Electric Vehicle Development and validation of the TRL simulator

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Abstract

As the number of manufacturers producing electric vehicles (EVs) continues to grow, there is an ongoing need to undertake research into the technology and this nesescitates the development of appropriate research tools. To this end, TRL has further developed their car driving simulator, DigiCar, to allow it to be operated as an EV. The performance characteristics of DigiCar were matched to those of a Nissan Leaf by implementing the EV dynamics model provided by the simulator supplier, Oktal; adapting various characteristics of this model to match the driving characteristics of the Nissan Leaf; and adding functionality to the simulator so that the instrument panel of the Nissan Leaf was replicated for the driver. The implementation of this functionality in the TRL driving simulator is referred to as DigiCar EV. Participants performed a set of specific manoeuvres on the large loop test track at TRL and the same manoeuvres on a simulated version of the same test track in DigiCar EV. The results demonstrate that in many respects DigiCar EV is a good representation of a Nissan Leaf. The main differences related to acceleration and deceleration and these may have influenced adopted speeds.

Introduction

There has been significant investment into electric vehicle development in recent years; with a number of manufacturers launching pure electric vehicles (EVs) into the commercial market between 2010 and 2012. These are vehicles where rechargeable batteries are the only source of power for an electric motor. Whilst there are questions over the likely take up from consumers of EVs, there is an ongoing need to undertake research into the technology, including who will purchase the vehicles, how they will be used, how they will further develop and their safety. It is therefore necessary to have tools available to support the research needs of the industry. To this end, TRL has further developed their car driving simulator, DigiCar, to allow it to be operated as an EV. This report describes the development process, technical specification and behavioural validation.

Electric Vehicles

Due to the way the vehicle operates, there are fundamental differences between how an EV performs, compared to an Internal Combustion Engine (ICE) vehicle, all of

In D. de Waard, K. Brookhuis, F. Dehais, C. Weikert, S. Röttger, D. Manzey, S. Biede, F. Reuzeau, and P. Terrier (Eds.) (2012). Human Factors: a view from an integrative perspective. Proceedings HFES Europe Chapter Conference Toulouse. ISBN 978-0-945289-44-9. Available from http://hfes-europe.org

which should be considered when designing an electric vehicle simulator. In simple terms:

- Range –The range of most commercially available EVs is between 70 and 100 miles. This coupled with a recharge time of many hours can lead to driver's experiencing "range anxiety".
- Noise – Electric motors are considerably quieter than ICEs due to their having fewer moving parts and none of the sounds associated with the combustion of a fuel-air mixture.
- Acceleration – Electric vehicles tend to use a single fixed gear ratio, eliminating power loss through the transmission, and electric motors produce torque irrespective of engine speed. The result is that for a given engine power rating, accelerative performance is better for EV than an ICE.
- Regenerative braking – When decelerating, the change in kinetic energy is returned to the battery to be stored as electrical energy. This may also influence the retardation of the vehicle when the driver removes their foot from the accelerator and the brakes are applied

DigiCar

TRL has successfully operated a driving simulator for more than 15 years. The latest iteration is known as 'DigiCar' and uses a Honda Civic family hatchback (see Figure 1). Its engine and major mechanical systems have been replaced by a sophisticated electric motion system imparts limited motion in three axes (heave, pitch, and roll), providing the driver with an impression of the acceleration forces and vibrations that would be experienced when driving a real vehicle. All control interfaces have a realistic feel and the manual gearbox can be used in the normal manner (automatic gears can be simulated).

Figure 1: TRL's advanced research driving simulator, DigiCar

Surrounding the simulator vehicle are four large display screens onto which are projected the driving environment at a pixel resolution of up to 1920×1457 giving the driver a 210º horizontal forward field of view. The rear screen provides a 60º rearward field of view, thus enabling normal use of all mirrors. A stereo sound system with speakers inside and outside the vehicle generates realistic engine, road, and traffic sounds to complete the representation of the driving environment.

The software used to implement the simulation is called SCANeR Studio and was created by the French simulation company, OKTAL, to provide a flexible and powerful simulation software tools with a highly advanced traffic model.

