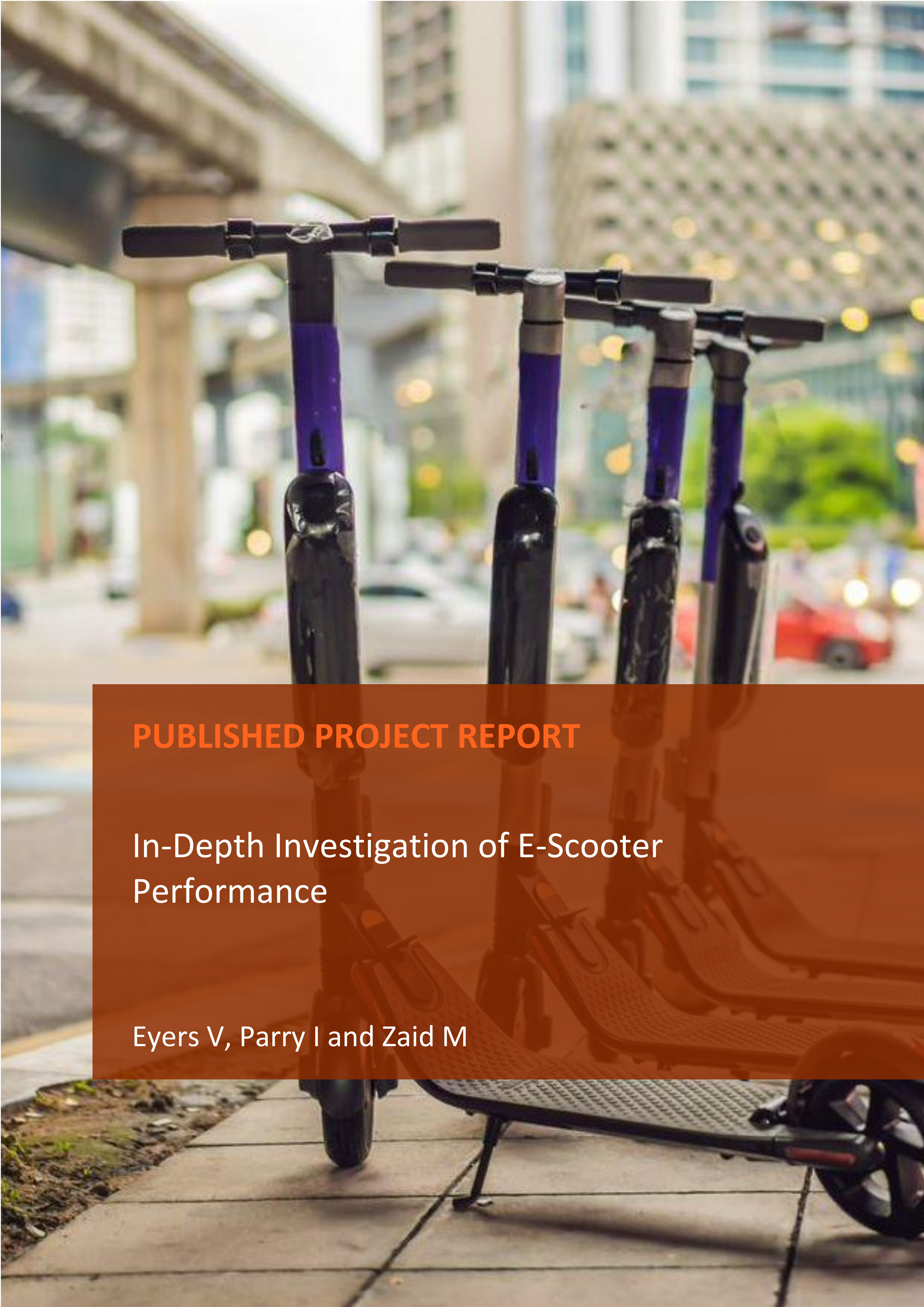

PUBLISHED PROJECT REPORT

In-Depth Investigation of E-Scooter Performance

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Executive Summary

E-scooter use is increasing, and with it, the number of collisions involving e-scooters. The rapid rate of uptake of devices has resulted in a gap in the reference data available for collision investigators to make use of in reconstructing collisions, data which is commonly available for other collision types.

The main aim of this study was to consider the capabilities of privately owned devices likely to be encountered in 'real world' collision scenarios and examine whether manufacturer-published data is realistic. Common characteristics and observations relevant to collision investigations were also recorded. A sample of donated, used devices was tested to determine the acceleration, deceleration and peak speed characteristics of different types of device. It was found that:

- Mean acceleration across all devices was 2.82ms^{-2} with a standard deviation of 1.14ms^{-2}.
- The strongest predictor of acceleration capability was motor size, with 500W devices having a mean acceleration around 2ms^{-2} greater than the 250 – 350W devices.
- Increasing rider mass produced inconsistent variations to acceleration. This is an area which warrants further study, particularly in relation to devices being ridden with a second rider instead of a heavier single rider.
- The effect of tyre pressure variation on acceleration was inconsistent.
- All devices were found to over-state their peak speed. Where fitted, speedometer readings over-stated true speeds by 2.5 – 5km/h, and peak speeds were found to be between 1.5 and 11km/h lower than manufacturer-stated maxim values.
- Deceleration rates across the sample were more consistent. The mean result for the whole sample was 3.43ms^{-2} or 0.350*g* (standard deviation 0.53ms^{-2}).
- Devices with disc brakes produced slightly higher decelerations than drum brakes and decelerations were greatest overall when using foot brakes (although with a significantly smaller sample).
- Wheel lock up was delayed or prevented when the rider was weighted, resulting in lower average deceleration rates.

In addition to these objective test results, assessment of the sample of e-scooters highlighted a number of maintenance issues which may be encountered among privately owned devices. In the sample, more than 50% of devices had brakes or steering in unserviceable condition, and 40% had broken or missing rear mudguards, often resulting in loss of the rear light assembly. Tyre maintenance was a common problem, with an average under-inflation of pneumatic tyres of 55% observed.

Lastly, in some exploratory stability and handling tests we found that vertical obstructions of up to 40mm could be mounted without destabilising the rider. Whether higher obstructions will have destabilising effects is partly dependent on the angle of approach, but predominantly dependent on rider input. The likelihood of destabilisation will rely on the rider's skill and experience. This is also true of swerve manoeuvres. Specific conditions for creating destabilisation and falls were not quantified in this study.

The study has produced a set of reasonable reference data that can be referred to in reconstructions of collisions. Although a number of areas worthy of further investigation have been identified, across general categories of acceleration and deceleration, consistent results were found. The study also highlighted relevant observations such as those relating to device condition and handling, which will be worthy of consideration when investigating e-scooter collisions.

1 Introduction

Recent years have seen a proliferation in the use of e-scooters (electric scooters) on UK roads. Since August 2020 DfT trials of e-scooter rental schemes have been taking place in 31 Local Authority areas[1]. These schemes have provided public access to shared e-scooters in (primarily) urban settings, to users with a full or provisional driver's licence.

E-scooters offer personal transport alternatives to the car and as such could assist in the push to reduce carbon emissions from transport, whilst also reducing the air quality impacts of car use. In the post-COVID-19 era e-scooters also offer an alternative to shared public transport and in addition to public cycle and e-cycle hire schemes, offer a form of publicly accessible personal transporter device.

In parallel with the roll-out of shared e-scooter trials, which includes an estimated 23,000 devices, PACTS[2] estimates there are 750,000 privately owned e-scooters in use in the UK. Privately owned e-scooters are currently classed as motor vehicles and as such need to be type-approved and insured, and the user requires a driving licence. Since these conditions cannot be met in practice, private e-scooters are illegal to use on roads and public areas; their legal use in the UK is restricted to private land only. Nevertheless, private e-scooters are now an increasingly common sight on the UK's roads and footways.

Whilst road collision data sources are evolving to accommodate the reporting of micromobility devices in road traffic collisions, the current evidence[3] shows such collisions are increasing; there were 1437 casualties in collisions involving e-scooters in the year ending June 2022, compared to 1033 in the previous year; in 2021 82% of these involved private e-scooters; 38% of all casualties sustained serious injuries; casualties are largely male (about 70%); and about 50% of casualties are under 24 years of age. Around 24% of casualties in e-scooter collisions were not the rider (predominantly pedestrians and cyclists but injuries to all types of road user were reported). The reported percentage of serious injuries is high relative to slight injury, and therefore it is likely that the actual number of e-scooter related injuries are under-reported.

The trend in e-scooter use, particularly uninsured private e-scooters with high rates of incident involvement, brings concerns for transport authorities, road safety practitioners and the providers of motor vehicle insurance. Should the trend towards e-scooter use continue, motor vehicle insurers may find claims derived from e-scooter incidents to increase significantly. To investigate claims arising from e-scooter collisions involving insured drivers it is necessary to review and test the specifications of e-scooters, particularly privately owned devices.

This study aimed to investigate the 'real world' capabilities of such devices and consider how they may differ from regulated rental devices, in order that reference data be made available for use in investigations of collisions involving them. Collision reconstructions

[1] Over 50 fleets have launched: https://zagdaily.com/featured/the-definitive-guide-to-the-uks-e-scooter-trials/

[2] PACTS-The-safety-of-private-e-scooters-in-the-UK-Final-Report (2022)

[3] Ibid & 'Reported road casualties Great Britain: e-scooter factsheet year ending June 2022', Department for Transport

frequently need to make use of published data to estimate likely values for variables such as bicycle or pedestrian speeds, acceleration and braking rates, where specific data for a collision is not available. An aim of this study was to produce such data relating to e-scooters which can be applied to reconstructions of incidents involving them. The TRL Expert Witness team delivers expertise in all areas of incident investigation, for public and private sector clients including solicitors, police and government bodies, in both Criminal and Civil proceedings. The data and learnings from this Strategic Investment Project supports TRL's on-going Expert Witness work, ensuring we can continue to offer robust and informed advice to our clients.

2 Devices used for testing

In some cases e-scooter manufacturers provide data on e-scooter performance and specifications, although often there is considerable ambiguity and missing or hard to find data. A secondary aim of this study was therefore to consider whether published data, when available, is actually realistic, and whether variation in other features would come to be relevant to collision reconstruction once the devices were being used in 'real world' situations. For the study, 26 donated e-scooters were received, which had been in use on public roads up to the time of donation. It is noted that published data such as acceleration and deceleration rates may often refer to results derived from testing with GNSS-based equipment, which may be considered insufficiently precise for collision investigation purposes.

