

xEV Brake Loading on Front and Rear Axles During Track Testing

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Summary

Environment and Climate Change Canada and Transport Canada collaborated to conduct track tests on two rear-wheel drive xEVs in order to determine the empirical relationship between deceleration rate, vehicle speed and rear-axle brake load. This study is the second phase in a larger endeavour to evaluate a potential positive regenerative braking bias during regulatory chassis dynamometer tests, which could affect the regulatory test fuel consumption and emission rates. Results indicate that rear-axle brake load is highly correlated to deceleration rate, and less so to vehicle speed. Regenerative braking energy was found to have a proportional relationship with rear-axle brake load, but this relationship deviates at low deceleration rates to maximize regenerative braking energy.

Keywords: BEV, HEV, Braking, Regenerative, Torque

1 Introduction

Electric vehicles, (hybrid electric (HEV), plug-in hybrid electric (PHEV) and battery electric vehicles (BEVs), known collectively as xEVs), are inherently more difficult to test than conventional internal combustion engine (ICE) vehicles. This is because xEVs can operate under multiple energy transmission modes within a single driving event, which includes multiple paths and directions (e.g. regenerative braking, engine powering wheels, engine charging battery, battery powering wheels, battery and engine powering wheels, etc.), whereas ICE vehicles operate solely with a single-path energy flow (i.e. from petrol fuel through the engine, transmission, drive-shaft and finally to the vehicle's wheels). Given that xEVs and ICE vehicles transmit and manipulate energy so differently, testing xEVs on chassis dynamometers with the goal of producing representative, reliable and repeatable results, while at the same time maintaining comparability to ICE vehicle test results is a difficult task. The Society of Automotive Engineers (SAE) has addressed these issues with its latest drafts of J1711 and J1634, recommended test procedures for HEVs and PHEVs, and BEVs, respectively. These standards are the building blocks for the *Canadian Environmental Protection Act's* (CEPA 1999) regulatory framework for testing xEVs and represent the collective expertise of industry, government and academia.

The CEPA 1999, and the U.S. Environmental Protection Agency (EPA) Code of Federal Regulations (CFR), allows any given xEV to be evaluated using a two-wheel (single-axle) chassis dynamometer with the provision that during the test the xEV operates as it would during regular driving on-road. In the case of xEVs, this blanket statement implies, amongst other things, that regenerative braking operate as it would if the vehicle were on-road and that the dynamometer is programmed to not participate, such as through providing augmented braking. In regards to the former implication, Argonne National Laboratory (ANL) conducted a multi-HEV study to evaluate the performance of regenerative braking systems on 2-wheel and 4-wheel chassis dynamometers [1]. Generally, xEVs only collect regenerative braking energy through the

drive-axle. During on-road driving, both axles of an xEV are engaged in braking. Thus, braking torque through the drive-axle is always less than 100%; often between 50%-90% on a dynamic inertia basis. On a chassis dynamometer, 100% of the drive and brake torque is applied through the drive-axle. Thus, the premise of the ANL study is that when tested on a chassis dynamometer, xEVs receive a positive bias towards regenerative braking energy, which could result in overestimating the xEV's fuel economy and underestimating its emissions. Although the ANL study found that there was no statistically significant difference in regenerative braking energy between the 2-wheel and 4-wheel chassis dynamometer tests, the study focussed on front-wheel drive (FWD) HEVs. Front-wheel drive vehicles typically rely on the drive-axle to provide braking torque. Conversely, rear-wheel drive (RWD) vehicles rely predominantly on the non-driven axle to provide braking torque, and thus the difference between the on-road and chassis dynamometer braking torque on the rear-axle is greater than for FWD vehicles.

This paper describes a portion of an on-going study to evaluate the effects of applying realistic braking loads, accepted chassis dynamometer braking loads, and 4-wheel chassis dynamometer braking loads on regenerative braking energy, fuel consumption and regulated emission rates. The full study includes three phases. The preliminary test phase involved testing two xEVs over the NYCC on a 2-wheel and 4-wheel chassis dynamometer while monitoring and measuring fuel consumption, emission rates and battery energy [2]. The second phase, described in this paper, involves constant deceleration tests conducted on a closed-loop track to map out rear-axle braking loads against discrete deceleration rates and vehicle speeds. The third phase will see the empirically determined brake loads on the rear wheels simulated on the 2 wheel chassis dynamometer, for both vehicles. Vehicle emissions, energy and fuel consumption will then be evaluated and compared to the standard and regulatory accepted test procedure results (2-wheel chassis dynamometer).

2 Experimental Method

Two xEVs were driven on a closed-loop track at various constant deceleration rates from 27.8 m/s to stop on the high-speed circuit. The tests were conducted only during mild weather conditions with no precipitation. Each test required a driver and a passenger. The passenger operated all the instrumentation, while the driver used a Driver Aid to properly carry out the tests. This exercise produced speed versus rear axle brake load curves at discrete and unique deceleration rates. These empirically determined rear axle-brake load-speed-acceleration maps were determined in order to apply them to the ERMS's in-lab chassis dynamometer controller so that 'real' brake load chassis dynamometer tests can be compared to 'standard' (100% rear brake load) chassis dynamometer tests.