Vehicle dynamics are updated at 100Hz whilst the visuals are refreshed at 60Hz so that the driver perceives a seemingly continuous driving experience. Data is then recorded relating to all control inputs made by the driver, including steering, pedals, gear, indicators; vehicle parameters such as speed, RPM; and parameters to assess behaviour in relation to other vehicles such as distance and time headways. The data recording rate is fully controllable dependent upon the trial demands, up to a rate of 100Hz.

Validation of simulators

Driving simulators are widely used in both research and training in situations where the activity is too dangerous to conduct in the real world, when the environment needs to be controlled, or when performance data needs to be recorded which is more difficult in the real world. It is therefore important to validate the simulator so that trainers and researchers can be sure that observed behaviour in the simulator is (at least) representative of that observed in the real world. There are three types of validation for simulators – physical validity (physical correspondence between simulator and its real world counterpart), face validity (driver perception of how well the simulator replicates the real world vehicle) and behavioural validity (how similar driving behaviour is between the simulator and the vehicle it is replicating). This study examined the behavioural validity of TRL's car simulator as an EV.

Development of DigiCar as an electric vehicle

To reflect the wider development of EVs by manufacturers, Oktal has developed an electric engine model for the simulator. Since the comparison vehicle in this project was to be the Nissan Leaf, we made further adaptations to the model so that its behaviour was more akin to that of the Nissan. We also used a Samsung Galaxy Tab tablet PC and Samsung Galaxy W smartphone display to recreate the instrument display panels of the Nissan Leaf.

Electric model development by Oktal

Oktal provided TRL with a generic EV model, drawn from their experience in EV applications. Their EV model is developed from their models of ICE vehicles with adaptations in two areas:

- Changes related to vehicle dynamics: e.g. total weight; weight distribution; engine and transmission embedded in electric propulsion architecture; suspensions adjustment (adaptation of stiffness and damping).

- Changes related to electric propulsion: e.g. battery charge and discharge model; electric engine characteristics (maximum torque, revolutions per minute, maximum power); possibility to have engine torque applied to individual wheels (like an electric hub motor) or have conventional transmission architecture; electric transmission defined by axle.

Electric model development by TRL

We adjusted the generic EV model provided by Oktal in order to give the model characteristics more similar to those of the Nissan Leaf. The kerb weight, dimensions and aerodynamic drag coefficient of the vehicle were changed to match those of the Nissan Leaf (Carfolio, 2012). A specific change was made to the efficiency of the transmission to quicken the accelerative characteristics of the model and match those of the Nissan Leaf. Official figures for the acceleration of the Nissan Leaf are difficult to obtain, therefore the acceleration figures used were taken from an online forum specifically focused on the Nissan Leaf (MyNissanLeaf.com, 2012) The efficiency of the transmission of the DigiCar EV model was adjusted to maximise correspondence with the reported acceleration times of the Nissan Leaf. The relative accelerative performance of the real and simulated vehicles is shown in Figure 2.

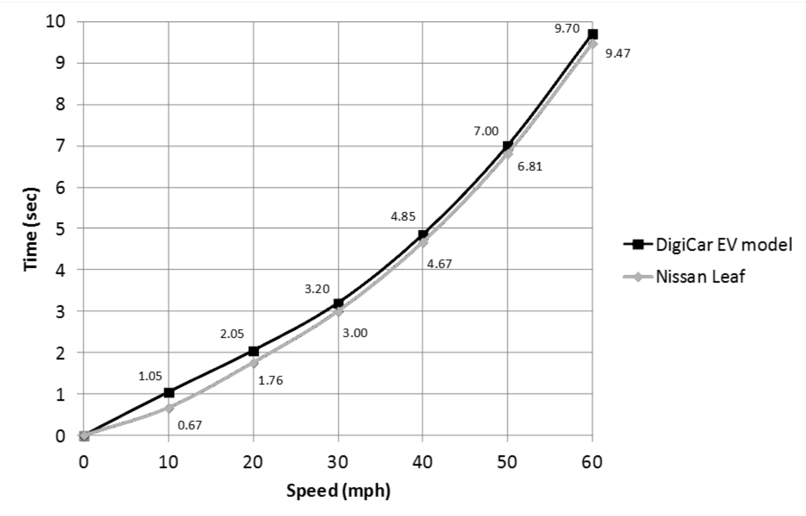

Figure 2: A comparison of the acceleration performance of the Nissan Leaf and the DigiCar EV model (acceleration times for the Nissan Leaf obtained from MyNissanLeaf.com)

Figure 2 shows that a good match between the acceleration of the real and simulated EVs was achieved. The biggest difference observed was in the initial (0-10mph) acceleration but thereafter the acceleration profile of the two vehicles showed good correspondence.