All devices were mechanically examined before testing for safety reasons. Those with unsatisfactory braking operation were, where possible, adjusted to ensure unladen locking of wheels under brake application. Devices were removed from testing if they could not be made safe.

Table 1: E-scooter sample specifications

Max rated speed (km/h)	**n**
20	4
25	12
30	3
Unknown	2

Motor Power (W)	**n**
250	6
300	4
350	6
500	3
Unknown	2

Weight (kg)	**n**
<13	7
13 - 15	10
>16	4

Tyre Type	**n**
Solid	10
Pneumatic	9
Mix (Pneumatic front, Solid rear)	2

Brake Type	**n**
Disc	16
Drum	4
Foot	1

Brake Location	**n**
Front	4
Rear*	17

Start Type	**n**
Push Start	18
Instant Power	3

Wheel Size (Inches)	**n**
≤ 7	3
8 – 8.5	12
9	1
≥10	5

*All drum brakes were located on the front wheel

n = number of devices

Of the 26 donated devices, two were inoperative and unsuitable for testing. A further three were rendered unusable because the brakes could not be made serviceable. The final sample therefore consisted of 21 devices; these were subjected to acceleration, deceleration and average speed testing (see section 3). The sample included several 'repeats' of the same make and model, and included some of the most common device types in use by private owners. The main device characteristics within the sample are shown in Table 1.

2.1 Findings from initial observations of devices

2.1.1 Speed modes

All of the sample devices had three speed modes. Terminology varied between manufacturers, but the most commonly used configuration was 'Eco', 'Drive' and 'Sport'. The manufacturer-stated maximum speed was available in 'Sport' mode, and the other two modes progressively throttled down the maximum achievable speeds to varying degrees. All testing was carried out in the maximum power/speed mode for each device since it is expected this will most likely be the most commonly used mode for most riders. Mode selection was commonly via a double press of the power button, and usually resulted in a change in a colour coded light on the control panel, often illuminating 'E' 'D' or 'S' (or a corresponding letter where terminology differed). In the context of collision investigation, this should allow investigators to easily determine what mode a device was being used in prior to a collision (since the mode is unlikely to easily be altered during a collision).

2.1.2 After-market tampering

The authors are aware that privately owned devices may be augmented or otherwise tampered with to increase performance. Comparison of testing speeds with manufacturer published data indicates this was not the case with any of the test sample; this may be an area for future investigation, although consistency of results will likely vary more widely for derestricted devices than unmodified ones.

2.1.3 Brake configuration

The majority of devices had a secondary regenerative or electronic brake in addition to a mechanical drum, disc or foot brake. Both types of secondary brake had a similar operation, with regenerative brake effort providing supplementary battery charging. Secondary braking was activated either by releasing the throttle, or upon application of the brake lever. Rarely, there was a separate lever for isolated activation of the secondary brake. In most instances the mechanical brake could not be operated independently of the secondary brake. Within the tested sample, the secondary brakes were of low efficiency and generally insufficient to effectively bring the device to a halt quickly. Therefore, in 'normal' usage, it is to be expected that the secondary brake would not provide an effective means of urgent braking in response to a hazard and that it would not be reasonable for a rider to be assumed to rely only on this in an emergency situation. However, riders may be expected to use the secondary brake alone in non-emergency situations.

In order to maintain consistency across devices when considering the maximum braking capabilities, all deceleration tests used the mechanical brake with secondary braking also activating as dictated by the device. The majority of braking was with the mechanically-braked wheel locked. The typical braking configuration was for the secondary brake to be located on the front wheel and the primary brake to be located on the rear wheel. This arrangement provides optimal stability under high braking. The exception was with a small number of relatively higher-powered devices where primary brakes were located on the front. High levels of braking at the front wheel were noted to cause instability through lifting of the rear wheel causing the device and rider to pitch forward, potentially leading to rider separation from the device.

2.1.4 Layout of controls

Throttle application was most commonly via a thumb lever on the right handlebar, or sometimes via a twist grip. Figure 1 shows a common layout of e-scooter controls, for a device without a speedometer, and Figure 2 shows a typical layout for an e-scooter with a speedometer. Where a device does not have a speedometer, a display typically showed a simple set of LED lights to indicate parameters such as battery strength and mode. All devices in the sample had either a speedometer or an LED display.

A table of device makes/models and relevant specifications is shown at Appendix A.

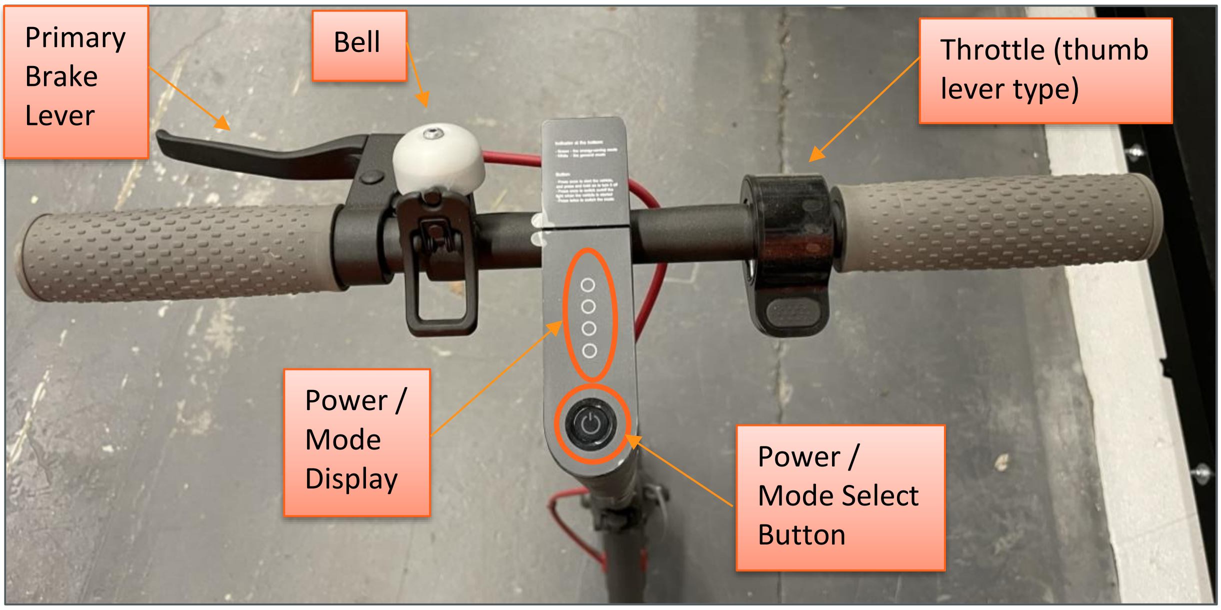


Figure 1: Typical layout for e-scooter controls (no speedometer)

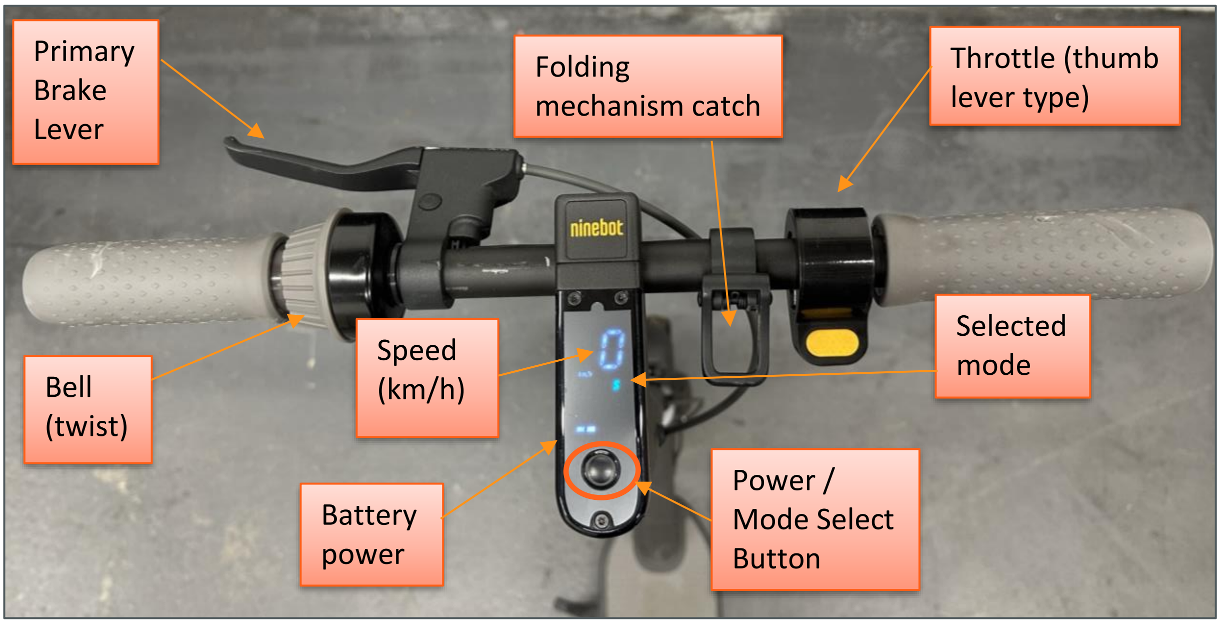


Figure 2: Typical layout for e-scooter controls (with speedometer)

3 Tests of acceleration, deceleration and average speed

3.1 Method

3.1.1 Test location and rider

All testing was carried out within a paved and level test area at TRL's head office in Crowthorne, Berkshire. The test area was 100 metres long by 13 metres wide, with a negligible gradient of 0.05°. The road surface consisted of asphalt with rolled stones, in good condition.

Figure 3: Test area with rider approaching the camera and speed gun, with a second speed gun at the far end

A single test rider was used for all testing, for consistency. Rider mass was 84kg, although additional mass was added for some tests, by the addition of a weighted backpack (20kg).

