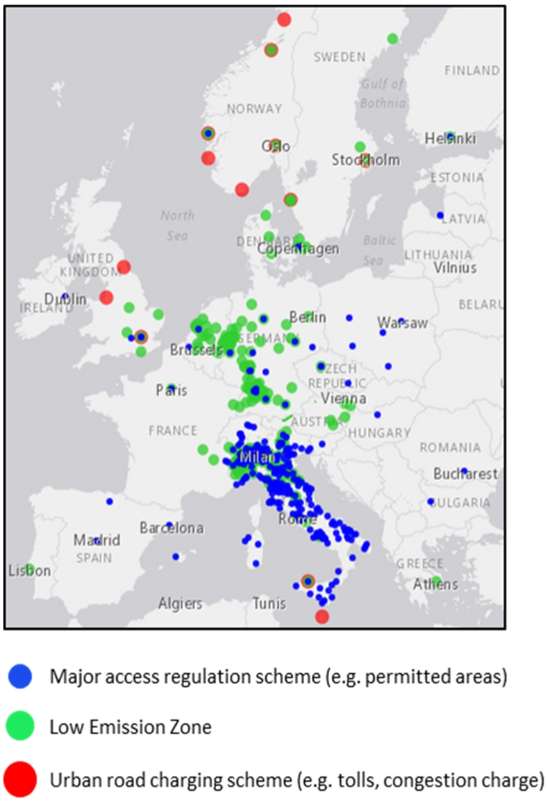

Figure 3: Map of Restricted Access Zones for vehicles in Europe

More locally, these vehicle emissions collect to create air quality problems, with a World Health Organisation (WHO) air quality model (Sep 2016) showing that 92% of the world population lives in places where air quality levels exceed WHO limits. Moreover, 40,000 deaths per year in the UK are linked to poor air quality, of which vehicle emissions are a major contributor.

Many countries & cities in the world have responded to this issue by introducing zones that restrict the use of internal combustion engine vehicles (ICEVs) in order to improve air quality (Figure 3). These zones come in many forms, on a variety of different road types, and with different rules & restrictions.

While early zones mainly target larger vehicles and/or older emissions standards, it is anticipated that zones will tighten standards to restrict the type of propulsion system and that motorcycles may also be restricted in future. The study author found very little, if any, data in the public domain on the real-world duty cycles, energy consumption and emissions performance of 2-wheeled vehicles. This report provides a first of a kind evidence base for the performance of scooters in the real-world environment.

3 Scooter testing procedure

This section explains the methodology used to test the scooters, including drive cycles, vehicle specifications and measuring equipment and facilities.

3.1 Drive cycles

3.1.1 WMTC test cycles

In order to gain understanding about the emissions and performance of city scooters, three drive cycles were tested at a specialised motorcycle testing facility. The first drive cycle was the World Motorcycle Test Cycle (WMTC), which is the legislative cycle for motorcycles developed by a group of experts commissioned by the United Nations (UN). It is representative of real-world on-road data collected in Europe, USA, China and Japan in a variety of motorcycle types with rated powers ranging from 5 to 75kW. The WMTC has 3 parts: part 1 is a low speed part, mainly representative of urban traffic; part 2 is a medium speed part and represents slower country road type of traffic; and part 3 is a high-speed part and represents faster country roads and motorways (1). There are reduced speed versions for each of the parts and the reduced speed version for part 3 was chosen (WMTC 3-1, Figure 4) because the electric bike could not reach the maximum speed in part 3 of the 3-2 cycle.

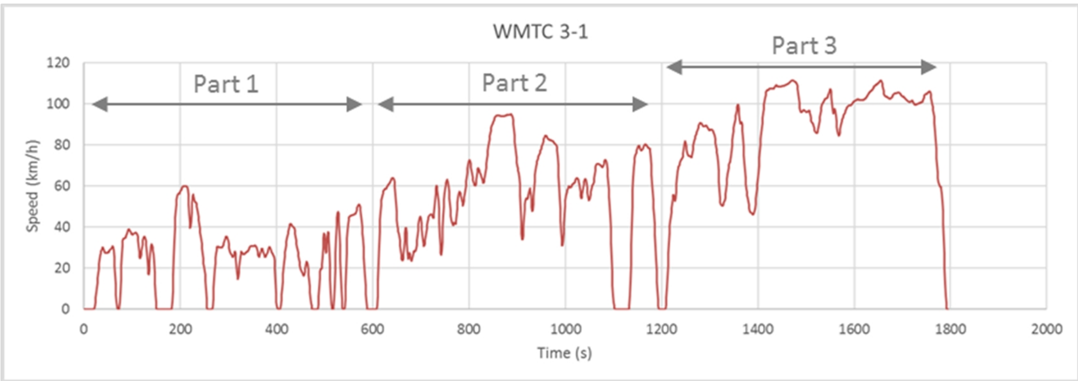

Figure 4: Legislative WMTC drive cycle (reduced speed version in part 3)

3.1.2 Real-world Cenex drive cycles

The other 2 drive cycles were developed using a large dataset of telemetry data from a scooter trial covering 11,000 miles in a large UK congested city. This data were used to create representative drive cycles of urban and extra urban driving environments in cities following the procedure explained in (2) and (3). All the trial data were classified into urban and extra urban microtrips by comparing their statistics to those of WMTC parts 1 and 2. Microtrips are trip segments limited by vehicle stops. A microtrip begins when the vehicle starts moving and finishes just before the vehicle starts moving again; it therefore includes an idling period. Microtrips are then randomly combined until a minimum duration of 30 mins is reached, so that the generated drive cycles have a similar duration to the WMTC. This process is repeated until a pool of 1,000 candidate drive cycles is obtained. The statistics of each candidate drive cycle are compared to the statistics of the whole dataset, and the candidate cycle with the best statistical match is the selected one. The representative cycles generated following this process are shown in Figure 5.

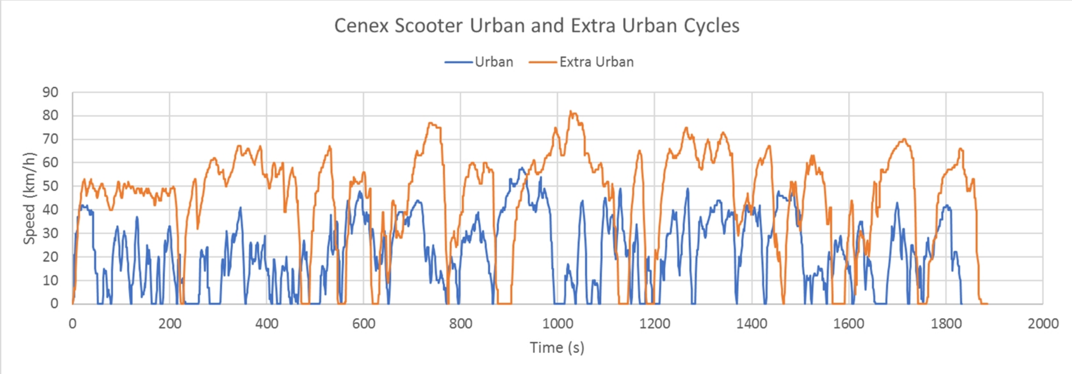

Figure 5: Representative scooter drive cycles generated by Cenex

The statistics of each of the tested drive cycles are shown in Table 1. The drive cycles created by Cenex present significantly higher accelerations and decelerations than the WMTC drive cycle, while the average speeds of the urban and extra urban cycles are slightly lower than WMTC parts 1 & 2 respectively. The kinetic intensity shown in this table is a non-dimensional variable that measures the changes in speed and elevation over a given drive cycle (4). Using this variable, the Cenex urban drive cycle is 34% more intense than the WMTC part 1, while the extra urban cycle is 26% more intense than the WMTC part 2. The trial data used to generate the Cenex drive cycles comes from scooters with electric powertrains, which present instant torque capabilities that can explain the high accelerations and kinetic intensities observed.

Table 1: Statistics from tested drive cycles

Variable	Units	Cenex urban	Cenex extra urban	WMTC 3-1		
				Part 1	Part 2	Part 3
Duration	s	1833	1885	600	600	600
Distance	km	11.3	23.6	4.1	9.1	14.4
Average speed	km/h	22.3	45.2	24.4	54.7	86.6
Average speed excl. idling	km/h	26.4	50.0	28.9	58.8	88.4
Average acceleration	m/s^2	0.77	0.60	0.45	0.43	0.22
Average deceleration	m/s^2	-0.81	-0.83	-0.50	-0.49	-0.31
Average microtrip duration	s	52	171	75	300	600
Idling time proportion	%	16	10	16	7	2
Kinetic intensity per km	Km^{-1}	2.51	0.68	1.87	0.54	0.16

3.2 Vehicles

The petrol and electric scooters chosen for the dynamometer testing are presented in this section. A 250cc petrol scooter featuring a single-cylinder four-stroke engine was used as a common baseline model observed in city centres. The alternative electric model of the scooter is an electric version with a similar power rating and similar technical specifications overall. Table 2 below shows the technical specifications as quoted by the manufacturers.