2.1 Vehicle Specifications

Regenerative braking and braking load distribution can depend on vehicle type (HEV, PHEV or BEV), drive-type (RWD or FWD) and vehicle mass. For this reason two vehicles were selected to span a range of possibilities; namely, a RWD HEV with a 3,000 kg mass and a RWD BEV with a 1,100 kg mass. The specifications for these two vehicles are provided in Table 1.

Table 1: Specifications of the HEV and BEV

Vehicle ID	EV1	EV2
xEV Type	HEV	BEV
Model Year	2013	2013
ETW (kg)	3000	1100
Drive	RWD	RWD
Transmission	CVT	eCVT
Fuel	Gasoline	Electric
Emission Standard	Tier2 Bin 5	Tier 2 Bin 1
ESS Type	NiMH	Li-Ion
ESS Capacity (kWh)	2	18
System Voltage (V)	300	300
Motor Power (kW)	60	55

2.2 Duty Cycles

Both xEVs were accelerated to approximately 27.8 m/s either on a straight or curved section of the track before the start of each test. Once speed was stabilized at 27.8 m/s, the driver decelerated to a stop at the constant deceleration rate indicated by the driver aid (see section 2.4). For each xEV, 27 unique deceleration tests were attempted; these are indicated in Table 2. The BEV could not be tested at the four lowest deceleration rates due to the design of its regenerative braking system, which activated when the brake pedal was released. Each test that could successfully be carried out was repeated three times. The overall test matrix for the track tests is provided in Table 2.

Table 2: Test matrix

	Test Repeats																											
Drive Cycle [m/s ²]	0.3	0.4	0.6	0.7	0.8	1.0	1.1	1.3	1.4	1.7	1.9	2.2	2.5	2.8	3.1	3.3	3.6	3.9	4.2	4.4	4.7	5.0	5.3	5.6	5.8			
EV1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3			
EV2					3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3			

2.3 Instrumentation

Battery activity, select CAN bus signals, vehicle location and speed information, and wheel torque were measured using the instruments listed in Table 3. The equipment used for each vehicle is shown in Figure 1 and described in Table 3. A HIOKI power analyser was used in conjunction with a clamp-on amp probe to measure the energy flow in and out of the traction battery. Strain gauge wheel torque sensors were installed on all four wheel hubs and connected to a sensor telemetry transmitter. Four receivers were used to relay the real-time measurements to a USB Link 90388 which processed the signals and for recording and real-time analysis on a laptop. These instruments were powered with the use of a deep cycle 12V marine battery and inverter. A FleetCarma C5 datalogger was also used to log select CAN bus signals on a microSD card.

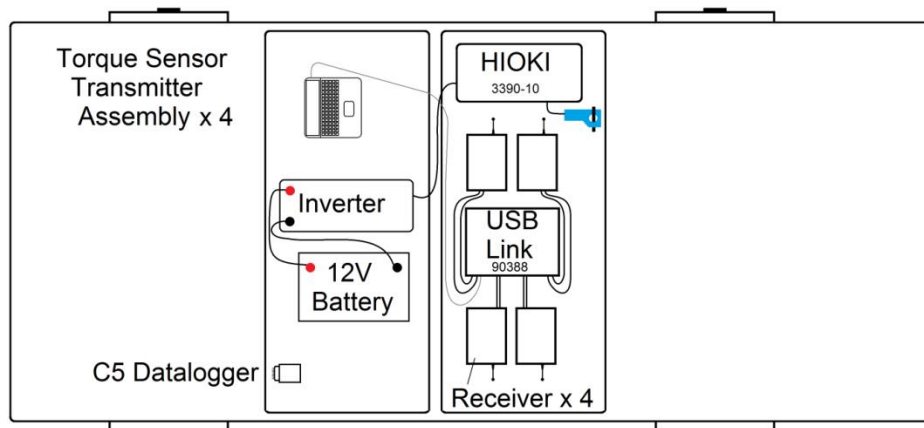


Figure 1: Schematic of equipment used during track testing

Table 3: Instrumentation specifications

Instrument	Manufacturer	Model	Units
Power Analyser	HIOKI	3390-10	1
200A Clamp-On Probe	HIOKI	4278	1
Inverter	MotoMaster	Eliminator Mobile Power Inverter - 1500W	1
12V battery	NorthStar	NSB-AGM31	2
CAN bus Decoder	FleetCarma	C5	1
Wheel Torque Sensor	Sensor Development	90360	4
Wireless Transmitter	Sensor Development	90360-883-0B0B0	4
Wireless Receiver	Sensor Development	90330 FM Receiver	4
USB Link	Sensor Development	90388	1

2.4 Driver Aid

A combination of computer transducer, Garmin GPS unit, closed-source computer monitor and Visual Basic developed software was used to allow the driver to monitor his speed in real-time, such that he could assess his accuracy in maintaining the speed-time trace. Figure 2 provides a schematic representation of these four pieces of equipment. Note that although the computer software was also programmed to measure real-time g-forces, this method of driver aid was disbanded due to poor user acceptance/engagement.