3.1.2 *Test procedure*

Starting at one end of the test area the rider accelerated at maximum capability, continued at maximum power at an indicated constant maximum speed, then decelerated at a user-defined maximum, i.e., the maximum rate at which the rider could maintain control.

For each run, the acceleration, peak/average speed and deceleration was measured. Each device was tested in four runs for a given configuration. Acceleration and deceleration was potentially variable and in the real-world will be highly dependent upon rider experience; for the purposes of the test a single rider was used ensuring consistency across the test sample. We consider that the tests undertaken reflect the deceleration which could be readily achieved by a moderately experienced, competent and alert rider.

Several familiarisation runs were carried out for each device before proceeding with the tests. Runs were completed in both directions to minimise any effects from the slight gradient, with a radar gun at both ends. For push start devices, acceleration had two phases.

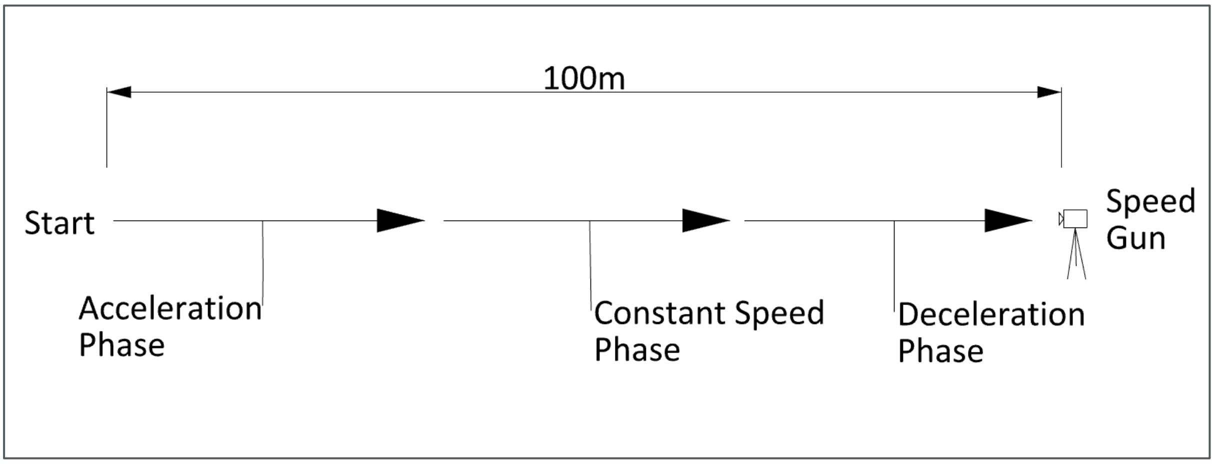


Figure 4: Schematic of the test area layout; the length of the constant speed phase varied and was dictated by the distance required for acceleration and deceleration

3.1.3 *Instrumentation*

Acceleration and deceleration were measured using a USB 3-axis accelerometer affixed to the front of the footplate. Where a device did not have a foot plate (e.g. if a device was designed to be ridden seated and did not have a foot plate) the accelerometer was rotated through 90° to fix to an alternative flat surface so the X axis still remained correctly orientated. The data was produced as a .csv file of acceleration values in the X, Y and Z axes. Multiple ‘runs’ could be recorded within a single file making data collection rapid. Due to file row number constraints, the final run or final deceleration segment was lost from some run groups.

Peak speeds were measured to the nearest km/h using a radar speed gun (see Figure 6), calibrated with tuning forks. Most devices with a speedometer provided speed in km/h. The maximum speed permitted for e-scooters within the UK DfT trials is 25km/h; all of the test sample were rated to a maximum of 25km/h or below, though we note that higher rated devices are available for purchase on the market and so may be encountered in private usage.

Figure 6: Speeds were measured using a radar speed gun mounted on a tripod at each end of the test area

Figure 5: Device and rider with the accelerometer mounted on the footplate and rider standing centrally

3.2 Analysis

The data file from the accelerometer included X-axis, Y-axis, Z-axis, time (128Hz) and other listed information as follows (see Table 2). An example extract from a raw data file is shown in Figure 7.

	A	B	C	D	E	F	G
1	;Title	http://www.gcdataconcepts.	x2-2	Kionix KXRB5-2050			
2	;Version	930	Build date	Oct 28 2014	SN:CCDC10021313C98		
3	;Start_time	1970-01-01	00:00:18.000				
4	;Temperature	-2.-25	deg C	Vbat	4140	mv	
5	;Gain	high					
6	;SampleRate	128	Hz				
7	;Deadband	0	counts				
8	;DeadbandTimeout	0	sec				
9	time	Ax	Ay	Az			
10	-11.663299	8563	12123	12968			
11	0.037358	-1050	-2084	-11099			
12	0.04517	-233	-2157	-10098			
13	0.052982	-295	-1122	-10371			
14	0.060794	-170	-263	-10814			
15	0.068606	-1259	139	-10749			
16	0.076418	-2104	-95	-7859			
17	0.08423	-902	-984	-9226			
18	0.092042	-75	-1097	-12972			

Figure 7: Raw accelerometer data

Table 2: Accelerometer data fields

Tag	Description
Deadband	A new sample from the sensor must exceed the last reading by the deadband value (a measure of sensitivity)
Deadband timeout	The period in seconds when a sample is recorded regardless of the deadband setting
Headers	The names of each column of data in the file
Sample Rate	Rate at which data is recorded to the microSD card
Start Time	The current time when the data file was created[4]
Temperature	Temperature of sensor in °C when data file was created
Title	The name of the USB Accelerometer X2-2 unit and sensor type
Vbat	Battery voltage measured at the file start time
Version	The version control information of the firmware, including unique serial number

3.2.1 Data conversion

As per the accelerometer manual, the raw data from the analogue-to-digital converter records the data file in signed "counts" units. To calculate the acceleration value in low gain mode (default), the axis values are divided by 6554. Similarly in high gain mode, the axis values are divided by 13108 to determine acceleration. Positive values correspond to acceleration in the direction of the axis.

For the study, X-axis acceleration was calculated by dividing by 13108 (High gain mode), as the e-scooter was known to have moved in the X-axis (which is forward) during the test runs.

By using kinematic equation 'v=u+at' the speed for each row can be calculated as all the necessary values are contained within the data file; u - initial speed (ms^{-1}); a – acceleration (ms^{-2}), t - time difference between 2 rows (s).

[4] The device time was not accurately set to present date/time due to a device fault

3.2.2 Using Python for calculation

	A	B	C	D	E	F	G	H	I	J
1		time	Time c	Ax	Ay	Az	Ax (g	a=ug	v=u+	Spee
2	**0**	-11.6633	11.70066	8563	12123	12968	0.653265			
3	**1**	0.037358	0.007812	-1050	-2084	-11099	-0.0801	-0.78582	-0.00614	-0.0221
4	**2**	0.04517	0.007812	-233	-2157	-10098	-0.01778	-0.17438	0.004777	0.017196
5	**3**	0.052982	0.007812	-295	-1122	-10371	-0.02251	-0.22078	0.003052	0.010987
6	**4**	0.060794	0.007812	-170	-263	-10814	-0.01297	-0.12723	0.002058	0.007409
7	**5**	0.068606	0.007812	-1259	139	-10749	-0.09605	-0.94223	-0.0053	-0.01909
8	**6**	0.076418	0.007812	-2104	-95	-7859	-0.16051	-1.57463	-0.007	-0.02519
9	**7**	0.08423	0.007812	-902	-984	-9226	-0.06881	-0.67505	0.001725	0.006209
10	**8**	0.092042	0.04404	-75	-1097	-12972	-0.00572	-0.05613	-0.00075	-0.00269
11	**9**	0.136082	0.007812	-1045	-827	-12017	-0.07972	-0.78208	-0.00536	-0.0193
12	**10**	0.143894	0.007812	-802	-1327	-11199	-0.06118	-0.60022	0.000673	0.002424
13	**11**	0.151706	0.007812	-622	-1500	-11956	-0.04745	-0.4655	-0.00296	-0.01067
14	**12**	0.159518	0.007812	-2445	-972	-11144	-0.18653	-1.82983	-0.01133	-0.04079

Figure 8: Exported data from Python

3.2.3 Value extraction

In total there were 48 raw data test files, each containing multiple ‘runs’. After plotting speed in an x-y graph from the exported Python data (see Figure 9), the three phases (acceleration, peak speed and deceleration) could be identified for each run. The peak speed values were validated against those recorded from the speed gun during the test runs.

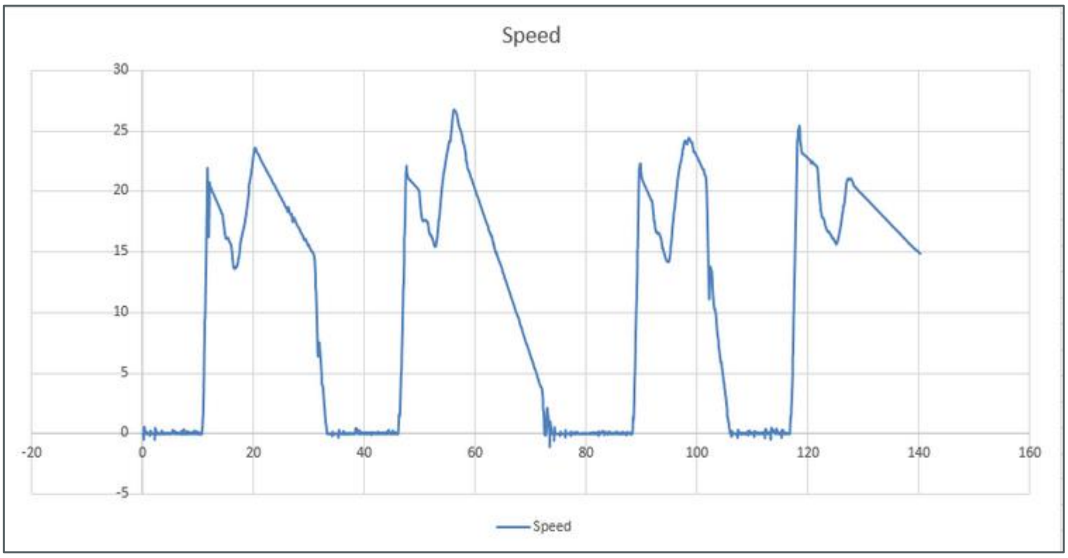


Figure 9: Speed – time graph (the final deceleration was lost from this file due to file row number constraints)

3.2.4 Plotting acceleration and braking phases

Every data file had a minimum of 2-4 acceleration and 1-4 braking phases, each test run was manually marked as A1, A2… for acceleration and B1, B2… for braking after manually examining the difference in increasing and reducing values of speed.