Figure 6: Yamaha X-Max 250 (petrol)

Figure 7: E-Fun Puma (electric)

Table 2: Quoted technical specifications of the tested scooters as provided by manufacturers

Make	E-Fun	Yamaha
Model	**Puma**	**X-Max 250**
Powertrain	Permanent magnet synchronous electric motor	Four stroke single cylinder 250cc petrol engine
Length (mm)	2150	2220
Width (mm)	725	775
Height (mm)	1220	1337
Wheelbase (mm)	1530	1545
Actual mass* (kg)	200	260
Max. mech. engine power (kW)	12.6	11.9
Top vehicle speed (km/h)	120	140
Transmission type	Fixed	Continuously variable transmission (CVT)
Fuel consumption	58 Wh/km	85 MPG (UK)
Battery/fuel tank capacity	7.2 kWh	11.8 litres
Battery type	Li-ion Nickel Manganese Cobalt (NMC)	N/A
Range (km)	134	354

* The actual mass is the weight of the motorcycle with a full tank of fuel and a driver of 75 kg (5).

3.3 Measuring process and equipment

The parameters shown below in Table 3 were measured in an emissions testing laboratory equipped with a low inertia chassis dynamometer suitable for motorbikes. Measured parameters consist of ambient conditions, emissions, energy use and operating parameters to allow enough data to develop and calibrate the scooter simulation models.

Table 3: Parameters measured during scooters tests

Measured variable	Petrol	Electric
CO_2	✓	N/A
NOx	✓	N/A
THC	✓	N/A
CO	✓	N/A
CH_4	✓	N/A

N_2O	✗	N/A
PM	✗	N/A
Motor/engine speed	✓	✓
Wheel speed	✓	✓
Fuel flow	✓	N/A
Battery pack voltage	N/A	✓
Battery pack current	N/A	✓
Chargepoint voltage	N/A	✓
Chargepoint current	N/A	✓
Dynamometer force	✓	✓
Dynamometer speed	✓	✓
Ambient temperature	✓	✓
Ambient pressure	✓	✓
Ambient humidity	✓	✓

The dynamometer consisted of a single roller that simulates the aerodynamic drag, the rolling resistance against the road and the inertia force required to accelerate the vehicle. The rear tyre of the scooter was placed on the roller (Figure 8) while the rest of the chassis was fixed to the ground as shown in Figure 9. This figure also shows the fan used to simulate the effect of the wind and hence the refrigeration of air-cooled components in the vehicles. The screen displays the actual and the scheduled vehicle speed, which the driver followed within a +/- 2 km/h tolerance. A high friction roller surface was used to ensure that the rear tyre does not slip during the tests.

The electric scooter was fully charged (0 to 100% state of charge) twice from a conventional domestic socket to measure the usable battery capacity. An energy monitoring device was also installed in the socket to measure the charging efficiency.

Figure 8: Rear tyre on dynamometer roller

Figure 9: Dynamometer testing setup

Both scooters were soaked at 25 degrees C during the 24 hours previous to the tests. All tests were performed from a cold start to simulate the conditions the vehicles would be driven in real life. N_2O was not measured in the petrol scooter because the measuring equipment had to be placed very close to the catalytic converter, which could potentially damage the equipment. This did not however cause a major issue as N_2O is not a regulated emission in motorcycles.

The facilities were not equipped with particulate matter (PM) measurement as these emissions are very low in motorbikes because the particulate filters remove almost all the PM. Moreover, a cause of PM emissions is direct injection technology, which is not fitted to scooters. The following pictures illustrate the testing equipment used.

Figure 10: Current and voltage measuring equipment in electric scooter

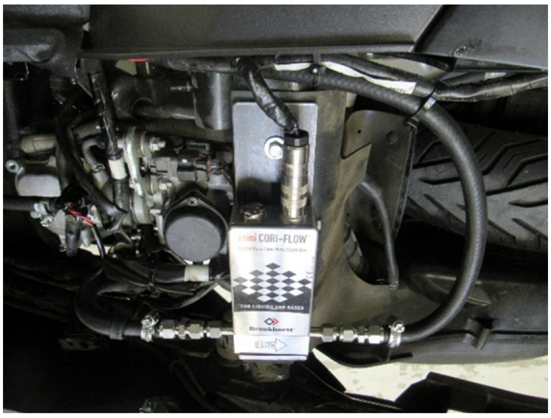

Figure 11: Fuel flow meter in petrol scooter

Figure 12: Tailpipe setup in the petrol scooter

Figure 13: Tyre speed optical sensor

Figure 10 shows the Hioki equipment with current and voltage clamps connected to the battery terminals in the electric scooter. These measurements are used to calculate the instantaneous power consumed by the vehicle. Figure 11 shows the fuel flow meter in the petrol scooter to measure fuel consumption. The petrol enters on the left of the device and exits on the right, while the top connection is the electronics that transmit the measurement data. A sealed pipe is connected to the tailpipe of the petrol scooter as seen in Figure 12. This pipe circulates the exhaust gases to the Horiba MEXA9200 equipment, where they are diluted with ambient air at a proportion set by regulation and are instantly analysed. Then, this diluted mix of air and exhaust gases is introduced in gas bags that collect the emissions for every 10 minutes of drive cycle and is analysed again. The values obtained in both analysis processes should be very similar, in this case the difference between them was under 1%. The optical sensor used to measure tyre speed is shown in Figure 13, the same type of sensor is used to measure the rotational speeds of the petrol engine and electric motor.

4 Scooter test results

This section shows the results of the tests on the petrol and electric scooters in terms of energy usage, tailpipe emissions, charging efficiency and battery capacity.

4.1 Energy use and WTW CO_2e emissions

The following graphs show the energy usage and WTW greenhouse gas CO_2e emissions of the scooters. The results for the EV include the measured charging efficiency of 85%. A battery round trip efficiency of 93% is also included in the results as measured by Cenex in past EV tests (not tested for scooters). Round trip efficiency is defined as the ratio between the energy that can be extracted from the battery and the energy that can be input via regenerative braking or charging. The percentage figures showed in the graphs are the difference between the results from the petrol and the electric scooters.

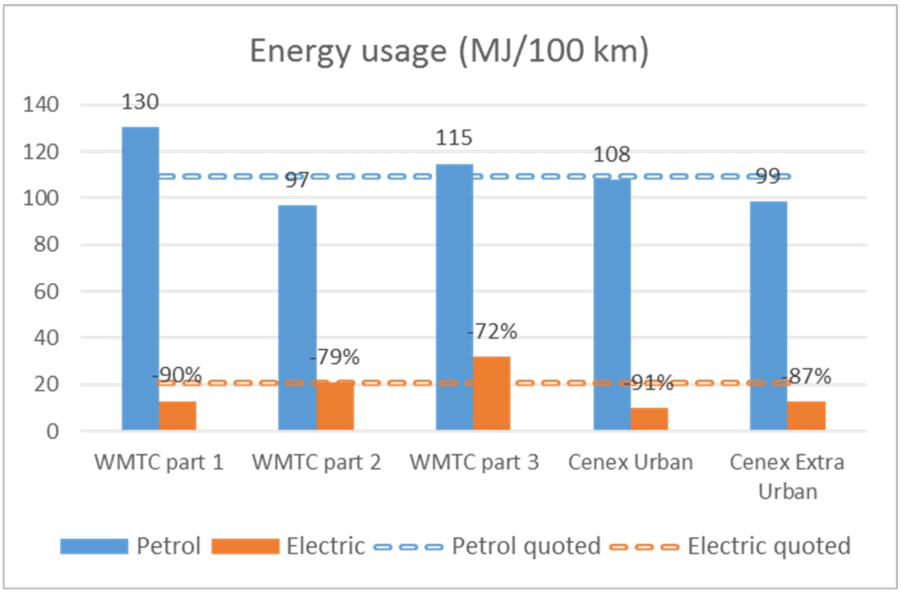

Figure 14: Test results - energy usage

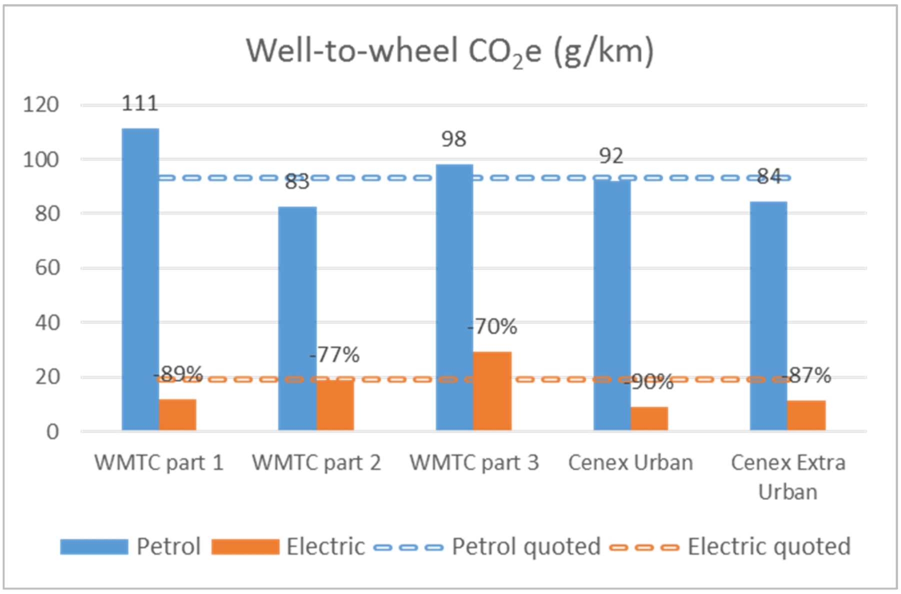

Figure 15: Test results - greenhouse gas WTW CO_2e emissions

In the case of cars, EVs typically consume 50 to 70% less energy than comparable ICEVs due to the large difference in efficiency between electric and petrol/diesel powertrains (6). However, as observed in Figure 14, the tested difference in energy usage was higher than this due to the low efficiency petrol engine in a scooter, compared with a car. Reasons for this can include the fact that the number of cylinders is reduced (1 x 250cc in the scooter against 3 or 4 x 400/500cc in a car petrol engine), which involves higher heat transfer losses due to a larger surface area to volume ratio. This also implies a larger crevice volume relative to cylinder volume, which provokes a lower combustion efficiency (crevice is the gap that needs to be present between the cylinder and the piston for the piston to move).The motor map in the electric scooter, in turn, has a similar efficiency to the motor in a larger electric vehicle.