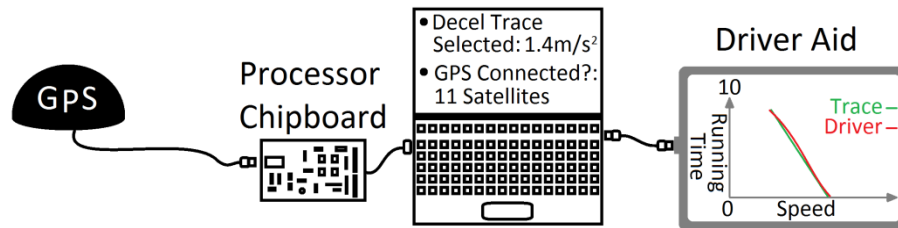


Figure 2: Driver's Aid instrumentation

3 Calculations

The track tests were designed so that each test was an evaluation of the rear-axle brake load at a specific and constant deceleration rate from 27.8 m/s to stop. In this way, we hoped to evaluate the effects of vehicle speed, if any, on rear-axle brake loading. Maintaining a constant deceleration rate between 27.8 m/s and 0 m/s was a challenging and critical issue to address. The best solution that could be developed in the timeframe available was to use a driver aid, which allowed the driver to correct for speed deviations from the constant deceleration drive cycle. It was understood from the outset that because the vehicles were being decelerated by drivers, and because those drivers were using visual aids, the resulting deceleration rates may not be linear; this turned out to be true. As a result, for every test (to varying degrees) the rear-axle brake load was not only a function of vehicle speed, which was the original intention, but also of deceleration rate. In order to isolate the relationship between vehicle speed and rear-axle brake load, and the relationship between deceleration rate and rear-axle brake load, each test was broken into segments that exhibited the most linear decelerations. Specifically, this translated to a numerical analysis of the vehicle speed for each test, whereby the segments of the test with the highest speed R^2 values were taken as individual deceleration events. A script was created in Visual Basic to analyze the correlation coefficients for each test's speed-time curve, initiating at the start time of the deceleration event. The speed-time segment duration being correlated was iterated, beginning with a duration of 1 second (i.e. a minimum deceleration time of 1 second), after which that deceleration segment was incremented in duration by 0.1 seconds and re-correlated. This procedure was repeated until the end-time of the test was reached. The highest correlation coefficient from that first series of correlation analyses was selected if it was greater than 0.99. The start time of the next analysis was then reset as the end time of the preceding analysis, and the process was repeated. However, if none of the correlation coefficients exceeded 0.99 from the correlation analysis, the start time was incremented by 0.1 seconds from its original value and the process was repeated. Table 4 exemplifies this procedure numerically while the results of this process are graphically illustrated in Figure 3.

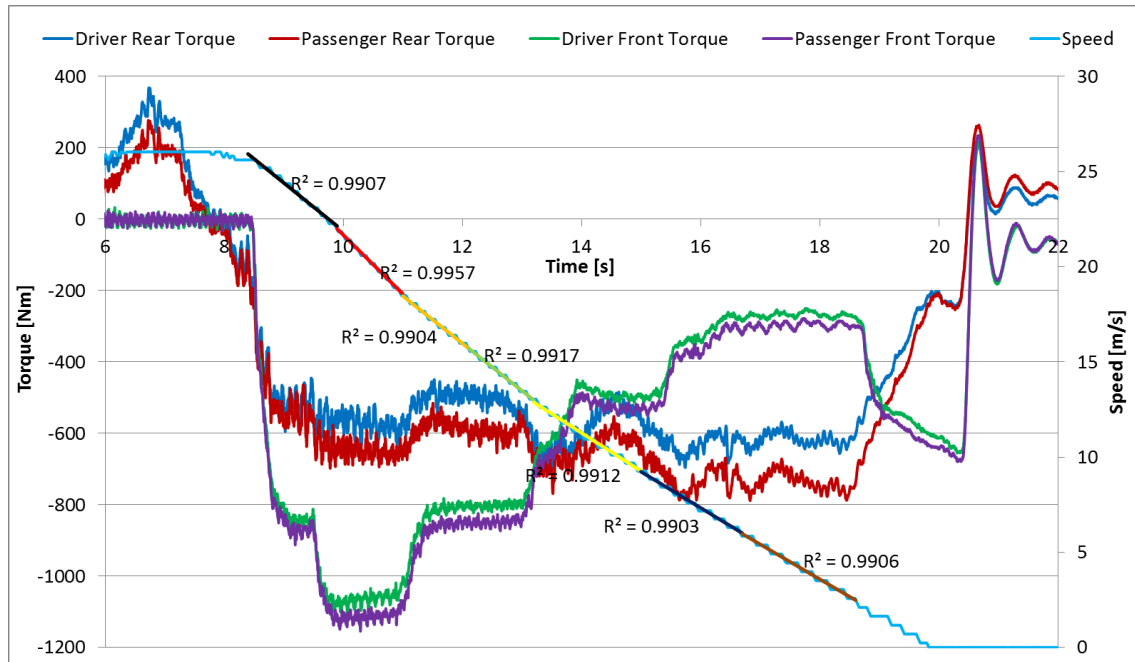


Figure 3: Linearized segments of HEV 2.2 m/s² test repeat number 2

Table 4: Example of iterative correlation coefficient determinations

Start Time End Time	Correlation Coefficients					
	0	0.1	1.2	2.5	...	9.5
start time + 1.1	0.899	0.991	0.899	0.665	...	0.668
start time + 1.2	0.841	0.998	0.993	0.611	...	0.656
start time + 1.3	0.746	0.981	0.999	0.621	...	0.568
⋮	⋮	⋮	⋮	⋮	⋮	⋮
10.5	0.221	0.896	0.537	0.533	...	0.168