Instruments

The sensory feedback to a driver when operating an EV is different to that experienced when operating a vehicle powered by an ICE; consequently, it was considered important that the feedback provided by the instruments in the simulator should provide the driver with the same information that is delivered by the instruments in the real vehicle.

The development in the simulator used an android tablet PC secured over the standard instrument panel to replicate the lower display on the Nissan Leaf and an android smartphone mounted across the top of the dashboard to replicate the upper display on the Nissan Leaf. These were programmed to display the relevant feedback on the screen. Figure 3 shows a comparison of the two setups.

(a) Instrumentation in Nissan Leaf (b) Instrumentation in DigiCar

Figure 3: A comparison of the instrumentation presented in (a) the Nissan Leaf and (b) that created for the DigiCar when running as an EV.

Two critical feedback sources were presented on the simulated instruments – speed (on the upper display) and the power/regenerative braking measure (on the lower display).

Some functionality of the Leaf dashboard was excluded from the simulated version as being less relevant for the specific validation task in this project. Specifically, this included the circular display giving an indication of driver efficiency, and the range and temperature measures.

Validation of the simulator

Study overview

Participants were asked to drive two routes designed to be as similar as possible: a simulated route and a real world route. The simulated route was modelled to replicate the TRL large loop test track, which was used for the real world route. Their performance and subjective impressions of both drives were compared to assess how, and the extent to which, driving DigiCar as an EV differs from driving a real EV. The method is based on that used in by Diels, Robbins & Reed (2012) in validating DigiCar as an ICE vehicle.

This research tested the hypothesis that there would be no difference in driver behaviour or subjective measures between the DigiCar EV and the Nissan Leaf.

Participants

A limited number of participants were recruited. To reduce variability in driving performance narrow selection criteria were adopted. This resulted in participants being male, experienced, middle-aged, and frequent drivers (see Table 1). While this limits the extent to which the simulator validation can be generalised to the wider population, it does improve the likelihood of achieving statistically robust results.

Table 1: Recruitment criteria and participant sample

	Recruitment criteria	**Mean (SD)**	**Range**
Age	Between 25-50 years old	34 (8) years	25-48 years
Driving experience	Have held a UK driving licence for at least 5 years	17 (8) years	7-29 years
Annual mileage	Drive at least 5,000 miles per year	12,222 (4,703) miles per year	6,000-20,000 miles per year

There were 18 participants recruited in total although one completed only the track drive and not the simulator drive. This participant was removed from all analysis of the data and all analysis presented are based on the remaining 17 participants only.

Vehicle

Participants driving TRL's' DigiCar are seated in a complete 2002 Honda Civic 1.6i SE whose external appearance is identical to a road legal vehicle (Figure 4(a)). A 2011 Nissan Leaf was used in the real-world component of the trial (Figure 4(b)).

(a) TRL DigiCar (2002 Honda Civic 1.6SE cabin) (b) Nissan Leaf (2011 model year)

Figure 4: Vehicles used in the study

In Vehicle Data Recorder (IVDR)

Data for three axis acceleration, speed and GPS location were collected on every drive. This data was recorded using a Racelogic VBOX Micro (Figure 5) – hereafter, referred to as 'the VBOX'.

Driving tasks

The driving tasks were completed using TRL's test track (see Figure 8). The test track is located on a secure secluded site providing a carefully controlled and safe operating environment. The track consists of five different sections, all of which can be operated independently of each other. This research utilised only one section; the large loop (see Figure 6 for a plan of the large loop). Participants progressed in a clockwise direction around the track, completing two familiarisation laps and four test laps.