The quoted performance of the scooters are the values given by the manufacturers for the WMTC combined cycle. The tested energy consumption for the petrol scooter in the combined WMTC was only 0.8% higher than the quoted value. In the case of the electric scooter, the tested energy usage was 3.3% lower than the quoted value. These differences are quite small considering that the manufacturers obtain the values from tests performed in different facilities and by different drivers than the tests performed for Cenex.

The WTW greenhouse gas CO_2e emissions were calculated using the latest emission factors provided by the Department for Environment, Food and Rural Affairs (DEFRA) (7). The electric scooter emitted 70 to 90% less WTW CO_2e than the petrol scooter (dependant on the drive cycle) due to the significant difference in efficiency between both vehicles.

4.2 Tailpipe emissions

Table 4 below shows the tailpipe emissions measured for the petrol scooter across the tested drive cycles and the Euro regulatory limits. The tested model of the petrol scooter is certified under the Euro 4 standards introduced in 2017, while future versions of the vehicle will comply with the Euro 5 standards to be introduced in 2020.

Table 4: Tailpipe emissions from petrol scooter

Petrol scooter: tailpipe emissions in g/km					
Drive cycle	THC	CO	NOx	CH_4	CO_2
Euro 4 limits (2017)	0.170	1.140	0.090		
WMTC part 1	0.608	2.307	0.078		89
WMTC part 2	0.049	0.751	0.038		69
WMTC part 3	0.107	4.283	0.098		76
Cenex urban	0.270	1.163	0.026	0.047	74
Cenex extra urban	0.141	1.072	0.025	0.033	68
Euro 5 limits (2020)	0.100	1.000	0.060		

The regulation sets the acceptable limits of pollutants as measured in the WMTC part 2. As shown in Table 4, when comparing the tested values in the petrol scooter to the regulation values, they were 71%, 34% and 58% lower than the Euro 4 limits for THC, CO and NOx respectively. The tested pollutant levels were still 51%, 25% and 37% lower than the Euro 5 limits. The vehicles are however perhaps optimised to perform well in part 2 of the cycle, because the pollutant levels for parts 1 and 3 of WMTC were significantly higher than those for part 2 and some of them were outside the regulatory limits. The petrol scooter performed very well in NOx for the Cenex cycles, with a reduction of 71% against the Euro 4 standard. The values for THC and CO were worse than the regulatory limits in the urban cycle but they were within the limits for the extra urban cycle. The comparison for NOx between the Euro limits and the tested values is shown in Figure 16 below.

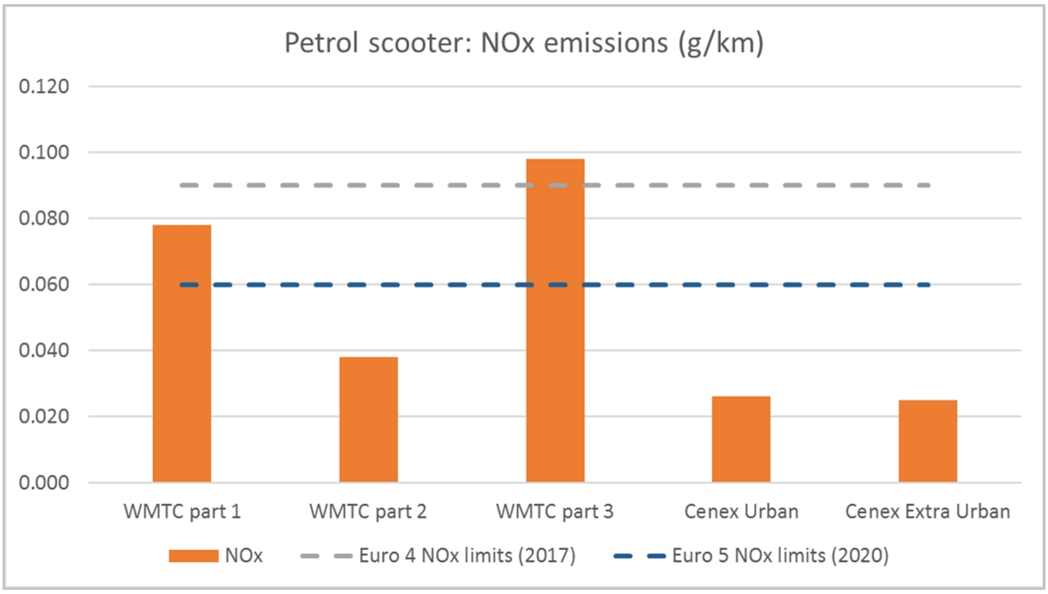

Figure 16: Comparison of NOx emissions with Euro limits

NOx and PM are the vehicle pollutants that affect the human respiratory system the most. As scooters are mostly driven in cities with a high population density, the instantaneous emissions of NOx in the petrol scooter were analysed further in Figure 17 and Figure 18 below (PM was not measured).