4 Results

4.1 Summary of Tests

The three repeat tests for each test condition outlined in Table 2 were averaged and are shown in Figure 4 and Figure 5, for the HEV and BEV, respectively. For the HEV the rear-axle braking load decreases from 89% to 30% between -0.3 m/s² and -5.8 m/s². To provide context, at a deceleration rate of 0.3 m/s² the HEV took 100s to reach a stop from 27.8 m/s (100 km/h) and the brake pedal was only lightly feathered. At a deceleration rate of 5.8 m/s² the HEV came to a stop within less than 4 s and skid marks were left on the track, but ABS was not activated. Proportionally, the regenerative braking energy decreased as deceleration rates increased, but not linearly. Regenerative braking energy peaked sharply at 170 Wh at -1 m/s², making this mild deceleration rate optimal for recuperating braking energy.

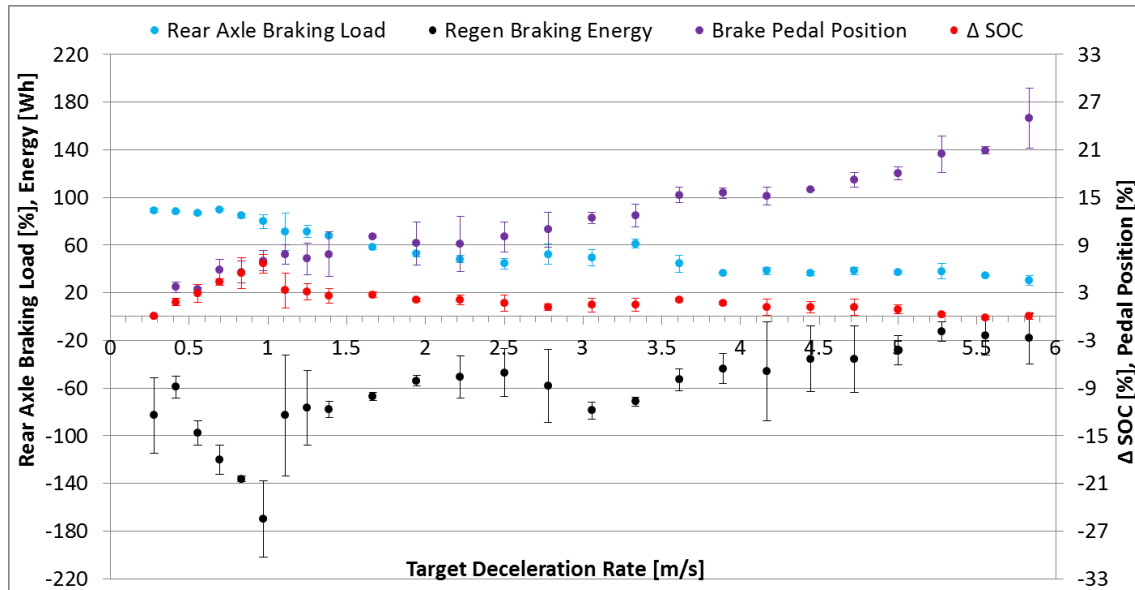


Figure 4: Averaged track deceleration rear-axle brake loading, regenerative braking energy, brake pedal position and change in battery state-of-charge for the HEV

The rear axle braking load, regenerative braking energy, brake pedal position and change in state-of-charge (SOC) of the battery for the BEV is shown in Figure 5. Note that the BEV coasted in the drive gear at less than -3 m/s^2 without the use of brakes. The authors attribute this to an aggressive RBS strategy that simply requires the accelerator pedal position to be zero to activate. Similar to the HEV, the rear-axle braking load decreases from 89% to 39% between -0.8 m/s^2 and -5.8 m/s^2 . Regenerative braking energy is generally proportional to rear-axle braking load, decreasing from 65 Wh to 4 Wh. The change of SOC reflects this in its sinusoidal decrease from 0.37% to 0.10% between -0.8 m/s^2 and -5.8 m/s^2 . Two notes of interest: first; the change in SOC is on the order of less than 1%, which is due to the high battery energy capacity and two; the apparent sinusoidal decrease in ΔSOC is hypothesized to be coincidental, as the coefficients of variations for these ΔSOC values are on the order of 45%. On a different note, the brake pedal position only increases from 0 to 15%, implying that the vehicle is capable of providing a much higher braking force than was needed at the already hard deceleration rate of 5.8 m/s^2 .