3.2.5 *Using Python for calculation and exporting the results*

Python was programmed to analyse the marked runs from the data files and to collate all the individual results in a single spreadsheet. Other values such as temperature, start date and time, speed from speed guns were also included in the spreadsheet. Table 3 shows the programmed values for calculation.

Table 3: Values extracted via Python programming

Values	Description
Time_Taken	The difference of time between the first and last marked rows in a particular test run
Final_speed_mps_v	The last marked row of speed value in a particular test run
Initial_speed_mps_u	The first marked row of speed value in a particular test run
Acceleration_rate_a	Calculated from using kinematic equation '(v-u)/t' by substituting the above values
Mu_value	Calculated by dividing acceleration rate by 9.81
Top_speed	The highest value of speed among the marked rows
Average_acceleration	Calculated the average acceleration rate from the marked rows

3.2.6 *Final compilation of data*

The data were grouped by device and acceleration/deceleration, then filtered by test parameters (e.g. weighted, altered tyre pressures, cold tests etc) and device specifications (e.g. motor power, brake type and tyre type). The mean and standard deviation were then calculated, first for the various runs for a single device with common test specifications, then for the various groupings. A small number of anomalous runs were identified and removed; these were where the standard deviation was greater than 1 before removal of the anomaly. The source of the anomalies varied but were generally thought to be due to rider error or inconsistency, or abandonment of a test due to an identified hazard approaching the test area. Ultimately, 215 runs were considered, 113 acceleration and 102 deceleration. A snapshot of the final datasheet is shown in Figure 10.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	scooter_number	csv_number	Combine	temp	start_date	start_time	Test Conditions	Peak Speed kph	type	type	Runs	time_taken_t	final_speed_mps_v	inital_speed_mps_u	acceleration_rate_a	mu_value	top_speed	average_acceleration
2	5	6	5-6	27	2/13/2036	8:48:31 AM	As is	20	acceleratic	1	A1	2.038545	4.038721	0.031743	1.965607	0.200368	14.5394	1.965767
3	5	6	5-6	27	2/13/2036	8:48:31 AM	As is	22	acceleratic	2	A2	3.811462	4.907148	0.079197	1.266693	0.129123	17.66573	1.257853
4	5	6	5-6	27	2/13/2036	8:48:31 AM	As is	20	acceleratic	3	A3	2.499481	4.16654	0.01388	1.661409	0.169359	14.99954	1.655694
5	5	6	5-6	27	2/13/2036	8:48:31 AM	As is	22	acceleratic	4	A4	4.420835	5.267627	0.089294	1.171347	0.119403	18.96346	1.168619
6	5	6	5-6	27	2/13/2036	8:48:31 AM	As is	22	decelerati	2	D2	0.718538	2.057193	4.618658	-3.56483	-0.36339	16.62717	-3.52508
7	5	6	5-6	27	2/13/2036	8:48:31 AM	As is	20	decelerati	3	D3	0.726289	0.018907	2.567975	-3.50972	-0.35777	9.244711	-3.47188
8	5	6	5-6	27	2/13/2036	8:48:31 AM	As is	22	decelerati	4	D4	1.007568	2.649218	5.361866	-2.69227	-0.27444	19.30272	-2.67102
9	5	7	5-7	26	2/13/2036	8:51:27 AM	Tyres as is,	20	acceleratic	1	A1	2.225858	5.014631	0.001667	2.252149	0.229577	18.05267	2.243652
10	5	7	5-7	26	2/13/2036	8:51:27 AM	Tyres as is,	22	acceleratic	2	A2	2.390231	5.727625	0.1974	2.313678	0.235849	20.61945	2.300158
11	5	7	5-7	26	2/13/2036	8:51:27 AM	Tyres as is,	20	acceleratic	3	A3	2.03845	4.799687	0.135394	2.288157	0.233247	17.27887	2.266789
12	5	7	5-7	26	2/13/2036	8:51:27 AM	Tyres as is,	20	acceleratic	4	A4	2.65576	5.368791	0.027761	2.011112	0.205006	19.32765	2.001782
13	5	7	5-7	26	2/13/2036	8:51:27 AM	Tyres as is,	22	decelerati	2	D2	0.788789	3.517514	5.824118	-2.92423	-0.29809	20.96682	-2.89524
14	5	7	5-7	26	2/13/2036	8:51:27 AM	Tyres as is,	20	decelerati	3	D3	0.703001	2.364064	5.099253	-3.89073	-0.39661	18.35731	-3.84766
15	5	7	5-7	26	2/13/2036	8:51:27 AM	Tyres as is,	20	decelerati	4	D4	0.632816	3.172418	5.775174	-4.11297	-0.41926	20.79065	-4.06072
16	6	1	6-1	21	2/13/2036	8:00:38 AM	As is	20	acceleratic	1	A1	2.09326	5.192539	0.006172	2.477651	0.252564	18.69314	2.468236
17	6	1	6-1	21	2/13/2036	8:00:38 AM	As is	20	acceleratic	2	A2	2.499572	5.397289	0.004016	2.157679	0.219947	19.43024	2.151835
18	6	1	6-1	21	2/13/2036	8:00:38 AM	As is	20	acceleratic	3	A3	2.007232	4.031052	0.2066	1.905336	0.194224	14.51179	1.894796
19	6	1	6-1	21	2/13/2036	8:00:38 AM	As is	20	acceleratic	4	A4	2.116604	5.588959	0.113437	2.586937	0.263704	20.12025	2.571787
20	6	1	6-1	21	2/13/2036	8:00:38 AM	As is	20	decelerati	1	D1	0.718504	3.055305	5.779324	-3.79124	-0.38647	20.80557	-3.75571
21	6	1	6-1	21	2/13/2036	8:00:38 AM	As is	20	decelerati	2	D2	0.718752	1.549435	4.43931	-4.02069	-0.40986	15.98152	-3.98158
22	6	1	6-1	21	2/13/2036	8:00:38 AM	As is	20	decelerati	3	D3	0.64038	1.911571	4.750677	-4.43347	-0.45193	17.10244	-4.39332
23	6	2	6-2	22	2/13/2036	8:05:49 AM	Tyres as is,	19	acceleratic	1	A1	1.820068	5.02757	0.264122	2.617181	0.266787	18.09925	-0.29188

Figure 10: Snapshot of final output after compiling all data into a single spreadsheet

3.3 Results

3.3.1 Acceleration

The average acceleration rate for the full acceleration period was considered. Although for push start devices the acceleration has two phases, there will be some variation in the initial phase, so considering the average of the full acceleration period gave more consistent and reproducible results. Although throttle input can, theoretically, be moderated, in effect the devices have a minimal range and tend to operate in more of an 'on or off' manner, likely reducing variation based on rider input.

Across the total sample, mean acceleration was 2.819ms^{-2}. The full sample had a high standard deviation, of 1.139, indicating grouping was relevant. Acceleration was similar for the groups 250W, 300W and 350W (i.e. all the lightest devices), with a slight decrease in acceleration with increased motor power and mass. A significant variation was then found between the lower powered/massed devices and the 500W devices (all of which were in the heaviest group). The average acceleration of the 500W group was 4.625ms^{-2}, nearly 2ms^{-2} greater than the lower powered groups.

Table 4: Acceleration results summary

Group	n (tests)	Mean Acceleration (ms^{-2})	Mean Acceleration (*g*)	Standard Deviation (ms^{-2})	Notes
All powers	58	2.819	0.287	1.139	
250W	12	2.664	0.272	0.459	All 12/12.5kg
300W	10	2.494	0.254	0.520	All 13.5 / 14.2kg
350W	17	2.425	0.247	0.894	12 - 19.1kg
500W	15	4.625	0.471	0.548	All 17kg
Pneumatic tyres	21	4.004	0.408	0.883	11 of 21 were 500W
Solid tyres	29	2.087	0.213	0.625	No 500W devices

Whilst the average acceleration of the pneumatic tyres group was found to be significantly greater (by around 2ms^{-2}) than the solid tyres group, pneumatic tyres were found to be fitted to all of the higher powered 500W devices. We consider it unlikely that there is a specific correlation between tyre type and rate of acceleration; instead, it is more likely that pneumatic tyres and higher power rating are more premium features in the private e-scooter market.

For tests with a weighted rider (a 24% increase from 84kg to 104kg), the effect on acceleration was found to be inconsistent. For two of the five devices tested, acceleration was greater when weighted. This was an unexpected result; the initial hypothesis was that a heavier rider would accelerate more slowly. Further testing is warranted in this area, particularly in relation to the effect of a second rider rather than a heavier single rider which is an area of potential rider non-compliance.

Table 5: Acceleration data; weighted vs unweighted

Unweighted vs Weighted (+20kg)					
Device #	**Mean Accel. Unweighted (ms^{-2})**	**Unweighted Standard Deviation (ms^{-2})**	**Mean Accel. Weighted (ms^{-2})**	**Weighted Standard Deviation (ms^{-2})**	**Accel. Variance (ms^{-2})**
5	1.512	0.369	2.203	0.136	+0.691
6	2.272	0.308	2.286	0.173	+0.014
12	2.858	0.173	2.815	0.349	-0.043
23	4.363	0.103	4.187	0.204	-0.176
24	2.063	0.274	2.048	0.066	-0.015
Average	2.889		2.834		
		Mean Change	+0.094		

For 'Cold' tests, the devices were left outside for 3 hours and then ridden in temperatures close to 0°. The difference was minimal for some devices and resulted in a slight increase in acceleration rate for others (see Table 6).