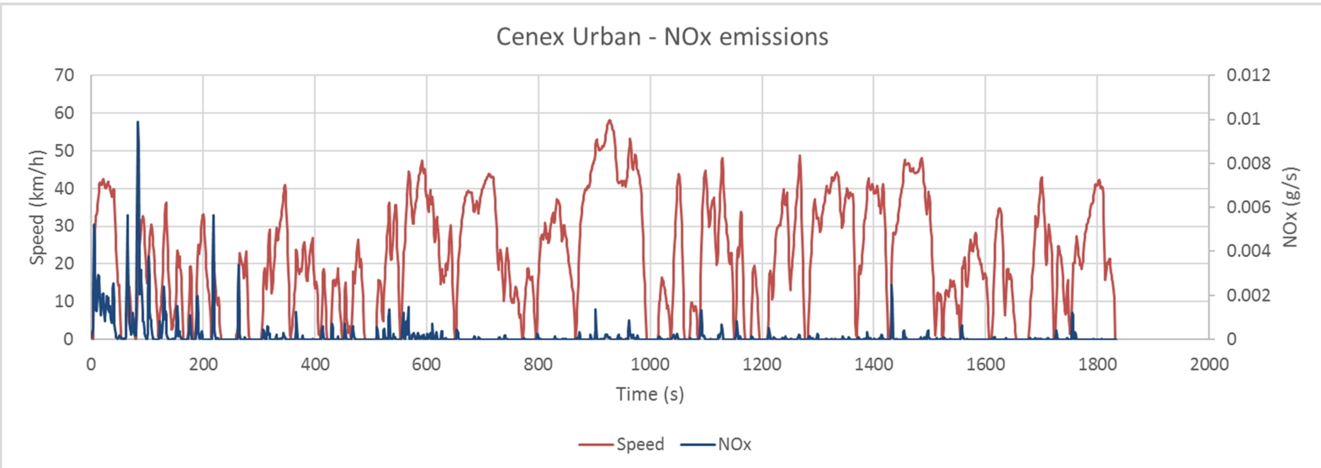

Figure 17: NOx emissions for petrol scooter in Cenex urban cycle

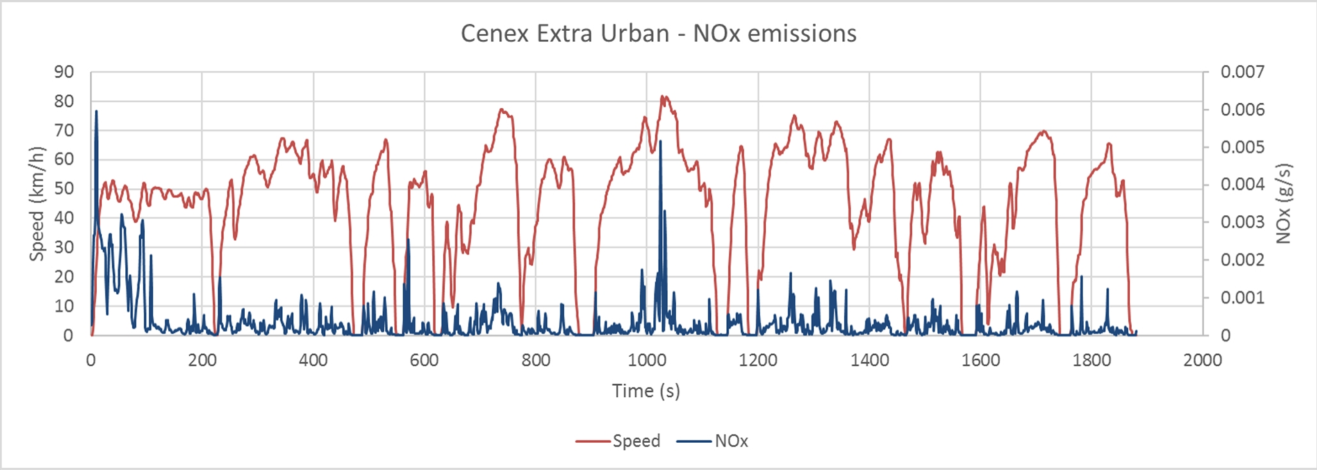

Figure 18: NOx emissions for petrol scooter in Cenex extra urban cycle

The effect of a cold start can be observed in both Cenex real-world drive cycles (shown above), in which it took between 4 and 5 minutes for the 3-way catalytic converter to reach the effective operating temperature and for the NOx emissions to stabilise at lower levels. A catalytic converter is a device fitted in the scooter exhaust containing materials such as platinum that transform NOx, CO and THC into CO_2, water and nitrogen via reduction and oxidation reactions. The cold start phenomenon was also observed in the THC and CO emission traces. To put this phenomenon into context using the Cenex urban cycle as an example, between 73 and 88% of the THC, CO and NOx emissions from the cycle were produced solely in this phase despite the fact that this cold start phase only represented 16% of the test duration.

4.3 Charging and battery efficiency

The charging efficiency in the electric scooter is defined as the ratio between the energy introduced in the battery and the energy extracted from the charging socket. The measured charging efficiency was 85%, which is similar to tests performed by Cenex in cars. The measured usable battery capacity was 29% less than the quoted value, yielding a range of 92 km as opposed to the quoted 134 km (31% less).

Table 5: Charging tests in the electric scooter

Electric scooter charging tests: full charge from a domestic socket						
Experiment	Quoted battery capacity (kWh)	Energy at battery terminals (kWh)	Energy from socket (kWh)	Efficiency	hh:mm	Average charging power (kW)
Charge 1	7.2	5.1	6.0	84.3%	04:43	1.3
Charge 2		5.2	6.0	85.9%	04:43	1.3
Average		5.1	6.0	85.1%	04:43	1.3

5 Vehicle modelling methodology

This section explains the structure of the vehicle models developed to replicate the performance of the scooters, as well as the process followed to calibrate them.

5.1 Model structure

Models of the scooters were created using the MATLAB/Simulink environment. There are two main vehicle simulation approaches (8):

- **Backward-facing approach:** This approach is typically used to estimate fuel consumption and emissions given a specific drive cycle. The driver behaviour is not modelled, and the forces required to drive the vehicle forward are calculated directly from the drive cycle. These forces are translated into a torque that must be provided by the component directly upstream. The vehicle linear speed is also translated into a required rotational speed. These calculations are carried backwards through the drivetrain against the tractive power flow direction, until the fuel consumption needed to meet the drive cycle is obtained.
- **Forward-facing approach:** This method is generally used to design hardware such as vehicle controllers. A driver model is included to account for the difference between the actual speed and the required speed, so that consequent brake and throttle commands are developed. The torque requirement is computed from the throttle command and then translated into the tractive force at the tyre/road interface.

A backward-facing approach was adopted in this case because the objective is to predict fuel and emissions rather than the design of components. A schematic layout of the model can be observed in Figure 19:

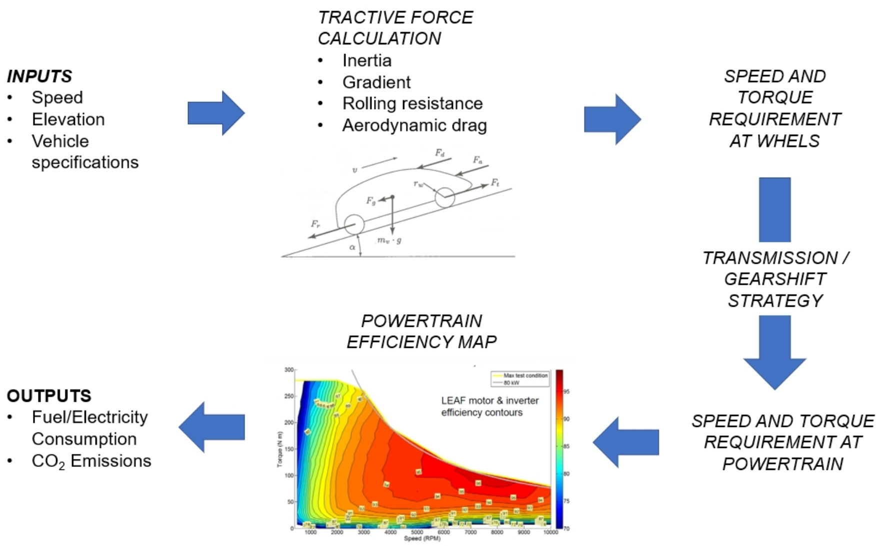

Figure 19: Vehicle model layout

Three main modules form the modelling process: tractive force calculation, transmission/gearshift strategy and fuel consumption calculation. Firstly, the speed and torque required at the wheels are calculated from the vehicle speed and the tractive force. Then, these two variables are translated into their counterparts at the engine through the transmission. As neither of the scooters have a gearbox, modelling of a gearshift strategy was not required in this case.

Once engine speed and torque are obtained, the efficiency of the components between the engine output and the power source needs to be modelled. This efficiency is dependent on the operating point of the vehicle, i.e. the speed and torque requirements. Therefore, component maps are required as a function of these 2 variables and are derived from test data or literature. The outputs of these maps are fuel/electricity consumption and CO_2 emissions.

5.2 Model calibration methodology

In order to analyse the results of the model and compare them to the calibration data, it is key to evaluate different parts of the model independently instead of looking at the final result (the fuel consumption) in the first instance. In the latter case the assumptions taken in the different modules of the model can interact and affect the final result, therefore being difficult to ascertain which of them is causing any mismatch in the outcome. However, if the modules are analysed separately, we can isolate the effects of the different assumptions and address any mismatches that are associated to them. There were three main modules in the model and they were evaluated independently: tractive force calculation, transmission, and powertrain map. Each of them was linked to a different variable measured in the tests, as shown in Table 6.

Table 6: Model variables used for calibration

Module	Variable used for calibration	
	Electric scooter	Petrol scooter
Tractive force	Dynamometer force	Dynamometer force
Transmission	Motor rotational speed	Engine rotational speed
Powertrain map	Battery power	CO_2 emissions

Tractive force. In order to calibrate the tractive force module, the force requested at the tyre-road interface was calculated as the sum of these forces:

- **Inertia**: force required to accelerate the vehicle. Only linear inertia was considered, rotational inertia of components such as wheels and axles is only relevant to heavy vehicles like trucks.
- **Gradient**: force needed to climb a slope, which was assumed to be zero as the tests were performed on a dynamometer.
- **Rolling resistance**: it represents the friction with the road, the coefficient was provided by the testing house as per (5).
- **Aerodynamic drag**: it represents the friction with the air, the coefficient was provided by the testing house as per (5).

The modelled force was then compared with the force measured by the dynamometer.

Transmission. The objective of this module is to accurately calculate the transmission ratio, which is defined as the ratio between the engine and the wheel rotational speed. If this ratio was correctly estimated, the modelled engine speed and the tested one should be very similar, and we would be ready to proceed with the last module: the powertrain map.

Powertrain map. This map provides an efficiency of the engine or motor given the values for speed and torque. The map was then refined so that the fuel or electricity consumption from the model were similar to the tested values within a +/- 5% tolerance level and the calibration would then be finished. The calibration process is shown in Figure 20.

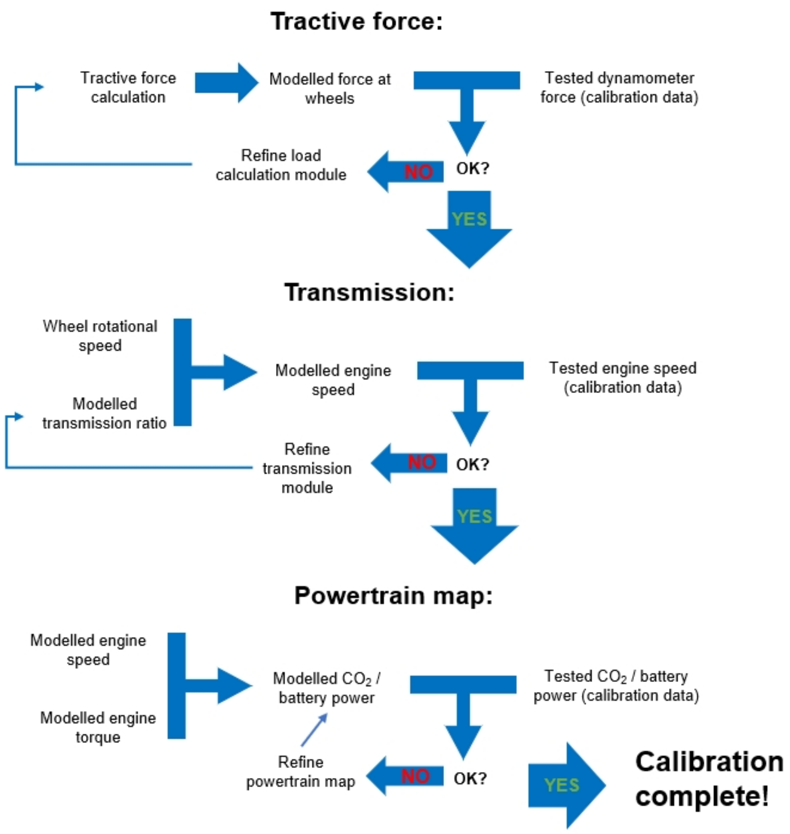

Figure 20: Process to calibrate a vehicle model

5.3 Model calibration results

5.3.1 Electric scooter

The tractive force calibration was highly accurate as shown in Figure 21. This is because the road load factors (aerodynamic drag and rolling resistance coefficients) and the tested mass were given by the testing house. The dynamometer simulates the road load in a controlled environment using these values. The tests excluded the impact of wind, rain, payload and road surface conditions, which are highly variable in real-world conditions.