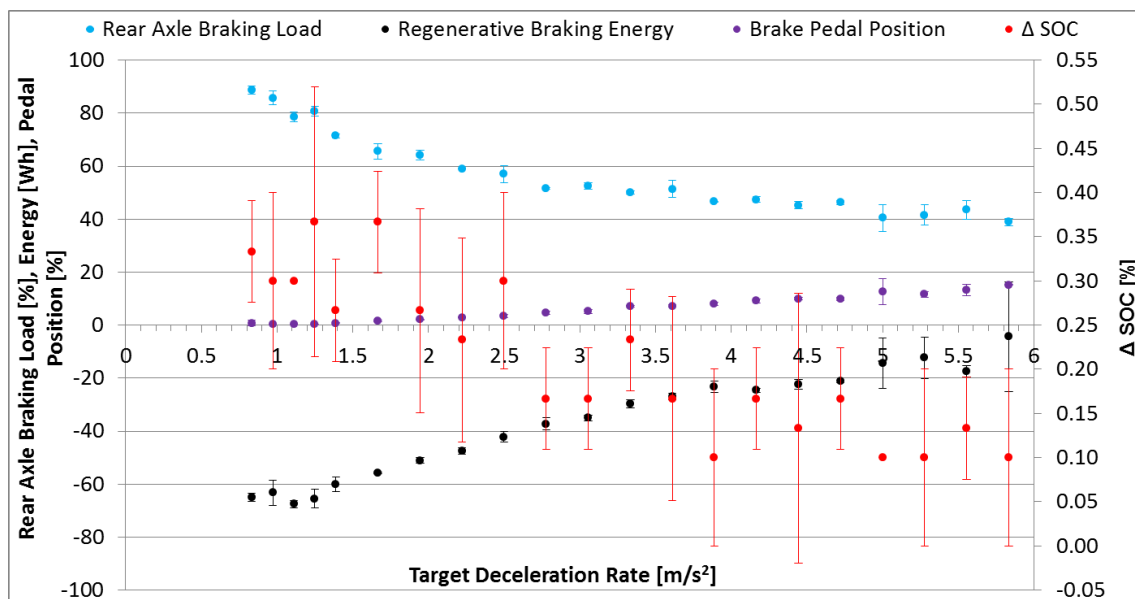


Figure 5: Averaged track deceleration rear-axle brake loading, regenerative braking energy, brake pedal position and change in battery state-of-charge for the BEV

4.2 Modal Test Results

Two modal test results are presented in Figure 6 and Figure 7 for the HEV and BEV, respectively. Both tests are examples of the -2.5 m/s^2 test condition. As can be seen for both vehicles, at near 0 m/s , the front brakes are relied upon to bring the vehicle to a stop. Although these two figures are for the -2.5 m/s^2 tests, this observation was consistent for every single test conducted on both vehicles. This may be explained by the electronic control design of the brake systems, of which the most important goal is to minimize slippage while responding as closely as possible to the user input (i.e. brake pedal input). In the event that wheel slippage is not an issue (i.e. most braking events) the next priority for an xEV is to maximize regenerative braking energy by transferring brake load to the drive axle (i.e. axle that is mechanically connected to the motor/generator). At low speeds, however, regenerative braking energy is greatly reduced in order to exercise the front brake rotors, and because there is less kinetic energy to provide useful stopping power. As such, the braking systems engage the front brake rotors to contribute more substantially.

In Figure 6, the speed-time curve is almost completely linear, and the resulting torque curves for the front and rear axles are also almost completely linear (plateau). This particular test, and others like it, supports the empirical theory that vehicle speed does not affect the front-to-rear axle braking load ratio. Rather, the deceleration rate of the vehicle seems to be the only major factor in determining the brake load ratio on the front and rear axles.

Finally, as can be observed in Figure 6 and Figure 7, the regenerative braking energy recuperated by the HEV (38 Wh) is nearly identical to that recuperated by the BEV (41 Wh), despite its smaller battery size and the fact that the HEV battery depth of discharge (DOD) is substantially less than for the BEV. This may be attributable to the HEV's much greater axle torques during the braking event, which at some points total up to 4 times greater than for the BEV. The profiles of regenerative energy recuperated by both vehicles for all deceleration rates tested may be seen in Figure 4 and Figure 5.