Table 6: Acceleration data; warm vs cold

Warm vs Cold					
Device #	**Mean Accel. (ms^{-2})**	**Standard Deviation (ms^{-2})**	**Mean Accel. Cold (ms^{-2})**	**Standard Deviation (ms^{-2})**	**Accel. Variance (ms^{-2})**
6	2.272	0.308	2.544	0.279	+0.272
21	2.296	0.237	2.866	0.488	+0.570
22	3.469	n/a	3.470	0.261	+0.001
24	2.063	0.274	2.142	0.939	+0.079
Average	2.525		2.756		
		Mean change	+0.231		
Warm tests range 13 - 21°C, 'Cold' tests range 0 - 2°C					

The effect of tyre pressures on acceleration was found to be inconsistent, producing results with both increased and decreased acceleration. Tests were conducted with tyre pressures at the levels present at the time of donation, which, for all devices with pneumatic tyres, were below recommended levels. Where possible, the pressures were increased to the recommended values and re-tested. "As provided" tests were with no alteration made to the tyre pressures as at the time of donation, wherein the average underinflation was 55% (see further discussion in section 2.1). Fully inflated tyres were set to the manufacturer's recommended pressures.

Table 7: Acceleration data; tyre pressure variation

As Found vs Fully Inflated Tyres										
Device #	**'As Provided' Pressure (psi)**		**Recommen-ded pressure (psi)**		**Mean Accel. (ms^{-2})**	**St. Dev. (ms^{-2})**	**Mean Accel. Inflated (ms^{-2})**	**St. Dev. (ms^{-2})**	**Accel. Variance (ms^{-2})**
	Front	Rear	Front	Rear					
3	12.5	24	55	55	4.425	0.448	4.633	0.145	+0.208
10	16.5	36	31	36	4.808	0.841	4.430	0.199	-0.378
22	23	50	26.5	50	3.469	n/a	2.468	n/a	-1.001
				Average	4.234		3.844		
					Average change		-0.690		
As Found vs Fully Deflated Tyres									
Device #	**'As Provided' pressure (psi)**		**Recommen-ded pressure (psi)**		**Mean Accel. (ms^{-2})**	**St. Dev. (ms^{-2})**	**Mean Accel. Deflated (ms^{-2})**	**St. Dev. (ms^{-2})**	**Accel. Variance (ms^{-2})**
	Front	Rear	Front	Rear					
10	16.5	36	31	36	4.808	0.841	4.579	0.463	-0.229
23	24.5	36	36	36	4.363	0.103	4.704	0.050	+0.341
					Average change		+0.056		

The most significant factor in acceleration rate was thus found to be the motor power, and, specifically, whether the device was 500W or less.

3.3.2 Peak speed

All devices were found to over-state their maximum speed, both in published/manufacturer data and, in those with a speed display, on the device speedometer. All devices were found to over-state their maximum speed by between 2 and 5km/h and the mean over-read was 15% (full details are shown at Appendix B). This was irrespective of rider mass or length of ride. Variations due to significant gradients were not tested, so maximum speeds achieved may be found to be greater on extended downhill rides.

Increasing rider mass had variable results; in two cases there was a negligible increase or decrease in peak speed; two cases had a decrease in peak speed of close to 1km/h, and one device had an average increase of more than 2km/h. Again, this is a potential area for further work, incorporating greater mass variations and longer test runs. The effect of a second rider has not yet been tested.

Table 8: Peak speed variation for weighted and unweighted rider

Unweighted vs Weighted (+20kg)					
Device #	**Mean Peak Speed (km/h)**	**Standard Deviation (ms^{-2})**	**Mean Peak Speed Weighted (km/h)**	**Standard Deviation (ms^{-2})**	**Mean Speed Variance (km/h)**
5	16.542	2.123	18.820	1.467	+2.278
6	18.189	2.520	18.103	0.462	-0.086
12	15.726	4.375	14.351	0.112	-1.375
23	22.673	0.518	22.759	0.142	+0.086
24	14.189	1.390	13.363	0.340	-0.826
Average	17.464		17.479		
		Average change	+0.094		

3.3.3 Deceleration

Deceleration was more consistent across the whole sample than acceleration. Across the full sample, mean deceleration was 3.429ms^{-2} or 0.350*g*, with a standard deviation of 0.526ms^{-2}. Separated by motor power the mean deceleration varied between 3.2 and 3.6ms^{-2}, but devices with higher acceleration rates did not necessarily give higher deceleration. A similar variation was found between disc/drum and foot brakes, at about 3.4 and 3.8ms^{-2} respectively, although the sample size for foot brakes was very small, and this type of braking may be subject to more variation overall than braking with a hand lever, based on factors such as rider experience level. Deceleration was slightly higher for pneumatic tyres than solid. This was not explained by a link with brake type or factors such as wheel size (for example, if larger wheels accommodated bigger disc brakes), as there was variation in both throughout the sample of pneumatic tyred devices.

Table 9: Deceleration results summary

Group	n (tests)	Mean Deceleration (ms^{-2})	Mean Deceleration (*g*)	Standard Deviation (ms^{-2})
All powers	53	-3.429	0.350	0.526
250W only	13	-3.525	0.359	0.578
300W	12	-3.613	0.368	0.321
350W	11	-3.210	0.327	0.803
500W	9	-3.456	0.352	0.252
Disc brakes	39	-3.419	0.349	0.581
Drum brakes	12	-3.393	0.346	0.328
Foot brakes	2	-3.842	0.392	0.214
Pneumatic tyres	24	-3.508	0.358	0.422
Solid tyres	26	-3.397	0.346	0.600

For weighted rider tests, wheel lock up was either delayed or prevented. Overall deceleration results were lower with the weighted rider, by an average of 0.193ms^{-2}, although deceleration was increased for one device in the sample. Again, this would be an area requiring further, in depth, study. Weight positioning may also be relevant to braking, both with respect to deceleration rate and stability under braking.

Table 10: Deceleration data; weighted vs unweighted

Unweighted vs Weighted (+20kg)					
Device #	**Mean Decel. Unweighted (ms^{-2})**	**Standard Deviation (ms^{-2})**	**Mean Decel. Weighted (ms^{-2})**	**Standard Deviation (ms^{-2})**	**Decel. Variance (ms^{-2})**
5	-3.223	0.329	-3.601	0.621	+0.378
6	-4.044	0.323	-3.379	0.028	-0.665
12	-3.439	0.313	-3.329	0.239	-0.110
23	-3.754	0.043	-3.617	0.288	-0.137
24	-3.842	0.214	-3.412	0.186	-0.430
Average	-3.770		-3.434		
	Average change		-0.193		

Deceleration was significantly lower in the cold tests (see Table 11). This may be a simple matter of unconscious rider behaviour, i.e. not squeezing the brake lever as hard when the hands were cold, but this is purely speculative.

Table 11: Deceleration data: cold vs not cold

Warm vs Cold					
Device #	**Mean Decel. (ms^{-2})**	**Standard Deviation (ms^{-2})**	**Mean Decel. Cold (ms^{-2})**	**Standard Deviation (ms^{-2})**	**Decel. Variance (ms^{-2})**
6	-4.044	0.323	-1.793	0.075	-2.251
21	-1.954	0.114	-1.312	0.179	-0.642
22	-3.939	0.207	-1.847	0.030	-2.092
24	-3.842	0.214	-1.803	0.253	-2.039
Average	-3.445		-1.689		
		Average change	-1.756		
'As is' tests range 13 - 21°C, 'Cold' tests range 0 - 2°C					

When tyres were inflated from their 'as provided' values to manufacturers specification (see Table 7 for recommended and as provided tyre pressures), mean deceleration increased by an average of 0.491ms^{-2} (see Table 12). Full deflation produced inconsistent results, although with an admittedly small sample.

Table 12: Deceleration data; tyre pressure variation

"As Provided" vs Fully Inflated Tyres					
Device #	**Mean Decel. (ms^{-2})**	**Standard Deviation (ms^{-2})**	**Mean Decel. Inflated (ms^{-2})**	**Standard Deviation (ms^{-2})**	**Decel Variance (ms^{-2})**
3	-3.203	0.515	-3.498	0.433	+0.295
10	-3.379	0.033	-4.118	0.817	+0.739
22	-3.939	0.207	-4.182	0.082	+0.243
Average	-3.507		-3.933		
		Average change	-0.491		
"As Provided" vs Fully Deflated Tyres					
Device #	**Mean Decel. (ms^{-2})**	**Standard Deviation (ms^{-2})**	**Mean Decel. Deflated (ms^{-2})**	**Standard Deviation (ms^{-2})**	**Decel Variance (ms^{-2})**
10	-3.379	0.033	-3.802	0.188	+0.423
23	-3.754	0.043	-3.119	0.301	-0.635
		Average change	0.106		

As noted, a large number of devices had brakes in poor condition. For safety it was necessary to adjust brakes to a serviceable level prior to testing, where possible, and no testing was carried out on devices with sub-optimal braking. If a brake is found to be incapable of locking a wheel, overall braking capability is likely to be reduced, but this will be difficult to quantify in any consistent way. This may need to be investigated further on a case-by-case basis.

4 Tests of stability and handling

A series of stability and handling tests were carried out to investigate the fundamental characteristics of e-scooter motion when encountering vertical faces and when being steered through obstructions requiring lateral movement.

4.1 Method

The stability and handling tests investigated the test device and rider behaviour when:

(i) traversing vertical faces of various heights at 90° and angled approaches, and;

(ii) negotiating a path between offset obstructions which required a rider to swerve. The tests were intended to provide a preliminary exploration of device and rider behaviour which could inform future phases of work.

All tests were conducted within the level asphalt test area (described in section 3.1.1) and where appropriate all tests were carried out with tyres inflated to recommended tyre pressures.

4.1.1 Vertical face tests

The test rider travelled over vertical faces 20, 30, 40, 50 and 70mm in height. These faces were constructed of layers of multi-ply timber. Both 90° and 45° angled approaches were tested.

Three devices were used for these tests; these had wheel diameters of 6.5, 8 and 8.5" (165, 203 and 516mm) and footplate ground clearance of 80, 75 and 85mm, respectively, for Devices A, B, and Cs. Devices A and C had pneumatic tyres and Device B had solid tyres.

In all tests the rider was instructed to approach the vertical face at the fastest speed that they were comfortable with. In several cases multiple runs were undertaken as the rider established confidence and established their maximum 'comfort' speed. The test speeds were recorded and are reported below.