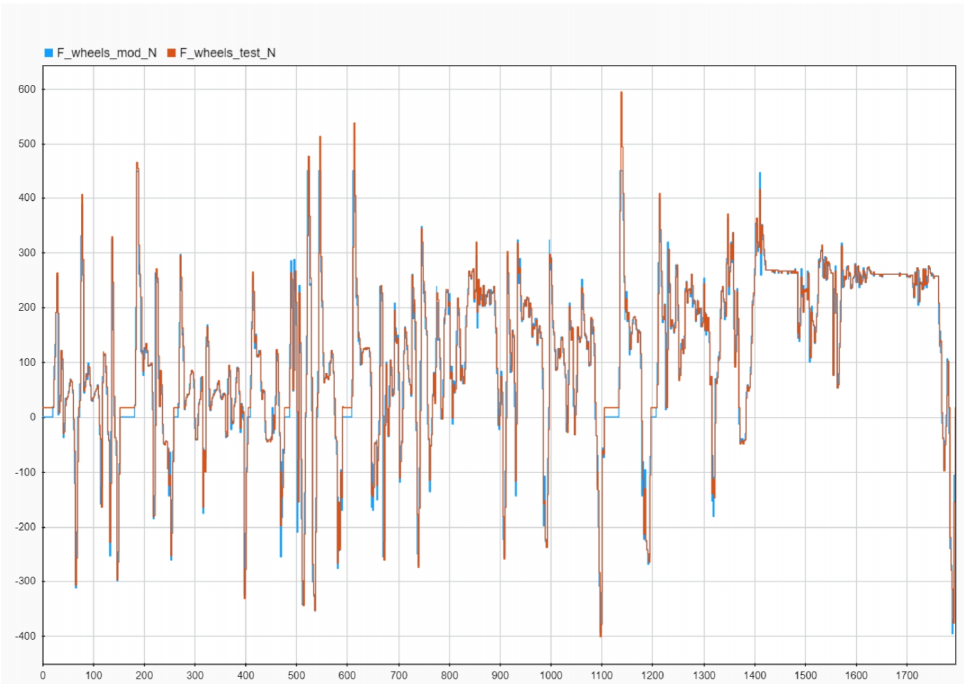

Figure 21: WMTC tractive force calibration in electric scooter

The electric scooter has a fixed transmission ratio, which was derived from the test data by comparing measured wheel rotational speed and motor speed. Therefore, the calibration was highly accurate as observed in Figure 22. The mismatch observed in the last part of the drive cycle happened because of a measurement error due to the fact that the scooter was reaching its maximum speed.

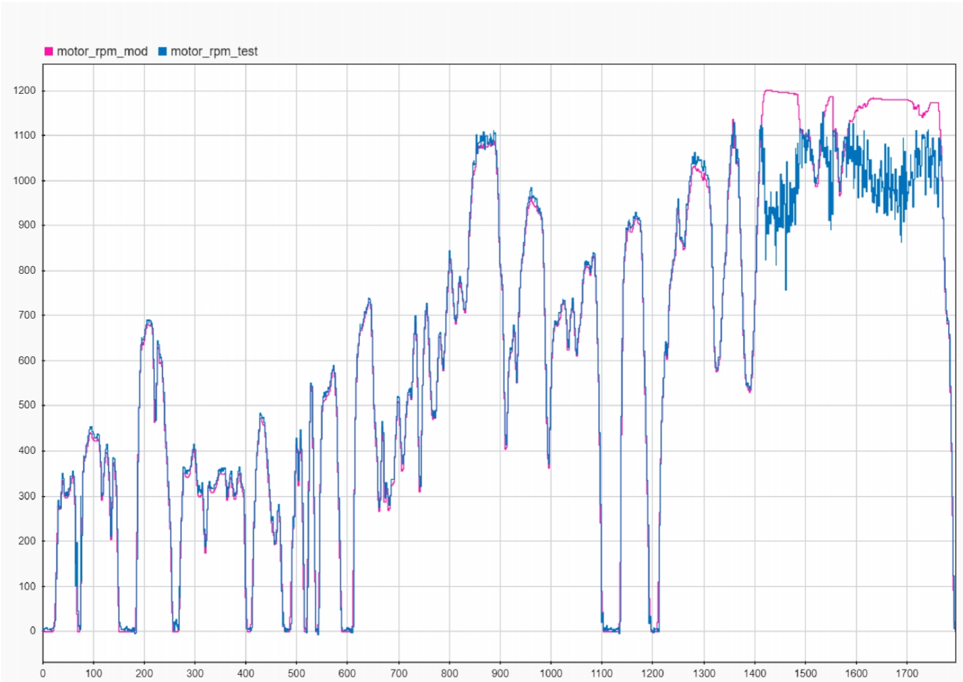

Figure 22: WMTC motor speed calibration in electric scooter

Finally, an attempt to obtain an electric motor map from the test data was unsuccessful. Therefore an existing motor map from a Nissan Leaf (9) was used as a base map and adjusted until a correct calibration of battery power was achieved, as observed in Figure 23. The map was refined in selected regions of speed and torque where there was a mismatch between the tested battery power and the modelled one. The powertrain torque was limited to a constant maximum value given by the manufacturer. The map refining took place separately for positive torque / acceleration (when power flows from battery to powertrain) and negative torque / deceleration (when power flows from powertrain to battery).

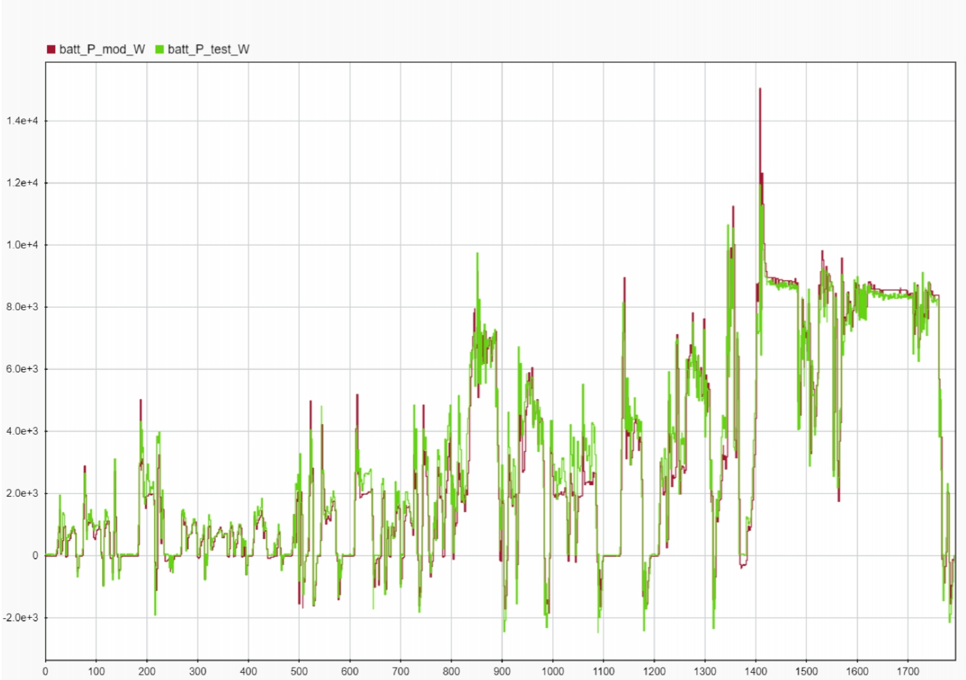

Figure 23: WMTC calibration of power at battery terminals in electric scooter

It must be noted that vehicles activate different zones of the speed-torque map in different drive cycles. Therefore, all 3 drive cycles tested (WMTC, Cenex urban and extra urban) were used for the calibration of the scooter models. This is a challenging task because a good calibration for a certain drive cycle can lead to a big mismatch in another drive cycle, and it is important to ensure that a vehicle model is accurate in a variety of driving conditions. This was achieved by the scooter models as the 3 drive cycles tested show a variety of urban, rural and high-speed driving. The calibration results are shown in Figure 24, where the cumulative net energy used by the battery as measured in the battery terminals is compared to the modelled results before and after the motor/generator map was refined. The percentage shown is the difference between the tested and the modelled results after the calibration.