Figure 6: TRL's test track - large loop in foreground

During the test laps participants completed a series of set manoeuvres. Five set manoeuvres were defined that were performed in both car and on the test track:

- Curve task (laps 1 and 3): progress through curve as you would normally.
- Preferred cruising speed task (laps 1 and 3): drive through the long straight of the large loop at which ever speed felt comfortable, but not above 90kph.
- Overtaking task (laps 1 and 3): approach a series of traffic cones blocking the lane ahead and move to the right in order to pass after passing a fixed point.
- Junction task (laps 2 and 4): decelerate on approach and stop the vehicle at intersection and subsequently accelerate as you would normally (approach speed and initial braking position were at drivers' discretion).

- Stopping task (laps 2 and 4): stop the vehicle 15 metres in front of a set position from a steady speed. To record performance in this task, the experimenter marked the ground where the vehicle stopped and measured the distance to the cones after the trial had been completed.

Virtual test track

To enable a direct comparison between driving behaviour in the simulator and the real world, it is beneficial to assess the driver whilst keeping the geometrical and geographical environmental characteristics constant. To this end, a virtual version of the TRL test track was created. Figure 7 shows the driver's view of the real (left) and virtual (right) task track on approach to the bridge.

Figure 7: View from the inside of a vehicle on the test track (left) and in the simulator (right)

Subjective measures

Participants were asked to complete a questionnaire during the course of the study. This was designed to elicit responses from participants about their experience of the performance of the vehicle and the simulator and to evaluate the quality of the simulated experience. Data on these measures will not be presented in the present research.

Results

Junction task

For the Junction Task, participants were required to approach a fixed position on the track as if they were approaching a junction with a stop sign and then to pull away once they had checked for approaching vehicles. This task was included as a measure of both braking and acceleration. Figure 8 shows mean speeds adopted by participants at 10 metre intervals before and after the junction stopping position.

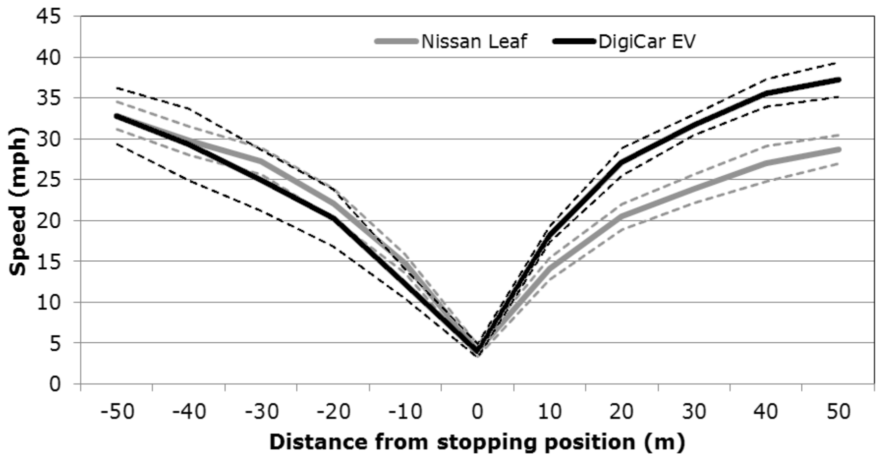

Figure 8: Mean vehicle speed (dashed lines show 95% CI) in the junction task leading up to, and away from stopping position in the simulator and real vehicle

Average participant speed across 10 metre increments for all junction tasks was calculated and compared to compare the Nissan Leaf and DigiCar EV conditions. Kolmogorov-Smirnov tests were performed on the data sets to establish if they were normally distributed. Results showed the data to be normal for all but two data sets (Nissan Leaf – 0m, $D(16) = .23$, $p = .01$; and Nissan Leaf – +50m, $D(14) = 25$, $p = .02$). Therefore paired samples t- tests were performed on the data for each distance increment, except at the 0m and 50m intervals, which were analysed using a Wilcoxon test. The results of the pairwise comparisons can be seen in Table 2. Results indicate a difference in deceleration behaviour on approach to the junction compared to acceleration behaviour away from the junction with the speeds between every distance increment after the junction being significant and almost none of the difference on approach to the junction being significant (only the -10m interval was significant on approach ($t(14) = 1.79$, $p = .04$)).