4.1.2 Lateral swerve tests

A rider's ability to negotiate lateral swerves at speed was tested using a chicane created by placing traversable obstacles at measured intervals and having the test rider steer between them. A comparable real-world scenario for these tests was considered to be an incident in which an e-scooter rider needed to swerve to avoid the front of a vehicle which had stopped in its path, whilst avoiding swerving further across a road than is necessary.

The obstacles for this test were formed by placing two plyboard sheets (measuring 1.2 metres in width) on the ground at set intervals (see Figure 11). The minimum lateral deviation required to navigate between the two plyboard sheets was, therefore, 1.2 metres. Longitudinal distance between the sheets was varied between 4 and 6 metres. At least three runs were undertaken at each distance with the rider instructed to make the turn as close as possible to the start of the gap between the plyboard sheets. Both left-right and right-left swerves were tested.

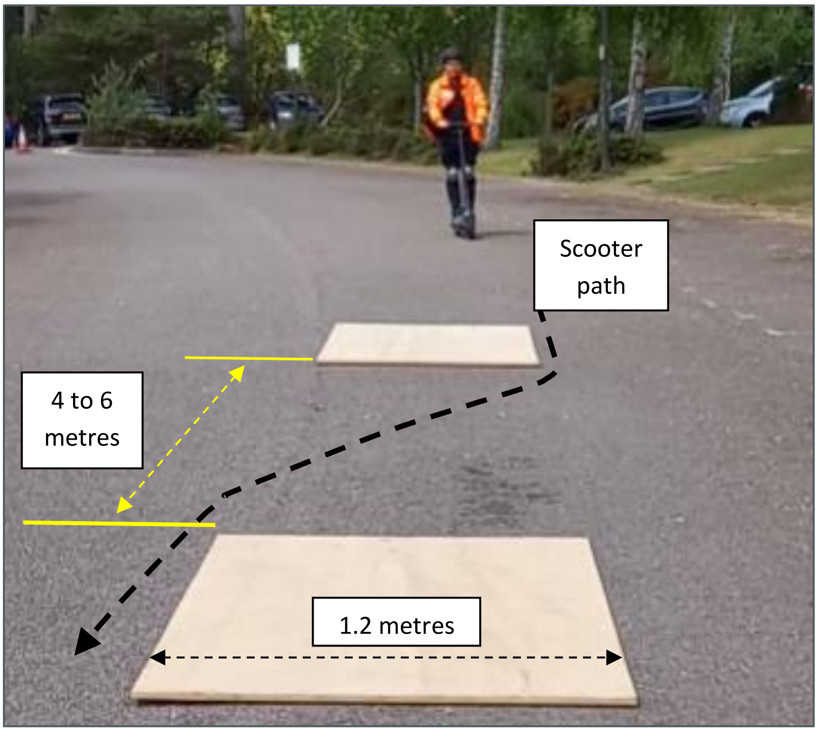


Figure 11: The layout of the chicane for testing lateral swerves

4.2 Results and observations

4.2.1 Vertical face tests

It was found that each of the vertical face heights could be mounted by the e-scooter at 90°, but the rider's comfort speed reduced with face height. At 45° all vertical faces except the 70mm face could be mounted without the e-scooter becoming destabilised.

It was noted that the ability of a rider to traverse a vertical face is likely to be highly dependent on rider skill, confidence and awareness of the presence of the feature.

In both the 90° and 45° angled approaches, the test rider was able to mount the vertical face at heights of up to 50mm with no manual lifting of the front wheel to assist the traversal. The rider was able to traverse shorter faces of up to 40mm at full speed (25km/h), and the rider's maximum comfort speed with the 50mm vertical face was 18km/h.

Figure 12: Photo of 8" (203 mm) wheel diameter e-scooter with the 70mm obstacle

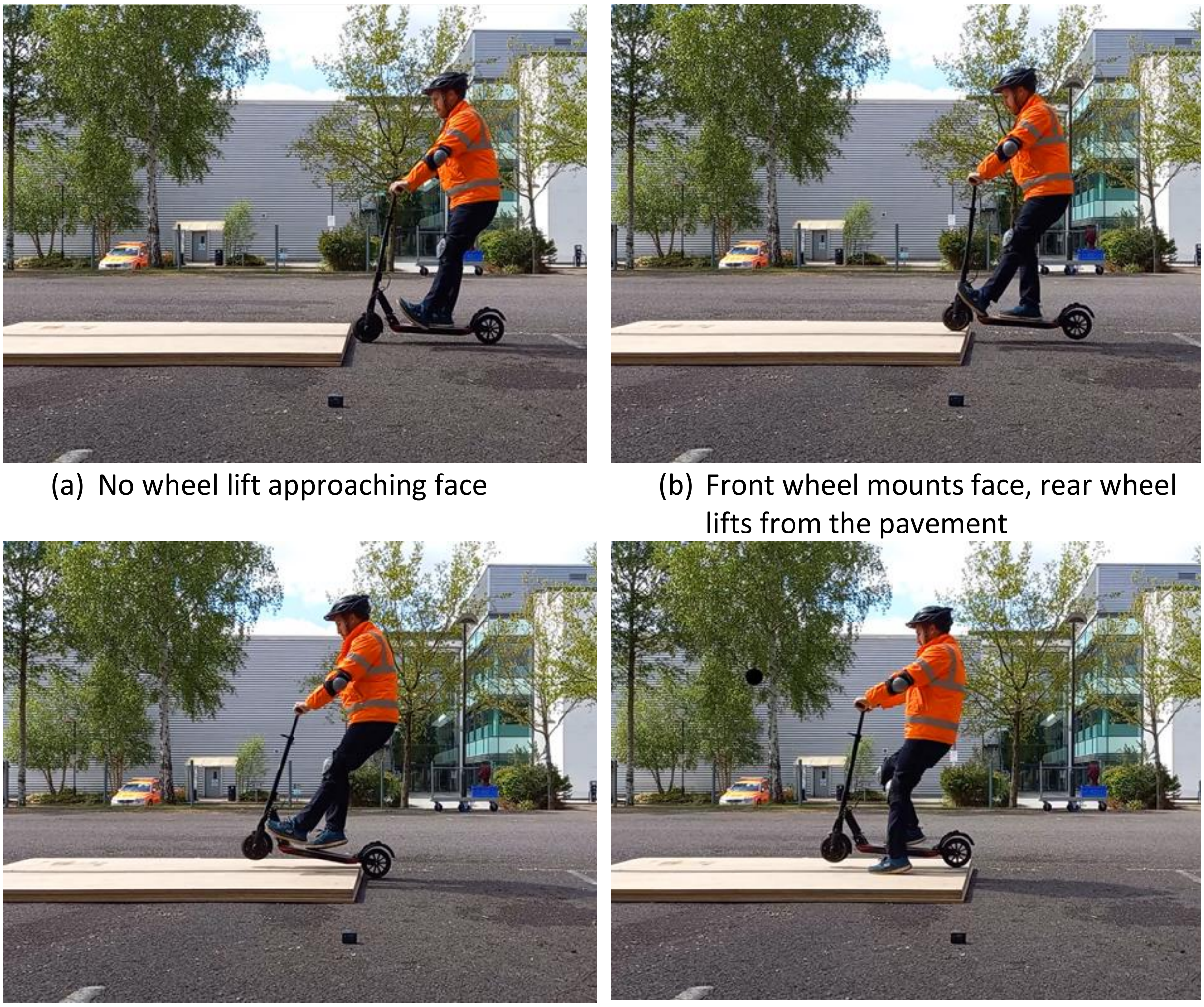
The 70mm face could be traversed with no manual lifting of the front wheel; however, this caused significant destabilisation as shown in Figure 13. A more comfortable traversal was assisted by the rider lifting the front wheel slightly before the traversal. A maximum 'comfort' speed of 11km/h was reached with no lifting on all e-scooters and 16km/h with lifting.

Figure 13 presents a sequence of images which demonstrate the motion experienced by a rider during a 70mm vertical face impact. This test, firstly, caused the back wheel to lift from the ground, followed by front wheel lift as the rear wheel contacted the vertical face. In this case the rider was destabilised and a foot was placed on the ground to regain control.

With a 90° approach angle, no obvious lateral deviation was observed on any tests. With an approach of 45°, obstacles of ≤40mm could be mounted with the same ease as at 90°. With an unskilled or unsuspecting rider, a pitch-over event would likely be caused when the obstacle height is close to the wheel radius.

The 50mm vertical face could be mounted at an approach of 45° but increasing speed caused the front wheel to experience a small amount of sideways movement and in some cases the rear wheel of the e-scooter slid along the vertical face for a short distance, causing the rider to become destabilised. The 50mm obstacle had the same effect at a 20° approach angle, but smaller obstacles could still be mounted at a lower approach angle.

Where the rear wheel only experienced a lateral slide along the vertical face, this had the effect of creating a tyre mark on the edge of the face and a curved mark on the upper surface of the step as the tyre mounted the elevated surface of the vertical face. This motion destabilised the rider causing them to put a foot down to maintain stability.



(a) No wheel lift approaching face

(b) Front wheel mounts face, rear wheel lifts from the pavement

(c) Front wheel lifts with rear wheel vertical face contact, the rider experiences vertical force (upwards)

(d) Rider stabilises the e-scooter by placing a foot on the ground

Figure 13: Example e-scooter motion when mounting a 70mm vertical face

No attempt was made to 'hop' the e-scooter for any 90° or 45° tests. For 90° approaches it was noted that a skilled rider could, most likely, achieve higher traversal speeds over the 50mm and 70 mm vertical faces with more significant actions to assist the traversal, such as greater lifting of the front wheel before reaching the face or hopping the e-scooter should the rider ability and device weight allow. At a 45° approach such actions would risk the rear wheel sliding along the vertical face if the rear wheel was not lifted by the rider action. It was noted that the relationship between the obstacle height, the ground clearance of the foot plate and the front and rear wheel sizes determined the risk of grounding by the e-scooter during a traversal. Any such grounding would have the effect of a) causing contact damage to the underside of the e-scooter and b) lifting the e-scooter's rear wheel. In severe cases the combined effect of the grounding and rear wheel lift could create a destabilising vertical impulse to the rider.