Apart from the motor efficiency, the following factors were assumed:

- A mechanical transmission efficiency of 95% (10).
- An efficiency in the power electronics of 96%, (11) and (12).
- A charging efficiency of 85%, as measured by the testing house.
- A battery round trip efficiency of 93%, as observed by Cenex in previous tests with electric vehicles.

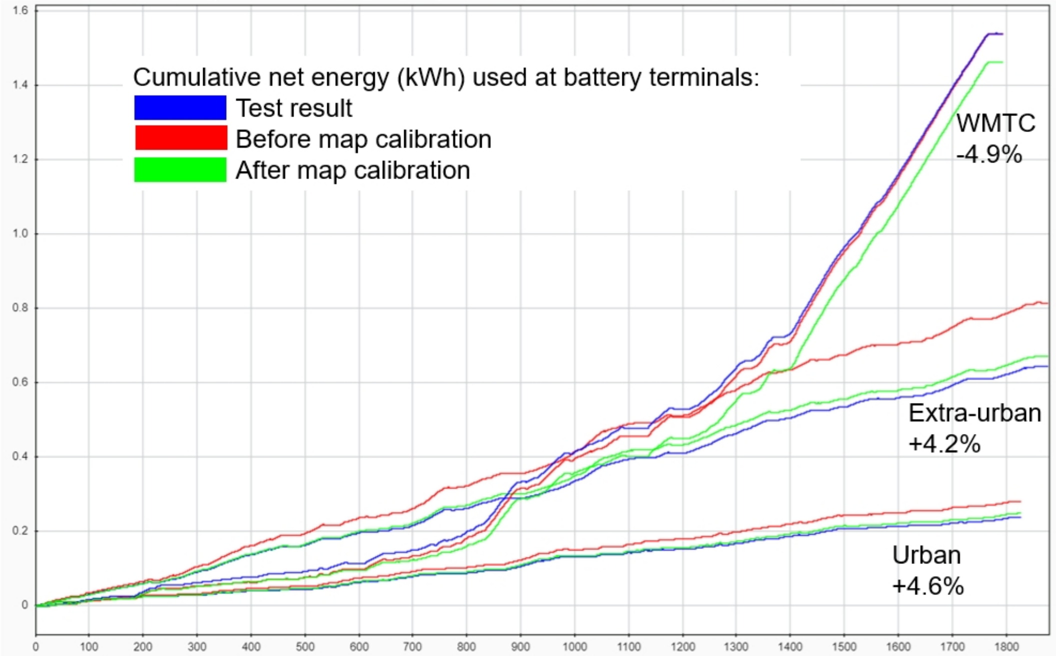

Figure 24: Calibration of cumulative net energy measured at battery terminals

5.3.2 Petrol scooter

The tractive force calibration was highly accurate for the same reason explained in 5.3.1. The petrol scooter has a pulley-based continuously variable transmission (CVT), also known as variator. As explained in (13), it consists of two pulleys connected with a V-shaped belt. By changing the axial position of the moveable sheave of each pulley, the pitch radius of the belt is changed and in turn the transmission ratio is modified as shown in Figure 25. One sheave of each pulley is connected to a hydraulic circuit and is controlled by the centrifugal force. With the hydraulic circuit the clamping force on each pulley can be varied, by modifying the clamping force the radius of each pulley can be changed, and so the transmission ratio.

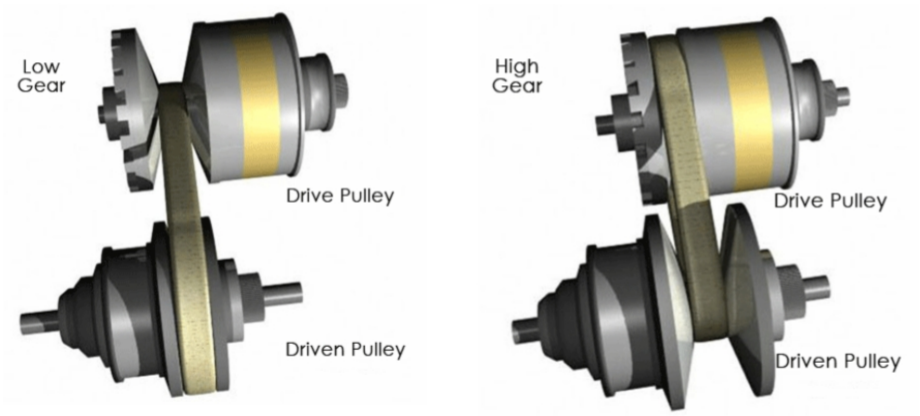

Figure 25: Different positions in a continuously variable transmission (CVT)

To model its performance, the transmission ratio from the tests was calculated as the ratio between the measured engine speed and the measured tyre speed. This transmission ratio was then plotted against the tyre speed as shown in Figure 26. The best fit for the trend across the results of all the tested drive cycles was a power curve that represents the centrifugal forces involved in a variator. This curve was fine-tuned and increased by 5% to match the engine rpm measured in the tests as shown in Figure 27. The measured rpm presents high levels of noise because the optical sensor used in the tests is capturing the vibrations of the combustion engine, so the model aims to have the best possible match considering this noise.

It must also be noted that the transmission model adopts a simplistic approach that is considered appropriate for the aim of the whole vehicle model, which is to estimate energy consumption. Further refinement could include modelling of the variator performance under different conditions of speed and torque as per (14).

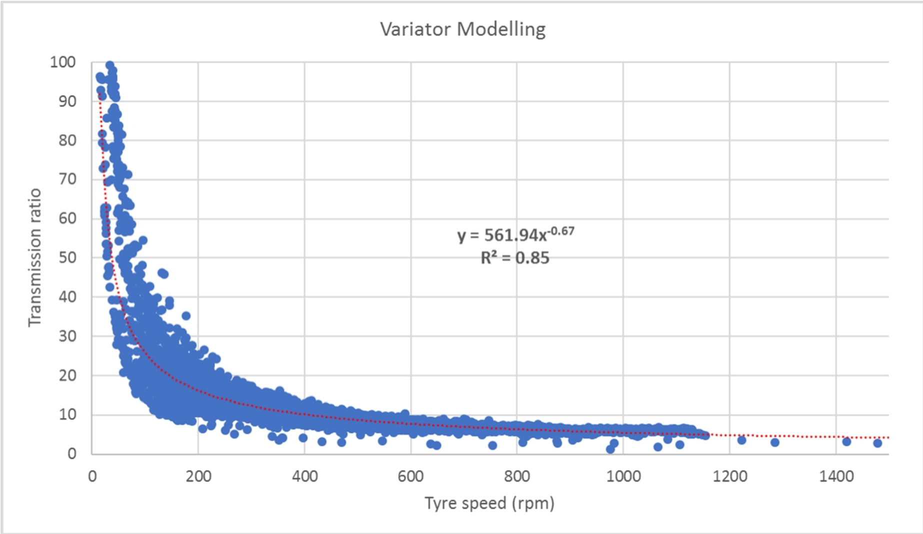

Figure 26: Power-curve fit of transmission ratio as a function of tyre speed

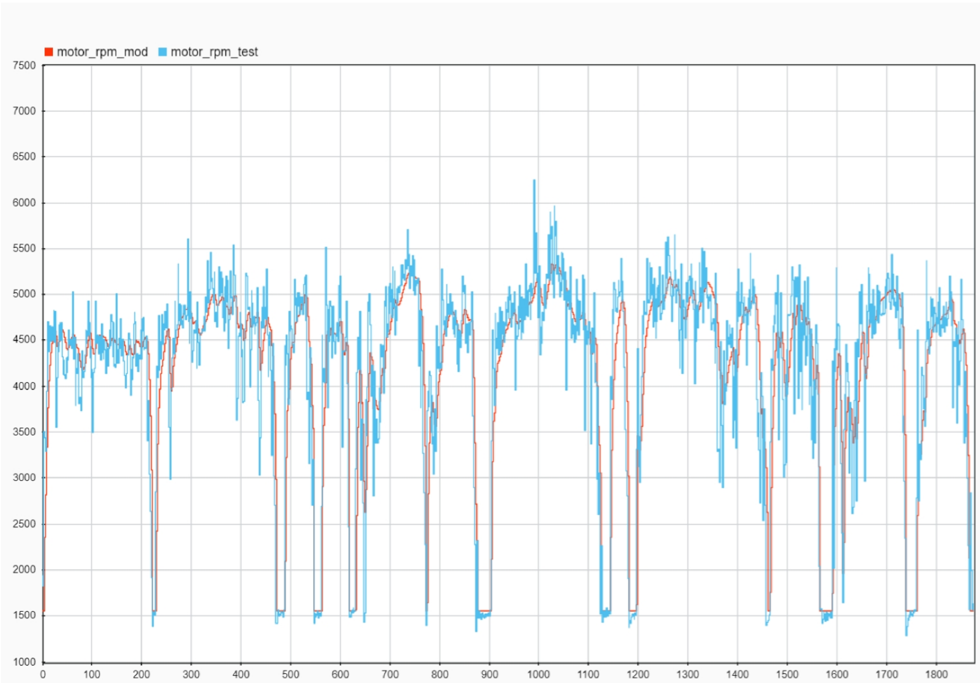

Figure 27: Extra urban calibration of motor rpm in petrol scooter

Once the tractive force and the transmission ratio were calibrated, the engine map was refined. The engine torque feeding into the map was limited by the maximum available torque at any given rpm, as shown in (15). An in-house 1.2 litre gasoline engine map for a small car was used as a starting point, and it was modified until the tested instantaneous CO_2 emissions matched the modelled ones in all 3 drive cycles. It must be noted that the final iteration of the scooter engine map was about half as efficient as the car map used as a starting point due to the lower volume per cylinder ratio as explained in 4.1. Moreover, the advanced materials and technologies used in some cars are not generally used in scooters, causing higher ancillary and friction losses. Apart from the engine efficiency map, a mechanical transmission efficiency of 95% was assumed as per (10). The idling fuel consumption and idling rpm were derived from the tests isolating the periods when the drive cycle speed is zero. The instantaneous calibration for the WMTC in CO_2 grams per second is shown in Figure 28 and the cumulative CO_2 emissions in grams before and after the calibration are shown in Figure 29.