These results indicate that driver behaviour on approach to the junction was very similar in the Nissan Leaf and DigiCar EV. However when accelerating away from the junction drivers in the DigiCar EV accelerated significantly more sharply (within 10m they were already 4mph faster, and by 50m they were 7.6mph faster).

Table 2: Junction task results of pairwise comparisons (paired samples t-test and Wilcoxon in italics) of spot speeds for Nissan Leaf and DigiCar EV

Distance from stopping position (metres)						**95% Confidence Interval***	
	t (Z)	**df**	**Sig. (2-tailed)**	**Mean difference**	**Std. Deviation**	**Lower**	**Upper**
-50m	2.05	13	.87	0.27	6.26	-3.34	3.88
-40m	1.67	13	.86	0.40	8.12	-4.29	5.09
-30m	0.73	14	.30	2.20	7.95	-2.20	6.60
-20m	0.75	14	.36	1.84	7.62	-2.37	6.06
-10m	1.79	14	.04	2.58	4.32	0.19	4.97
0m	*(-.63)*	*	*.53*	*-0.12**	*1.64**	*-1.03**	*0.79**
+10m	0.41	14	<.001	-4.06	3.48	-5.98	-2.13
+20m	2.10	14	<.001	-6.56	3.61	-8.56	-4.56
+30m	0.60	13	<.001	-7.44	3.70	-9.58	-5.31
+40m	2.50	12	<.001	-8.98	5.05	-12.03	-5.93
+50m	*(-2.80)*	*	*< .01*	*-7.61**	*4.29**	*-10.67**	*-4.54**

*Not present for Wilcoxon tests, results presented are for illustrative purposes only

Curve following task

Figure 9 shows the mean spot speed at curve positions A and B ('entry' and 'exit', respectively). It can be seen that participants drove consistently faster in the DigiCar EV compared to the Nissan Leaf.

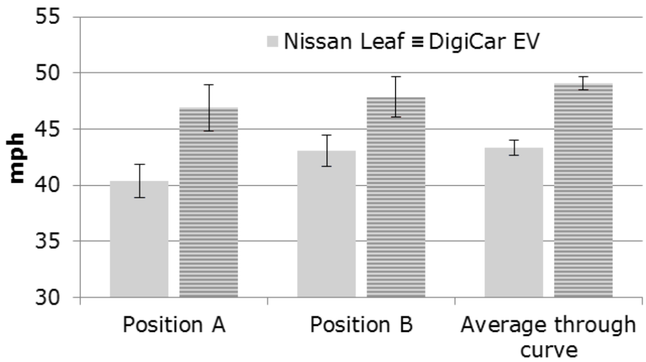

Figure 9: Mean (95% CI) spot speed (mph) at position A and B for Nissan Leaf and DigiCar EV conditions

Table 3 shows the results of the pairwise comparisons (Wilcoxon) for both spot speed positions and the mean speed between both points. Each of these comparisons achieved statistical significance.

Table 3: Pairwise comparisons of mean spot speed at position a and b and average between a-b for real and simulated curve task

Comparison	Z	Sig.		N	Mean	Std. Dev	Min	Max
Position A	-2.99	.03	Nissan Leaf	16	40.3	3.20	33.8	46.0
			DigiCar EV	16	46.9	4.43	37.1	52.0
Position B	-3.10	.02	Nissan Leaf	16	43.1	3.06	36.6	47.4
			DigiCar EV	16	47.9	3.84	37.3	55.4
Average through curve	-3.52	<.01	Nissan Leaf	16	43.3	1.50	41.9	46.4
			DigiCar EV	16	49.1	1.30	47.8	52.2

There is a clear difference in the spot and average speeds between drive conditions. Drivers in the DigiCar EV drove at higher speeds at the entry position (6.6mph), the exit position (4.8mph), and on average through the curve (5.8mph).

Stopping distance task

The distance participants stopped from an on-road obstruction (three adjacent traffic cones, arranged perpendicular to the road direction) were compared between the two vehicle conditions. The stopping positions were plotted and visually inspected for trends (see Figure 10); this suggested that there was greater variation in stopping distances in the DigiCar EV condition.