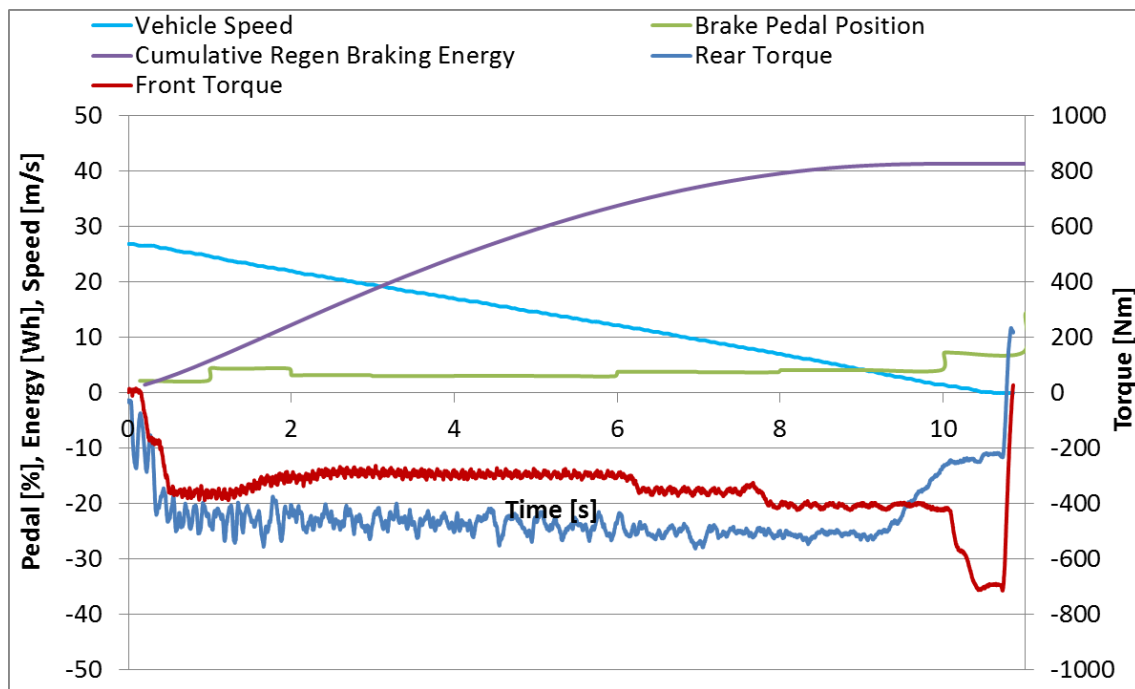


Figure 6: BEV 2.5 m/s^2 test repeat number 1

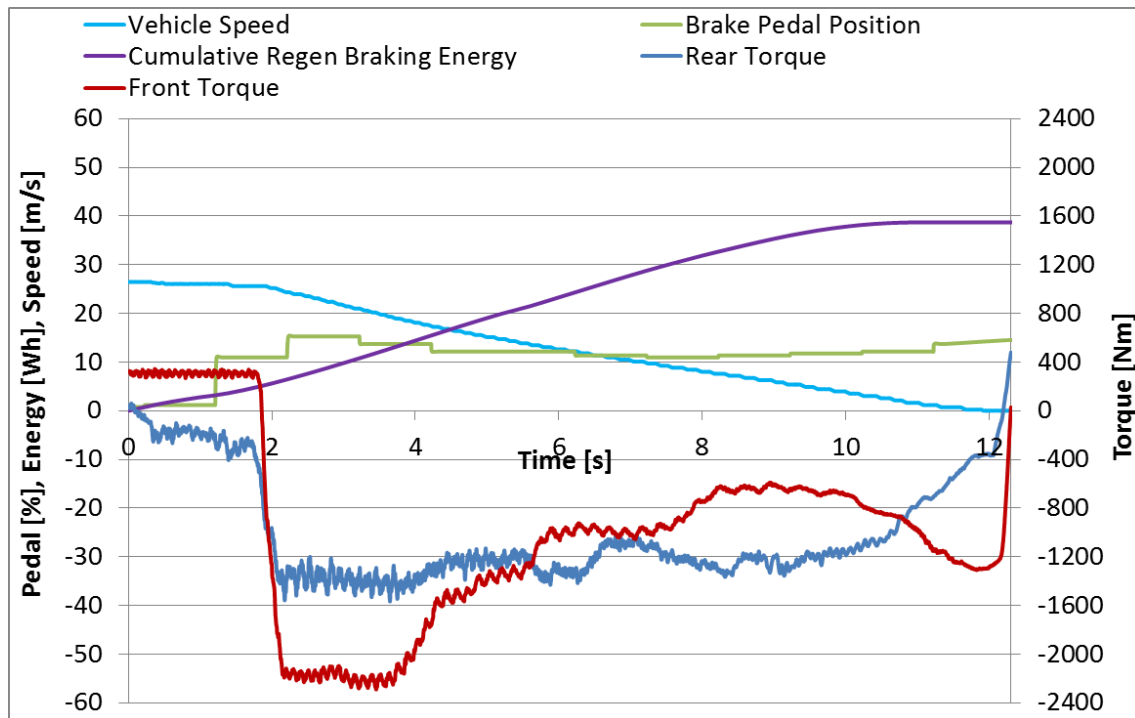


Figure 7: HEV 2.5 m/s² test repeat number 1

4.3 Rear-Axle Braking at Constant Decelerations

Figure 8 presents the aggregate and average of 14 unique and linear ($R^2 > 0.99$) 4.3 m/s² deceleration events for the HEV, which were derived using the method outlined in Section 4. The aggregate of these 14 unique deceleration segments from the various tests conducted on the HEV is remarkably congruous and this was generally the case for all the deceleration binned graphs. Although speed was thought to not play a role in the rear-axle brake loading, it is evident from Figure 8 that this is not entirely true. For most deceleration rates that were binned, and for both xEVs, the rear axle brake load peaks at between 2 and 9 m/s and then tapers off at higher speeds; and as described in section 4.2 the rear-axle brake load drops off very quickly at low speeds (i.e. < 2 m/s). The HEV and BEV have a different number of deceleration bins for which curves similar to Figure 8 were produced. These deceleration bins were created based on histograms of all the unique deceleration segments developed for each xEV. The resulting 3-D curves of speed versus deceleration versus rear-axle brake loading are shown for the HEV and the BEV in Figure 9 and Figure 10, respectively.

The HEV used 100% rear brakes at all speeds between 0 and 27.8 m/s for deceleration rates less than 1.0 m/s². This is likely designed by the OEM to maximize regenerative braking potential at low deceleration rates. For decelerations greater than 0.8 m/s² the rear-axle brake load drops immediately to 50% or less for speeds greater than 22 m/s. In general, the rear-axle brake load is variable between speeds of 0 and 22 m/s in a parabolic-type curve. Except for a few decelerations at 0 m/s rear-axle load was generally greater than 0%.