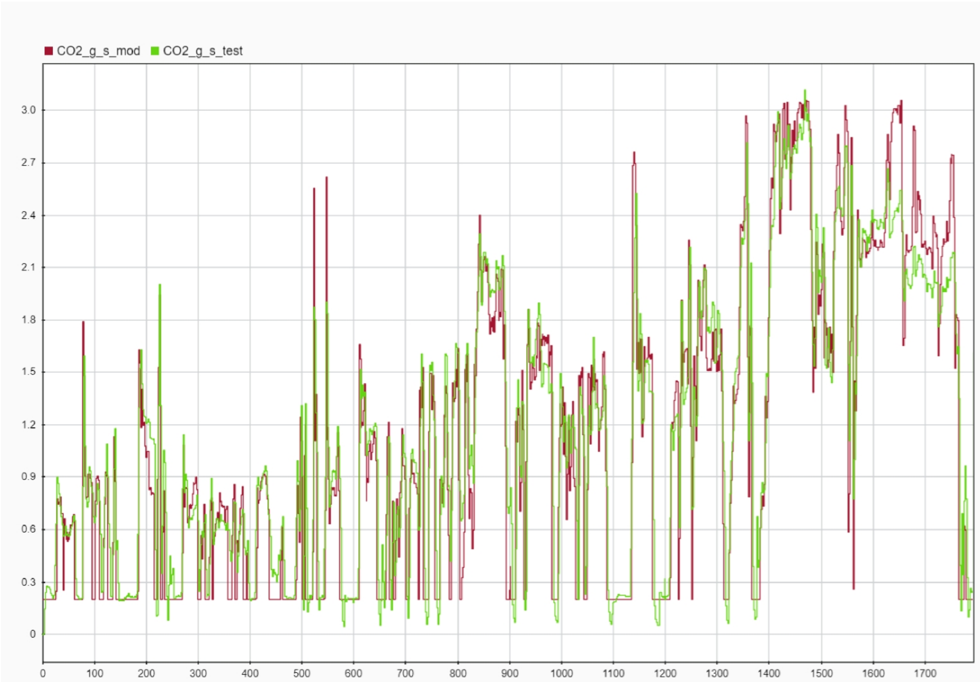

Figure 28: WMTC calibration of CO_2 emissions in grams per second

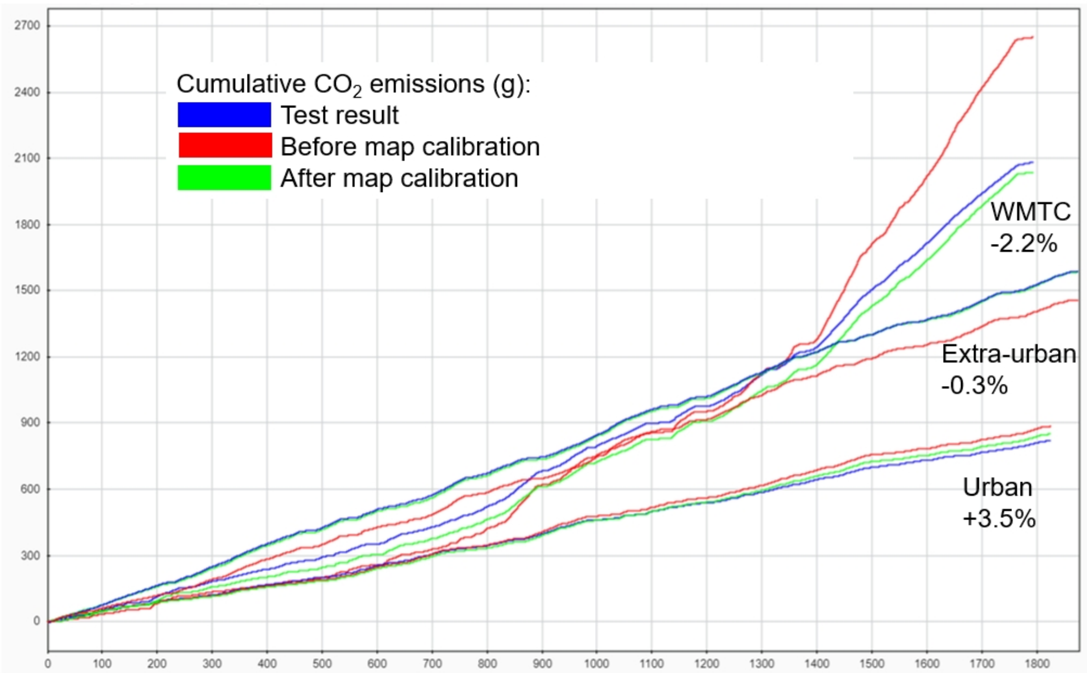

Figure 29: Calibration of cumulative CO_2 emissions

6 Simulation of standardised vehicles and future grid mixes

This section shows the results from the simulation of standardised scooter models across a mix of current and future grid mixes.

6.1 Scooter model standardisation

Once the electric and petrol models were calibrated, the inputs to the model (drive cycle and vehicle specifications) can be altered to simulate different scenarios. The power rating and mass of the 2 tested scooters is different, so the specifications of both vehicles were standardised as shown in Table 7, where the actual mass is the weight of the motorcycle with a full tank of fuel and a driver of 75 kg (5). A minor adjustment in the aerodynamic drag and frontal area was also made to standardise them, so that the only difference between the petrol and electric standardised models was the powertrain. This standardised model is representative of a 250cc scooter driven mainly in city centres, and it is called ‘medium-power scooter’.

Table 7: Simulated standardised scooter

<table>
<tr><td colspan="2">Example scooter</td><td>E-fun Puma</td><td>Yamaha X-Max 250cc</td></tr>
<tr><td colspan="2">Powertrain</td><td>Electric</td><td>Petrol</td></tr>
<tr><td rowspan="4">Scooter specifications</td><td>Actual mass (kg)</td><td>200</td><td>260</td></tr>
<tr><td>Max motor mech. power (kW)</td><td>12.6</td><td>11.9</td></tr>
<tr><td>Aerodynamic drag coefficient * frontal area (m^2)</td><td>0.49</td><td>0.51</td></tr>
<tr><td>Rolling resistance coefficient</td><td>0.009</td><td>0.009</td></tr>
<tr><td rowspan="5">Standardised model</td><td>Name</td><td colspan="2">Medium power (250cc)</td></tr>
<tr><td>Actual mass (kg)</td><td colspan="2">260</td></tr>
<tr><td>Max motor mech. power (kW)</td><td colspan="2">11.9</td></tr>
<tr><td>Aerodynamic drag coefficient * frontal area (m^2)</td><td colspan="2">0.51</td></tr>
<tr><td>Rolling resistance coefficient</td><td colspan="2">0.009</td></tr>
</table>

6.2 WTW emission grid mix scenarios

The electric and petrol ‘medium power’ scooters were then simulated over the 3 drive cycles to calculate the energy consumption and greenhouse gas WTW CO_2e emissions. In the case of the electric scooter, 3 different grid mixes were used to calculate the WTW CO_2e emissions:

- Current UK average grid mix as stated in (7), with the following split in the source of the energy generation: 45% natural gas, 40% nuclear and other renewables, 10% coal and 5% thermal renewables (16).
- UK grid mix from a predicted 2030 optimistic energy scenario based on a centralised generation and a high speed of decarbonisation. In this scenario there are high proportions of offshore wind and nuclear with grid flexibility provided by interconnectors and larger scale storage (17).
- UK grid mix from a predicted 2030 pessimistic energy scenario assuming decentralised generation and a low speed of decarbonisation. In this scenario generation is focused on smaller scale renewables, with some new large scale nuclear power stations but also

some small modular reactors. There would be greater emphasis on domestic and national energy solutions leading to lower levels of electricity interconnection (17).

6.3 Simulation results

Figure 30 below shows the WTW CO_2e emissions for the medium-power petrol and electric scooters, where the percentage figures represent the difference of EV vs petrol. For the current grid mix, the CO_2e savings from the electric compared to the petrol scooter ranged from 75% to 88% (depending on the drive cycle) due to the higher efficiency of EVs compared to petrol/diesel vehicles. For the 2030 grid mix scenarios, all the CO_2e savings were above 89% even with the pessimistic assumptions, with the optimistic grid mix yielding WTW CO_2e savings of almost 100%.

