Optimisation of Chassis Dynamometer Force Variability for Floor Anchor Restraint Systems

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Abstract: To ensure sufficient axle load correlation can be achieved between Climatic Wind Tunnel (CWT) chassis dynamometer testing and track testing, coast match methodology such as that seen in SAE J2264 should be utilised to ensure any facility-imposed forces are negated. Such methodology introduces increased test preparation time to carry out a coast match test prior to starting CWT testing. With increased pressure to reduce financial and environmental impact of CWT testing, an investigation into the repeatability of CWT vehicle installations was conducted. The investigation aimed to understand if a coast match test was required for subsequent installations of a vehicle into a CWT having completed an initial coast match test. An experiment was conducted to evaluate potential influencing factors, including tyre type, tyre pressure, dynamometer position and loading applied through the vehicle restraints. Analysis concluded that tyre pressure and loading applied through vehicle restraints led to the highest variability in applied force to the vehicle axles. Implementation of control techniques through inclusion of strain gauges to vehicle restraints reduced variability of axle loading normalised by track road load from a range of 13.2% - 4.5% down to 5.6 % - 1.8 % across speeds of 0-100 kph. Leveraging an improvement in vehicle installation repeatability allowed a singular coast match test to be utilised for subsequent vehicle tests, reducing both financial and environmental impact of CWT testing.

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1 Introduction

As part of the vehicle development cycle, Climatic Wind Tunnel (CWT) testing provides a crucial role in validating the thermal performance, robustness and efficiency of a vehicle. There are two main aspects of CWT testing, with the first being the control of environmental conditions, including Ambient Temperature, Relative Humidity, Solar Irradiation and Wind Speed. The second main factor is the force applied to the vehicle wheels via a chassis dynamometer. This is often referred to as the vehicle road load and is applied to the wheels via the chassis dynamometer rolling drums (often referred to as "rollers") located directly below each wheel. Figure 1 below shows an example of a chassis dynamometer within a CWT.

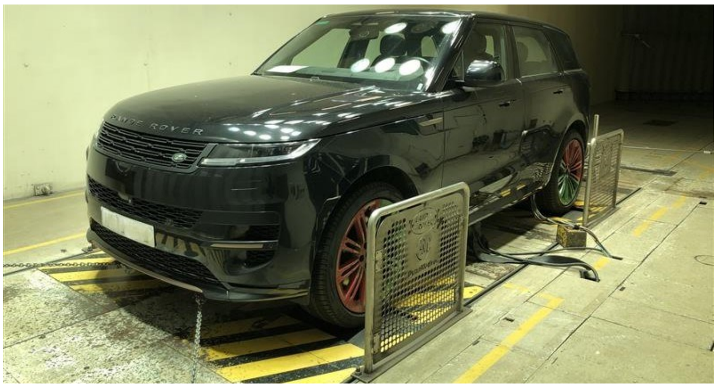


Figure 1 – Image of a chassis dynamometer within a CWT

A vehicle restraint system is utilised to maintain the vehicle in a stationary position on the chassis dynamometer, while ensuring the forces generated by the vehicle are transferred from the wheels to the power absorbers connected to the dynamometer rollers. To restrain the vehicle, a number of solutions are available. These include hub mounted, recovery point and floor anchor restraints. For this investigation only floor anchor restraint systems were evaluated due to the wider prevalence of those systems within UK based climatic facilities used for development.

As thermal system behaviour is highly influenced by the loading applied to the vehicle wheels, care must always be taken to ensure that the forces applied on a chassis dynamometer accurately reflect the real-world condition aimed to be evaluated. Coastdown match methodology, consisting of a ~1hr test prior to vehicle testing, is often utilised in line with best practices [1], to allows the differences in force between real world road load and dynamometer road load to be compensated.

To ensure all testing is carried out at the correct road load, a coastdown match test would be required at every instance a vehicle is installed onto a chassis dynamometer due to the variable vertical drive-axle static suspension deflection associated with lower control arm mounted floor anchor restraints. With increased financial and environmental pressures on vehicle development cycles, an investigation was highlighted to determine the level of variability between vehicle installations to evaluate if a singular coast match test could be utilised for subsequent vehicle installations.

If suitable control actions could be identified, a potential reduction in facility utilisation could be achieved through a reduction in the number of coast match tests required, both reducing the financial and environmental impact of vehicle development.