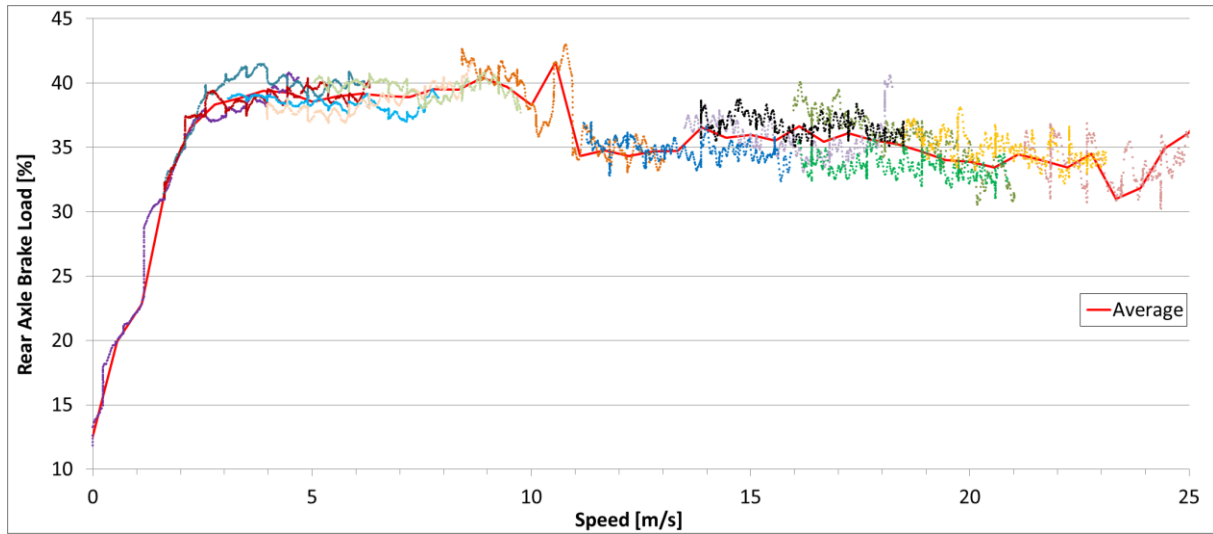


Figure 8: Aggregated and averaged rear-axle brake load versus vehicle speed profiles for the HEV at a deceleration rate of 4.3 m/s^2

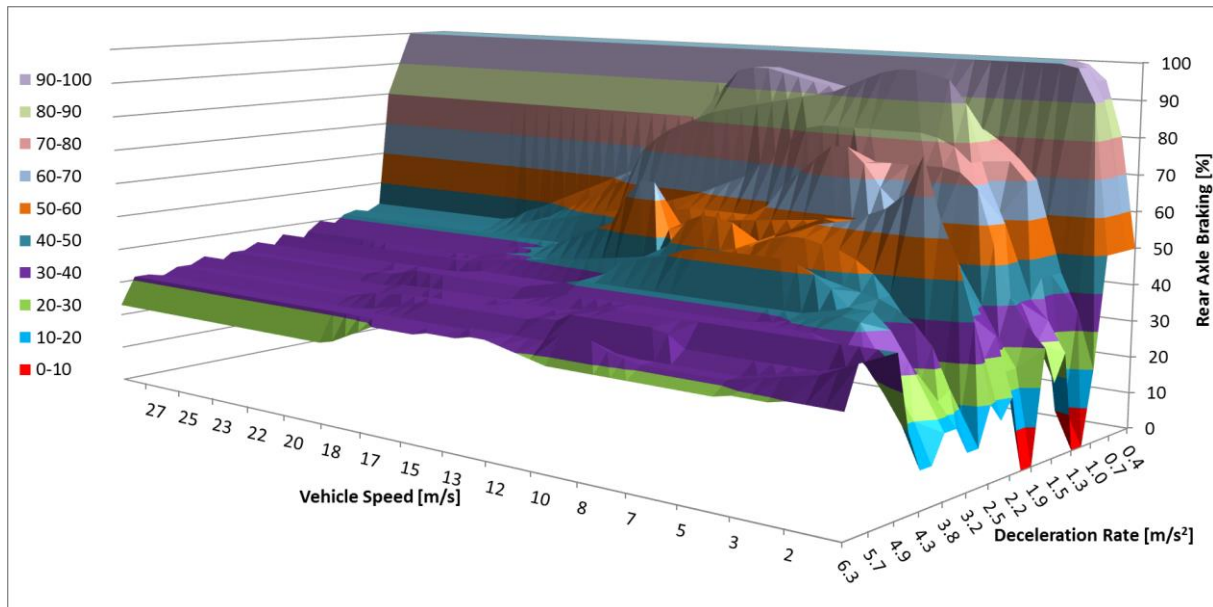


Figure 9: HEV rear-axle brake load curves as a function of vehicle speed and deceleration rate

Similar to the HEV, the BEV used 100% of the rear-axle brakes for deceleration rates less than 1.0 m/s^2 for speeds greater than 3.3 m/s . Unlike the HEV, however, the rear-axle brake load of the BEV gradually decreases from 100% to the 20-30% range at -5.7 m/s^2 .

The processed data used to make Figure 9 and Figure 10 will be used in the last phase of this study to re-program ERMS's chassis dynamometer controller to simulate the empirically determined brake loads for each xEV at discrete speeds and deceleration rates.