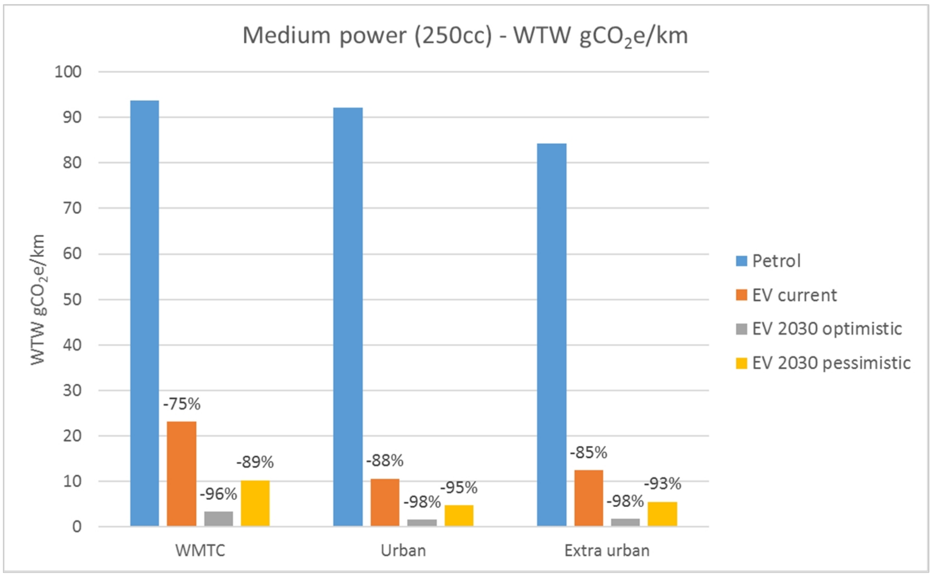

Figure 30: Simulated WTW GHG CO_2e emissions for medium-power scooters

Figure 31 below shows the energy usage for the modelled standardised scooters, with the percentage figures showing the difference of EV vs petrol. As mentioned in the test results (section 4), EVs normally consume 50 to 70% less energy than ICEVs (6); here the energy consumed by the electric scooter was 77 to 89% less than the petrol scooter. The reason for this lies in the low efficiency of the scooter gasoline engine (half as efficient as the engine in a small car, see 4.1 and 5.3.2) compared to the motor in the electric scooter, which operated at a similar efficiency to that of an electric car. There is a caveat to this with the electric scooter in terms of the regenerative braking performance being worse than the one in an electric car: in the Cenex urban cycle the ratio between energy entering the battery and energy exiting the battery was 12% for the scooter model, while for the model of a medium electric car this ratio was 15%.

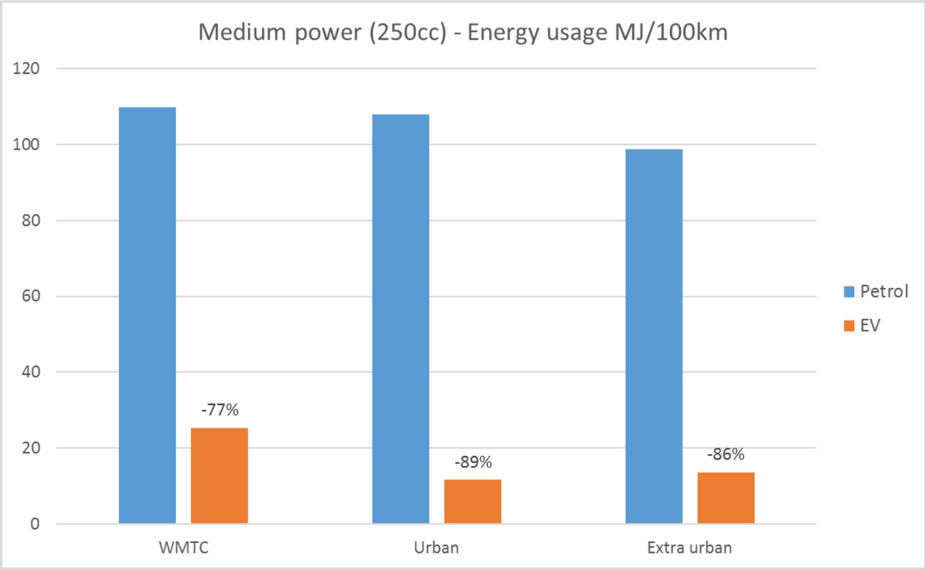

Figure 31: Simulated energy usage for medium-power scooters

7 Summary and recommendations

Scooter testing:

- A petrol scooter (Yamaha X-Max 250) and an electric scooter (E-Fun Puma) were tested in an emissions testing laboratory equipped with a chassis dynamometer for motorcycles.
- While typically EVs consume 50 to 70% less energy than ICEVs, the tested difference in energy usage when looking at scooters ranged from 72 to 91% less in the EV compared to the petrol scooter. The reason for this discrepancy is that, as discovered in the vehicle modelling task, the petrol scooter engine was much less efficient compared to a petrol engine in a car, whereas the motor in the electric scooter had a similar efficiency to the motor in an electric car. This means that there is potentially a bigger opportunity for environmental savings when switching from ICEVs to EVs in 2-wheel vehicles compared to larger vehicles.
- The tested WMTC fuel consumption in the petrol scooter was only 0.8% higher than the quoted value given by the manufacturer also for the WMTC. In the case of the electric scooter, the tested WMTC energy usage was 3.3% lower than the quoted value for the WMTC. In terms of the Cenex real-world drive cycles, the tested urban fuel/energy consumption figures were 1% and 53% lower than the quoted ones for the petrol and electric scooters. The tested extra urban values were 10% and 40% lower than the quoted ones for petrol and electric respectively. The electric scooter clearly performed above expectations in the real-world cycles showing a significantly lower energy consumption compared to the manufacturer specifications.
- Using the 2018 UK average grid mix, the electric scooter emitted 70 to 90% less greenhouse gas WTW CO_2e emissions than the petrol scooter.
- The THC, CO and NOx tested emissions from the petrol scooter were 71%, 34% and 58% lower than the Euro 4 regulatory limits in the WMTC part 2 cycle, the part of the cycle against which the Euro standards must be compared as per the regulation. If the comparison is made in WMTC parts 1 & 3, the tested values are similar or higher than the Euro 4 limits, which shows that the scooter is optimised to perform well in the part 2 of the WMTC. The petrol scooter performed very well in terms of NOx in the urban and extra urban cycles created by Cenex, with a reduction of 71% against the Euro 4 standard.
- The petrol scooter was tested under a cold start for every cycle to simulate real-world conditions. The effect of a cold start can be observed in the THC, CO and NOx emission traces as it took between 4 and 5 minutes for the catalytic converter to reach the effective operating temperature. Even though this cold start phase only represented 16% of the test duration, between 73 and 88% of the THC, CO and NOx emissions from the Cenex urban cycle were produced solely in this phase.
- The charging efficiency in the electric scooter was measured as 85%, while the measured usable battery capacity was 29% less than the quoted value, yielding a range of 92 km as opposed to the quoted 134 km.

Vehicle modelling:

- Backward facing models of the scooters were developed using the results from the tests. In these types of models, the forces required to drive the vehicle are calculated directly from the drive cycle and are translated into a power that must be provided by the upstream components.
- The three main modules in the modelling process are tractive force calculation, transmission and fuel consumption calculation, and they must be evaluated independently to isolate the assumptions made in each of the modules.
- The petrol and electric scooter models were calibrated to the test results for all the tested drive cycles under a tolerance in fuel/electricity consumption of +/- 5%.

Simulation of scenarios:

- The vehicle specifications were altered in the models to standardise them to a medium-power scooter equivalent to a 250cc model.
- 3 different electricity grid mixes were used to calculate the WTW CO_2e emissions in the EV: the current grid mix, a predicted 2030 low carbon intensity (optimistic) scenario and a predicted 2030 high carbon intensity (pessimistic) scenario.
- Using the current grid mix, the WTW CO_2e emissions from the electric scooter were 75% to 88% less than the petrol scooter. Using the 2030 grid mix scenarios, all the WTW CO_2e savings were above 89% even with the pessimistic assumptions, with the optimistic grid mix yielding WTW CO_2e savings of almost 100%. It must be noted that the major source of CO_2e savings comes from the change of technology rather than the use of a future grid mixes, although the use of EVs must be linked to an increased penetration of renewables to make environmental sense.
- The energy consumed by the electric scooter was 77 to 89% less than the petrol scooter due to the low efficiency of the gasoline engine compared to the electric motor.

Recommendations for further work:

The use of 2-wheel vehicles in cities may rise as cities become more congested and restrictions are placed on the type of vehicles able to operate within inner city boundaries. A literature review showed very little data available in the public domain regarding real-world 2-wheel driving cycles or air quality emission data. Whilst this study has identified some real-world duty cycle information and emission data from scooters, the author accepts this is from a very limited usage pattern and scooter sample size. This limited testing suggests that the well-publicised large discrepancies observed between real-world and legislative emission performance in cars is not as pronounced in the scooter vehicle segment. It is recommended that this work is further expanded to understand a wider breadth of operating cycles and the real-world emissions and energy consumption of motorcycles and scooters to understand further how lower emission variants of these vehicles can assist air quality improvements in cities and overall GHG reduction.

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