By lifting the rear wheel of the e-scooter a grounding event may also destabilise lateral movement of the e-scooter by replacing lateral tyre forces (cornering forces), between the rear tyre and the travelled surface, with lateral forces between the e-scooter base and edge of the vertical feature (a kerb for example). A grounding event would create a change in the point at which lateral forces are generated relative to the e-scooter and rider's centre of mass, (bringing this forward relative to the centre of gravity) and a change in the friction between the e-scooter and the road. In most conditions, the friction between a metal e-scooter base and a kerb-edge would be expected to be lower than a tyre and a typical pavement surface. These effects would significantly increase the risk of the rear wheel sliding sideways as a result of a grounding event. Such an event would destabilise the e-scooter and could cause a rider to fall.

4.2.2 Lateral swerve tests

Where our rider started to turn in the gap between the obstructions forming the chicane, the rider achieved a maximum speed of 17km/h through the 4m chicane length.

At a chicane length of 5m, the speeds achieved were similar to the 4m chicane, although the rider found these swerves to be more comfortable.

At a chicane length of 6m, a 1.2m lateral deviation was achieved comfortably with a speed of 20km/h.

Our test rider was, therefore, capable of swerving at least 1.2m laterally within at least 4m of longitudinal distance at a speed of 17km/h, and at 20 km/h within 6m of longitudinal distance.

In all cases, the test rider began and ended his swerve outside of the line of the 1.2m wide obstructions; the actual path followed was up to 0.25m from the edge of the obstructions on the approach and exit, therefore whilst the minimum lateral swerve distance in the test scenario was 1.2m, the actual lateral swerve distance achieved was closer to 1.7m.

This test was selected to represent a real-world swerve scenario. The test scenario involved a right-left or left-right swerve; however, if exposure to other traffic is not a concern then a lateral swerve in only one direction could achieve a much greater lateral swerve distance than reported at the above speeds, and chicane lengths. As it was difficult to eliminate the rider's anticipation of the swerve, it is likely that the observed speeds slightly overestimate the speed/lateral swerve relationship in a real-world chicane scenario.

In all cases, maintaining stability while steering is highly dependent on rider skill and experience, confidence and expectation.

Further testing might eliminate the impact of rider expectation by requiring a swerve in response to a signal, and rider experience and confidence might be examined by testing a group of individuals with varying experience of e-scooter riding.

4.2.3 Other steering control observations

It was found that the layout and type of the e-scooter's throttle dictated the ease of signalling. A number of the throttle devices fitted to the test devices were observed to instantly drop power to zero when the throttle was released; this was found to reduce stability when signalling with the throttle hand. Other throttle controls were found to reduce power more gradually on release and this improved stability whilst making hand signals.

Of the devices tested most e-scooters had a throttle control on the right side of the handlebar. Only one e-scooter had a throttle control on the left side. It was noted that a right-handed rider making a right turn may experience stability issues when controlling the e-scooter with their left hand and experiencing simultaneous deceleration, or vice versa. The provision of a throttle which prevents sharp deceleration on release could improve a rider's ability to maintain a constant speed during turn signalling and therefore improve pre-turn and turning stability. Equally the provision of dual throttles on both sides of the handlebar would reduce this problem.

None of the stand-on e-scooters tested had throttle locks (devices which allow constant power to be maintained without rider input). Only the seated e-scooter[5] in our sample provided this feature.

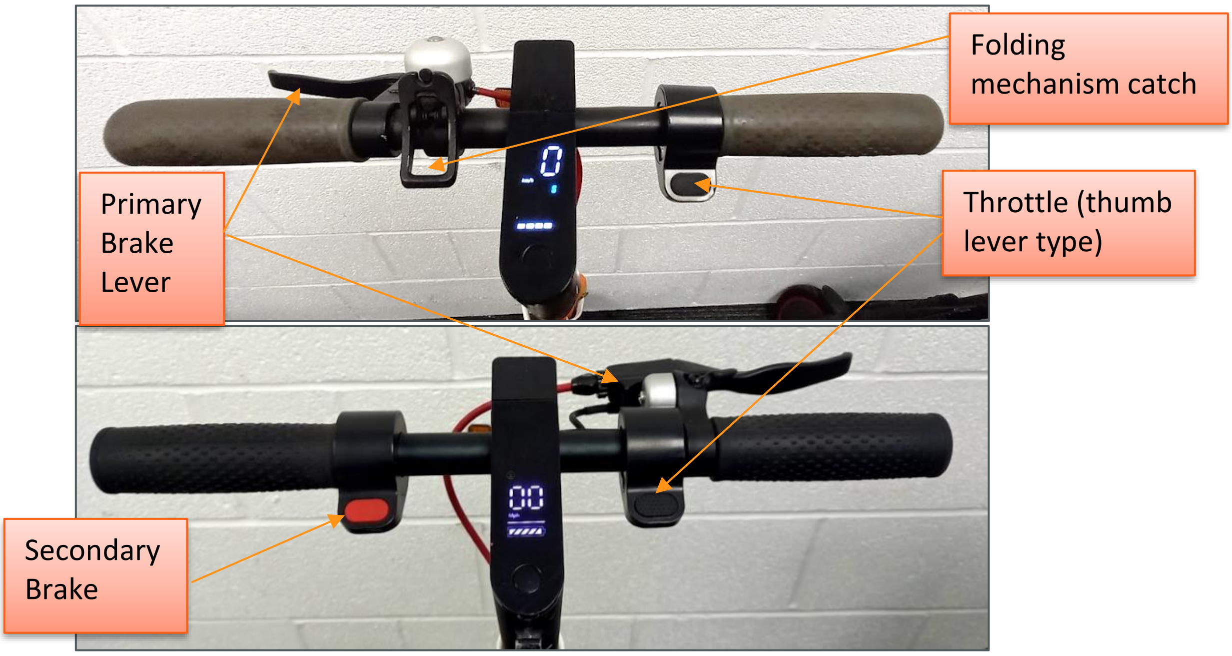


Figure 12: Example configurations of handlebar controls on two e-scooters

[5] A single device within the sample which was shaped like a small bicycle, but operated, and therefore classed as, an e-scooter (no pedals were fitted).

The stability of several test devices was considered in tight turning situations. None of the e-scooters could be ridden under power at their highest turn angles, nevertheless the high turn angles were advantageous when pushing the device. The radius of a turning circle was speed, rider skill and device dependent. The use of the throttle was also found to have an effect of turn radius, several devices tended to straighten the front wheel if power was applied during the turn, thereby extending the turn radius.

In our tests our right-handed test rider was able to turn left much more easily than turning right; a left handed turn preference was also reported amongst cyclists by Borysewicz (1985)[6]. The ability of a rider to make sharp or tight turns under power is likely, therefore, to be dependent on not only skill and experience but also a user's innate preference toward left or right turns.

5 Additional observations

5.1 Device condition and maintenance

Pre-testing inspections of the devices suggested that maintenance is likely to be a frequent problem for privately owned devices. More than 50% needed adjustment of brakes or steering (such as realigning handlebars or tightening headstock screws) before they could be deemed safe for testing.

Many devices had broken rear mudguards, possibly due either to the mudguard being used as a supplementary (or possibly 'comfort[7]') brake, or from otherwise becoming broken during handling. Mudguards were broken or missing completely from 10 of the 25 donated devices which were designed to have one. The fragility and breakage of rear mudguards is of particular concern as all of the devices with a rear light fitted had the rear light mounted on the mudguard. Given the number of devices (10/25) with a missing rear light as a result of mudguard damage in our sample, it is likely that a significant number of privately owned e-scooter devices being used today do not have an operational rear light.

Many folding mechanisms lock by attaching a loop on the handlebars to a hook on the mudguard, meaning the mudguards may become broken from heavy handed un-folding or manoeuvring while stowed. This can lead to problems such as exposed wiring (where fitted with a rear position or brake light), either creating a fire hazard or interference to operation of the rear wheel. There could also be interference with the exposed wheel from clothing or partially detached bodywork pieces.

Tyre maintenance was also found to be a frequent problem. Of the 13 devices in the sample with pneumatic tyres, none were inflated to the recommended pressures when presented for testing. The average under-inflation was 55%. Many were found to have valves which were inaccessible to standard manual or air-line inflation systems. Although some devices

[6] Borysewicz (1985), Bicycle Road Racing

[7] A term for habitual light and usually unnecessary application of the brake which creates a sense of control for the rider

are provided with conversion valves to improve access, difficulty inflating the tyres (particularly if the box contents is not retained, or devices are used second-hand) is likely to reduce the likelihood of many users checking and maintaining their tyres. Tyre condition was not a problem for those devices with solid tyres. However, testing did indicate that, unless fully deflated, a reduction in tyre pressure from manufacturer recommended levels did not cause a noticeable adverse effect to handling of the device.

5.2 Additional testing observations for investigators

The majority of devices tested were push start, meaning the rider pushes off with a foot and then applies the throttle. The power will not be applied unless the throttle is applied after the device is in motion. If the user pushes off with the throttle already held, the device will not apply power until the throttle is released and reapplied. This may affect overall acceleration rates, for example with inexperienced riders.

Devices with a driven rear wheel and a mechanical brake on the front wheel, lock and pitch very easily. The ability to maintain control under emergency braking for any device, but particularly those with braked front wheels, will be highly dependent upon rider skill/experience, and to some degree also rider position. The experienced rider may bend their knees and shift their weight backwards to maintain control where necessary, but an inexperienced rider is unlikely to do so and thus may be far more likely to experience a pitch-over under emergency braking. However, even an inexperienced rider may reduce the likelihood of pitch-over simply by virtue of standing further back on the footplate.

The ride was found to be significantly bumpier with airless tyres, particularly solid or undrilled tyres. This may have an effect on overall stability, but, again, was unquantifiable within this study. Many devices with airless tyres were fitted with a secondary form of suspension but the bigger factor for rider comfort still appeared to be pneumatic tyres.

Despite the potential variation from manufacturer specifications, particularly in relation to maximum speed, it is important to consider any available specification information. Much information is contained in labels on the side of the footplate, although these were not always present. Within the (UK-obtained) sample were two devices which appeared identical, but detailed examination of the specification label indicated that one was an EU market device while the other was a Chinese import. The latter had a higher motor power and speed rating. Therefore, in researching likely device specifications, it is important to ensure the information for the correct market is being considered.