2 Investigation

2.1 Restraint System Methodology

A floor anchor restraint system commonly utilises four floor anchors and chains that connect to steel straps fitted around the lower control arms of the vehicle. Typically, the floor anchors are connected to steel straps on the opposite side of the vehicle to reduce lateral vehicle movement. Figure 2 & Figure 3 below shows a floor anchor restraint system within a CWT, applied to a Range Rover Sport.

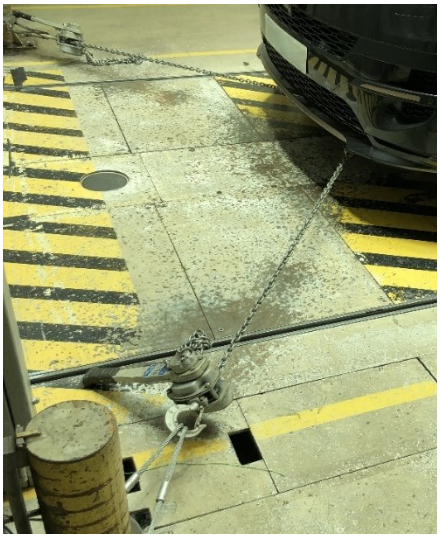


Figure 2– Front view of floor anchor restraint system applied to a Range Rover Sport.

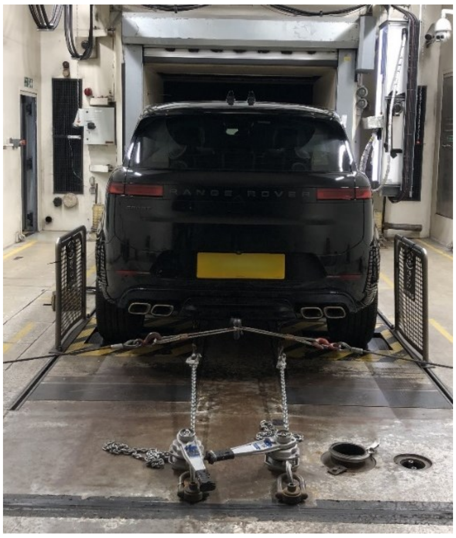


Figure 3 – Rear view of floor anchor restraint system & safety restraints applied to a Range Rover Sport

As can be seen in Figures 2 & 3, the tension of the vehicle restraints can be adjusted using the ratchet mounted next to the floor anchor point. A typical vehicle installation process involves positioning the vehicle on the dynamometer, setting the roller spacing to match the vehicle wheelbase and then restraining the vehicle to the dynamometer via the chains connected to the floor anchor restraints and lower control arm steel straps. The chain restraints are tensioned until deemed suitably pre-loaded by the facility operator. During this tensioning event, often static suspension deflection greater than 5mm is noted.

Post installation, the facility operator would inspect the vehicle and restraint arrangement before allowing a coast match test to be carried out.

2.2 Coastdown Match Methodology

To conduct a coast match test, a number of different methods can be utilised. For the purposes of this investigation, the Environmental Protection Agency (EPA) adopted process as detailed in SAE J2264 was utilised [2]. The methodology consists of the following process as shown below in Figure 4.