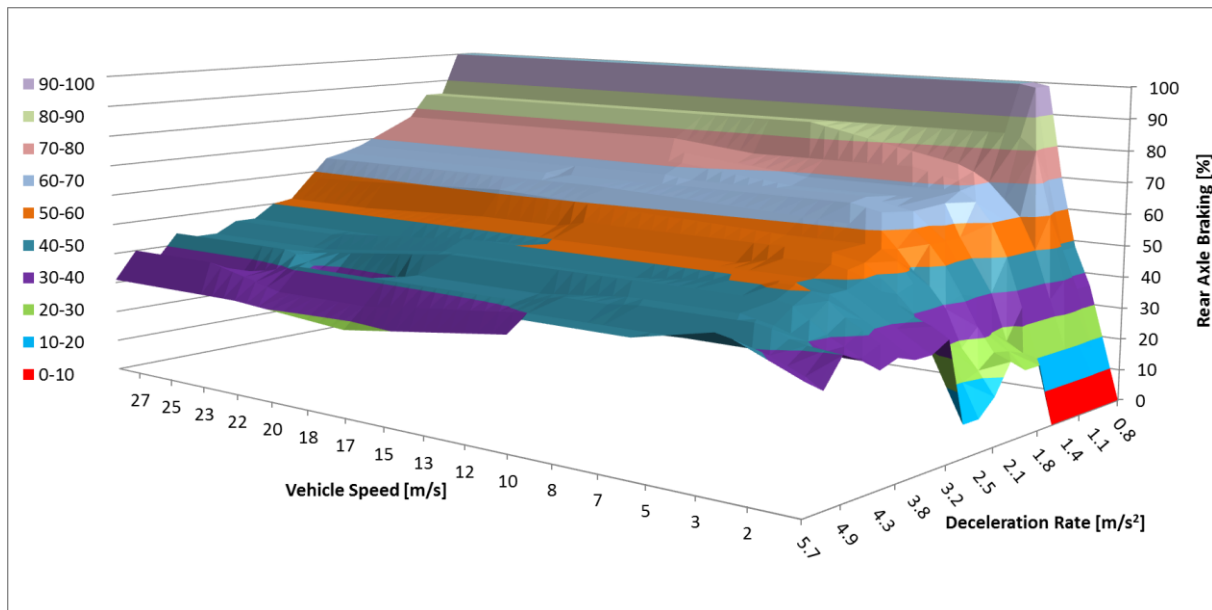


Figure 10: BEV rear-axle brake load curves as a function of vehicle speed and deceleration rate

5 Conclusions

Two rear-wheel drive xEVs were tested on a closed track to determine the empirical relationship between deceleration rate and rear-axle brake load. This study is the first phase in a larger endeavour to characterize regenerative braking in the real-world compared to chassis dynamometer testing.

One 3,000 kg RWD HEV and one 1,100 kg RWD BEV were decelerated from 27.8 m/s to stop at 27 unique and constantly applied deceleration rates. It was found that constant deceleration rates from 27.8 m/s to stop were not achieved for most tests to the degree required for evaluating rear-axle brake load. In order to determine the relationship between deceleration rate and rear-axle brake loading, the individual test repeats were parcelled into smaller linear ($R^2 > 0.99$) deceleration segments and then aggregated into select deceleration rate bins. These deceleration rate bins were then graphed all together in a 3D graph to show the relationship between speed, deceleration and rear-axle brake loads; this was done for both vehicles. It was found that for the HEV, rear-axle brake load was 100% for deceleration rates less than 0.8 m/s^2 and then steeply decreased to 50% or less for greater deceleration rates. Vehicle speed also influenced the rear-axle brake load, the relationship being parabolic in nature at speeds up to 22 m/s. The BEV generally showed similar trends at low deceleration rates, but instead of the rear-axle brake load decreasing steeply, it more linearly decreased with deceleration rate from 100% at 1.0 m/s^2 to 30% at 5.7 m/s^2 . In the final phase of this study, these relationships will be incorporated into a chassis dynamometer controller to simulate on-road rear-axle brake loads.

Despite not achieving linear ($R^2 > 0.99$) decelerations throughout entire tests, general trends were found between deceleration rate and brake parameters when analysing entire tests as single deceleration events. Rear-axle brake load decreased from 89% at 0.3 m/s^2 to 30% at 5.8 m/s^2 for the HEV and 89% at 0.8 m/s^2 to 39% at 5.8 m/s^2 . Cumulative regenerative braking energy decreased from 170Wh during a mild braking event to 13Wh during a hard braking event for the HEV and similarly 67 Wh to 4 Wh for the BEV. For both xEVs, regenerative braking energy peaked at a deceleration rate of approximately 1 m/s^2 .

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References

- [1] M. Duoba et. al., *Investigating Possible Fuel Economy Bias Due to Regenerative Braking in Testing HEVs on 2WD and 4WD Chassis Dynamometers*, Society of Automotive Engineers International, 2005-01-0685.
- [2] A. Loiselle-Lapointe et. al., *Effects of reducing the braking load of a rear-wheel drive hybrid electric vehicle on regenerative braking, fuel consumption, and CO2 emissions tested on a two-wheel and four-wheel chassis dynamometer*, The Society of Automotive Engineers of Japan, International Electric Vehicle Technology & Automobile Power Electronics Japan Conference Proceedings, 2014.

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