6 Conclusions

The intent of this study was to provide a dataset for collision investigators investigating collisions involving privately owned e-scooter devices. In the year to June 2022 there were 1349 collisions involving e-scooters, compared to 978 in the year ending June 2021. There were 1437 casualties in collisions involving e-scooters in the year to June 2022, compared to 1033 in the previous year. Around 30% of casualties sustained serious injuries, and there were 12 fatalities in 2022 compared to 4 in 2021. Such incidents require in-depth investigation to determine causal and contributory factors, and the outcomes of these investigations can guide the development of safety interventions. This paper provides relevant observations relating to the fleet of devices tested, their features and potential issues to be considered by investigators.

This is not intended as a wider safety report, although we have identified some safety related conclusions in terms of design, maintenance and general usage. We also identified some inconsistencies in e-scooter configuration; if it is to be expected that the usage of e-scooters will continue to grow, greater consistency in control and feature configuration control would be encouraged.

The tested sample is broadly representative of private e-scooter devices currently in use and likely to be encountered in real-world incidents. No public hire e-scooter devices were included in this study.

Some common problems of private e-scooter devices have been identified such as issues with tyre, brake, wheel-guard and lighting system maintenance.

For pneumatic tyres, tyre inflation pressure on most of the private e-scooters supplied was below the manufacturer-recommended pressure, however, in many cases the design of the inflation valve did not allow the connection of standard inflation devices.

Most of the e-scooters required maintenance of their braking system to optimise braking, this was most easily achieved by adjustment of the tension in brake cables on rear disc brakes.

The configuration of controls largely featured the throttle control on the right side of the handlebar, during hand-signalling to the right release of the throttle caused deceleration of several e-scooters, this could be destabilising to riders.

A number of the e-scooters had sustained damage to the rear mud guard. The mudguard design of most e-scooters was found to be susceptible to damage which in turn affected the low-level rear red light which was fitted to all e-scooters. Where mudguards had been removed no rear light was present. Removal of the mudguard also required the cutting of electrical wires for the rear light. Exposure of these wires could lead to electrical issues developing with the e-scooter.

None of the devices tested had been modified to enable greater power or speed. The maximum speed of the devices was found to be between 14.0 and 27.5 km/h, all but one of the devices were aligned with the maximum permitted speed of 25km/h for shared e-scooters involved in the current UK trials for DfT. All devices with a speedometer over-stated their true speed.

The acceleration of the devices was found to vary between 2.087 and 4.625 ms^{-2} (0.247 – 0.471*g*) with a mean value across all devices of 2.819ms^{-2}. Varying rider mass and tyre pressures resulted in variation to the acceleration rates which was inconsistent. The biggest predictor of acceleration capability was the motor power, with 500W devices producing average accelerations more then 2ms^{-2} higher than the ≤350W devices.

The rate of deceleration achievable on the devices was found to be between 3.2 and 3.8 ms^{-2} (0.326 – 0.387*g*) with a mean value across all devices of 3.429ms^{-2} or 0.350*g*. Nearly all e-scooters in the sample required maintenance of the braking system to ensure optimal brake performance during the tests. For collision investigators, an inspection of an e-scooter braking system will be necessary before conclusions can be drawn about the effectiveness of an e-scooter’s brakes and the rates of deceleration it could achieve.

Tests with e-scooters over vertical obstructions indicated that obstructions of up to 40mm in height could be mounted at 90° and 45° at full or nearly full speed (25 or 18km/h). Obstructions 50mm in height could, however, destabilise a rider on an angled (45°) approach. Obstructions 70mm in height, whilst traversable at low speed (11 km/h) with no lifting of the front wheel before contacting the vertical face, caused the rear and then front wheel to leave the ground during traversal and a significant vertical impulse was directed to the rider.

Rider skill and experience may enable riders to mount higher vertical faces by lifting or hopping the device. On higher vertical faces the risk of grounding also creates a mechanism which could destabilise the e-scooter.

Lateral manoeuvre tests demonstrated that e-scooters could be manoeuvred in left-right, right-left swerve scenarios at between 17 and 20km/h over a minimum 1.2 to 1.7m lateral deviation within a longitudinal distance of 4 to 6m. A single turn direction would achieve greater lateral movement over a shorter longitudinal distance.

For insurers, the testing demonstrates it is important to inspect devices involved in a claim because of the high incidence of defects, and the wide variation possible, which would need to be considered as part of a claim.

For investigators, the testing has provided a set of reference data for collision reconstruction where values must be otherwise be assumed in acceleration or avoidance scenarios. It has also identified important background information as to likely characteristics of devices, their condition and handling characteristics, which will be of relevance when reconstructing e-scooter collisions.

Appendix A Sample device specifications

Device Number	Published Weight (kg)	Motor Power (w)	Wheel Size (inches)	Tyre Type	Brake Type	Brake Location
1	12.5	250	7"	Solid	Disc	Rear
2	14.7	350	12"	Pneumatic	Disc	Rear
3	19.1	350	10"	Pneumatic	Drum	Front
4	12	250	8.5"	Pneumatic	Disc	Rear
5	13.5	350	8.5"	Solid	Disc	Rear
6	13.5	350	8.5"	Solid	Disc	Rear
7	Unknown		8.5"	Solid	Disc	Rear
8	12	350	8.5"	Solid	Disc	Rear
9	Unknown		8.5"	Solid	Disc	Rear
10	17	500	10"	Pneumatic	Drum	Front
11	17	500	10"	Pneumatic	Drum	Front
12	14.2	300	8.5"	Solid	Disc	Rear
13	14.2	300	8.5"	Solid	Disc	Rear
14	12	250	8.5"	Pneumatic	Disc	Rear
15	Unknown		8.5"	Mixture	Disc	Rear
16	19.1	350	10"	Pneumatic	Drum	Front
17	16	350	8.5"	Solid	Disc	Rear
18	12	250	8.5"	Pneumatic	Disc	Rear
19	12.5	250	7"	Solid	Disc	Rear
20	11	350	8"	Pneumatic	Foot	Rear
21	14.5	350	8.5"	Solid	Disc	Rear
22	14.2	300	8.5"	Pneumatic	Disc	Rear
23	17	500	10"	Pneumatic	Drum	Rear
24	13.5	300	9"	Solid	Foot	Rear
25	12.5	250	7"	Mixture	Disc	Rear
26	14.2	300	8.5"	Solid	Disc	Rear
Devices 9, 13, 16, 17 & 20 were not tested due to condition / defects 'Mixture' tyres = pneumatic front, solid rear						

Appendix B Test speeds

E-Scooter Number	Test Parameters	Listed Maximum Speed (km/h)	Average Speedometer Reading (km/h)	Average Speed Gun (km/h)	Variance Actual from Speedometer (km/h)	Variance Actual from Listed Maximum (km/h)
1	Condition as provided	25	N/A	16.0	N/A	-9.0
1	Weighted	25	N/A	14.0	N/A	-11.0
2	Condition as provided	25	N/A	20.0	N/A	-5.0
3	Condition as provided	25	25.0	22.0	-3.0	-3.0
3	Fully Inflated Tyres	25	25.0	22.5	-2.5	-2.5
3	Fully Inflated Tyres + 21kg	25	25.0	22.0	-3.0	-3.0
4	Condition as provided	20	18.5	16.0	-2.5	-4.0
5	Condition as provided	30	26.0	21.0	-5.0	-9.0
5	Weighted	30	25.3	20.5	-4.8	-9.5
6	Condition as provided	30	23.5	20.0	-3.5	-10.0
6	Weighted	30	22.5	19.0	-3.5	-11.0
6	Cold	30	22.0	19.0	-3.0	-11.0
7	Condition as provided	Unknown	N/A	20.0	N/A	N/A
8	Condition as provided	25	31.5	27.5	-4.0	2.5
10	Condition as provided	25	25.0	22.0	-3.0	-3.0
10	Fully Inflated Tyres	25	25.0	21.0	-4.0	-4.0
10	Low Tyre Pressures	25	23.3	19.5	-3.8	-5.5
11	Condition as provided	25	25.0	20.0	-5.0	-5.0
12	Condition as provided	25	23.3	19.5	-3.8	-5.5

12	Weighted	25	22.9	19.0	-3.9	-6.0
14	Condition as provided	20	N/A	16.5	N/A	-3.5
14	Low Tyre Pressures + 21kg	20	N/A	16.0	N/A	-4.0
15	Condition as provided	Unknown	N/A	21.0	N/A	N/A
18	Condition as provided	20	22.1	19.0	-3.1	-1.0
19	Condition as provided	25	N/A	20.0	N/A	-5.0
21	Condition as provided	30	29.0	24.8	-4.3	-5.3
21	Cold	30	29.8	24.0	-5.8	-6.0
22	Condition as provided	25	23.0	20.0	-3.0	-5.0
22	Fully Inflated Tyres	25	23.3	20.0	-3.3	-5.0
22	Fully Inflated Tyres + 21kg	25	23.8	20.0	-3.8	-5.0
22	Cold	25	23.0	20.0	-3.0	-5.0
23	Condition as provided	25	25.0	22.0	-3.0	-3.0
23	Weighted	25	25.0	22.0	-3.0	-3.0
23	Low Tyre Pressures	25	24.3	20.3	-4.0	-4.8
23	Low Tyre Pressures + 21kg	25	21.8	17.5	-4.3	-7.5
24	Condition as provided	20	20.0	17.0	-3.0	-3.0
24	Weighted	20	20.0	17.0	-3.0	-3.0
24	Cold	20	20.0	17.0	-3.0	-3.0
25	Condition as provided	25	26.0	23.5	-2.5	-1.5
26	Condition as provided	25	24.5	19.5	-5.0	-5.5

In-Depth Investigation of E-Scooter Performance

Use of e-scooters is increasing and with it, the numbers of collisions involving the devices. This study aimed to investigate the 'real world' capabilities of privately owned e-scooters to provide reference data which can be used for reconstructing collisions involving them. Using a sample of donated devices in used condition, the acceleration, deceleration, speed and handling characteristics of privately owned devices likely to be encountered in collision reconstructions were investigated.

The study has produced a set of reasonable reference data that can be referred to in reconstructions of collisions, relating to acceleration, deceleration and average speed, where consistent results were identified. Relevant observations were also highlighted relating to stability and handling, general device characteristics, and condition, which will be worthy of consideration when investigating e-scooter collisions.

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