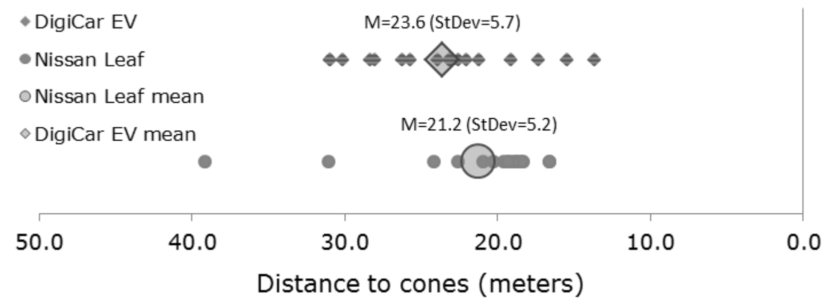

Figure 10: Mean stopping distances for both conditions

However, when the data was subjected to a Wilcoxon Sign Ranks test, the results just reached significance at the p = .20 level (z = -1.30, p = .19), suggesting that stopping positions differed between the two vehicle conditions. However, given the result only marginally satisfied our requirement for significance and the modest number of participants tested, this result should be interpreted with a degree of caution.

Overtaking task

The primary function of the overtaking task was to require participants' to avoid an obstacle by changing lane position; secondarily, they also had to adjustment their speed to execute this manoeuvre safely. As the positional data recorded during the Nissan Leaf condition was subject to a degree of error (a limitation of GPS accuracy – see 3.4) a fine-grained analysis of lane position behaviour was not practical, therefore, mean position across 20 metre increments were calculated and differences between the two conditions were compared.

A figure describing driver lane position and speed (mph) was drawn and can be seen in Figure 11. In initial inspection of this figure suggests there was little difference in lane position between the two conditions (note – the greater variation in the Nissan Leaf data is likely to be a consequence of the limited GPS accuracy of the IVDR). There appears to be a difference in speed between the two conditions. These data were subjected to statistical analysis to determine whether they are statistically significant.

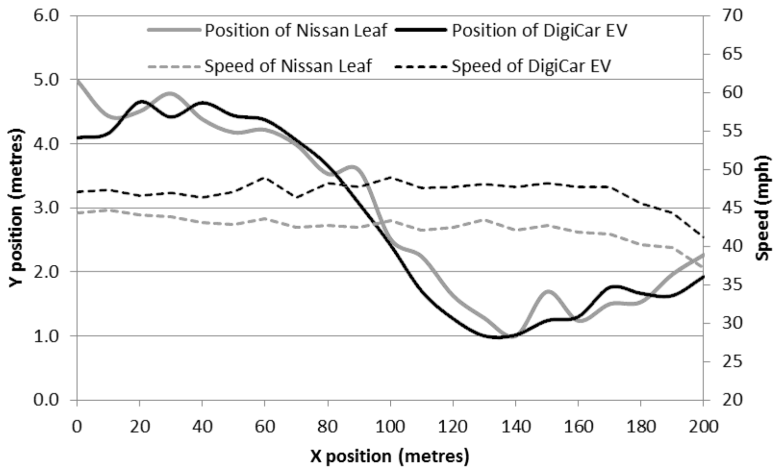

Figure 11: Driver lane position and speed throughout overtaking task

Analysis of lane position revealed no difference in position between the two conditions at any of the distance increments, indicating that drivers exercised similar levels of vehicle control and positional judgement in both conditions.

The difference in speeds suggested in Figure 11 did achieve statistical significance at all positions. Therefore, drivers drove at significantly higher speeds throughout the overtaking manoeuvre in the DigiCar EV condition than the Nissan Leaf condition.

Table 4: Results of pairwise t-tests between speeds in the two vehicle conditions

X position (metres)	Mean speed	Std. Dev.	Std. Error Mean	95% Conf. Interval		t	df	Sig. (2-tailed)
				Lower	Upper			
0	-5.68	3.58	1.60	-10.13	-1.23	-3.55	4	0.02
20	-2.69	5.33	1.38	-5.64	0.26	-1.96	14	0.07
40	-3.42	5.43	1.18	-5.89	-0.95	-2.89	20	0.01
60	-4.46	5.20	1.11	-6.76	-2.16	-4.03	21	0.00
80	-4.07	6.59	1.55	-7.34	-0.79	-2.62	17	0.02
100	-5.34	6.17	1.50	-8.51	-2.16	-3.57	16	0.00
120	-5.66	7.80	1.89	-9.67	-1.65	-2.99	16	0.01
140	-5.21	7.57	1.78	-8.97	-1.44	-2.92	17	0.01
160	-4.04	7.46	1.81	-7.88	-0.21	-2.24	16	0.04
180	-4.29	5.85	1.46	-7.40	-1.17	-2.93	15	0.01
200	-3.67	7.48	1.72	-7.27	-0.06	-2.14	18	0.05

Drivers did not vary in their lane position between the two conditions; however, they did execute the overtaking manoeuvre at significantly higher speeds in DigiCar EV than the Nissan Leaf.

Discussion

This study aimed to equip the TRL driving simulator, DigiCar, with the driving experience of a Nissan Leaf and to validate this with a small number of participants. The results demonstrated the implementation of DigiCar EV provides participants with a realistic experience of some aspects of driving such a vehicle.

In the junction task, it was evident that drivers in the simulator accelerated away from the junction more rapidly in the simulator than they did in the real car. Similarly, in the curve following and overtaking tasks, participants adopted higher speeds in the simulator than they did in the Nissan Leaf (by around 5-7mph). One can hypothesise a number of reasons why this might have been the case. Firstly, the Nissan Leaf was a very new car and participants may have felt that they needed to treat it with more care than they chose to exhibit in the simulator vehicle. Secondly, accelerating the real vehicle in the absence of the sound cues provided by an ICE may have had a greater influence over drivers in the real car than in the DigiCar, resulting in slower acceleration. Thirdly, although the DigiCar was calibrated against the performance of the Nissan Leaf for maximal acceleration, no such calibration was performed for slower speed accelerations. It may have been the case that in the real and simulated cars, participants chose to accelerate away from the junction by depressing the accelerator to half way between its rest position and its maximum position. If this yielded 50% of the available torque in the real car but 80% in the simulator vehicle, one would experience faster acceleration in the simulator vehicle for the same level of accelerator pedal depression. To tackle this acceleration issue in future, more work must be done to adjust the exact response of the simulator vehicle to driver inputs so that they match more closely those of the vehicle being simulated.

It could be suggested that a driver in a simulator vehicle chooses to accelerate and drive faster as there is no risk of them coming to any harm in the simulated situation and so they can proceed to drive faster than they would in the real world. However, Diels, Robbins & Reed (2012) conducted a validation of DigiCar as an ICE vehicle, finding that acceleration rates and speeds adopted did not differ between the simulated real environments. This suggests that if future trials are to be conducted using the DigiCar EV model, the experimental design must, as a minimum, take into account the likelihood that participants will adopt higher speeds in the simulator than they would in a real vehicle but (preferably) the adaptation of the simulator as an EV should be corrected to ensure that speeds adopted in DigiCar EV correspond more closely with those observed in the real world.

In the overtaking task, there was no significant difference between the positions observed for the real car compared to those for the DigiCar EV. In the stopping position task, data showed there was a marginally significant difference in stopping position. Therefore, these results suggests that the visual representation in DigiCar enables participants to judge distances reasonably well relative to the real world and that the handling characteristics of the DigiCar EV were sufficiently matched to the real Nissan Leaf for participants to perform the lane change task in a similar manner. However, the results highlighted that participants' judgement of distance in the real and simulated vehicles was relatively poor with the mean stopping position from the target cones more than 40% further away than the distance participants had been instructed to stop (15m) in each case.

In conclusion, it is clear that the DigiCar EV model has several shortcomings that need to be addressed before it could confidently be used as a Nissan Leaf equivalent. In particular, the characteristics of acceleration and deceleration should be examined to ensure that adopted speeds, acceleration and deceleration rates are a closer match to the real vehicle. However, aside from issues relating to matching exact performance of the Nissan Leaf, the DigiCar EV represents a good platform with which to conduct future studies examining driving of cars equipped with powertrains other than the traditional ICE model.

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