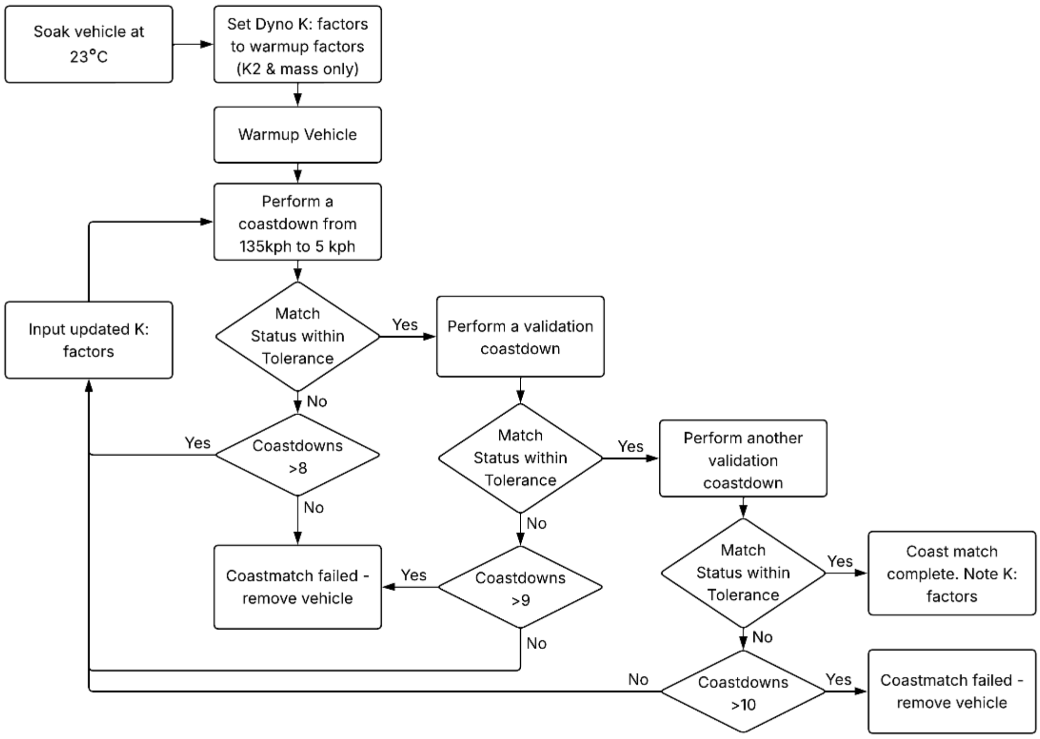


Figure 4 - EPA Coast Match Process

As seen in Figure 4, the coast match procedure consists of an iterative process, starting with a warmup phase followed by an iterative matching phase. The warmup phase is utilised to ensure driveline fluid temperatures are stabilised at a nominal running temperature prior to completing the matching process. The outcome of the matching process is a set of K: factors matched to the target road load and compensated for the additional imposed resistances of the vehicle test arrangement.

As detailed in SAE J2264 4.2.3, the coast match test completed may only be re-used for subsequent testing if the static suspension deflection is less than 5mm. As the deflection is often greater than 5mm for a floor anchor restraint system, a repeat coast down match test would be required to ensure the correct vehicle loading is applied for subsequent testing, aligned with best practices detailed in SAE J2777_202211 4.2 [1].

For testing the thermal performance of an Internal Combustion Engine (ICE) vehicle, the addition of a coastdown match test is relatively easy to contain as a stabilisation period for the driveline fluids is required prior to the test commencement, therefore no soak condition is required. However, for a Battery Electric Vehicle (BEV) or ICE efficiency testing, a pre-test soak is required during which time the vehicle cannot be driven, such as during test schedules shown in SAE J1634_202104 [3].

As a result, for BEV testing, a coast match test must be carried out prior to the vehicle soak in the CWT, leading to facility underutilisation as the vehicle cannot be soaked in a separate facility, which can result in over 9.5 hours of non-productive CWT time. Figure 5 below shows the process flow of carrying out BEV CWT testing from a soaked condition when a pre-test coast match test is required.

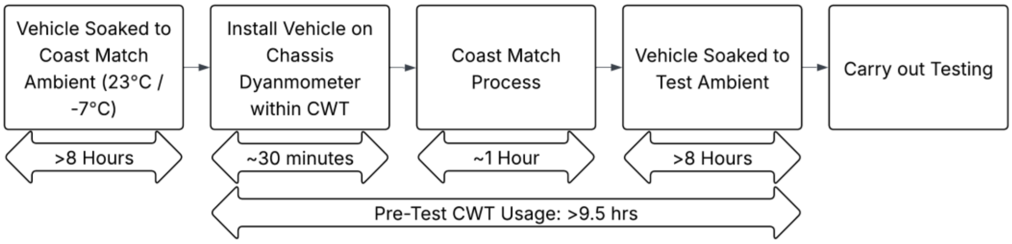


Figure 5 - BEV CWT Pre-Test Schedule with Coast Match

2.3 Repeatability Investigation

To determine the change in force applied to the vehicle between installations, an investigation into the major influencing factors was devised. A review of existing literature highlighted a number of key factors likely to influence the force applied to the vehicle, namely vehicle tyre pressure, tyre temperature, vertical loading and dynamometer wheelbase alignment. [3][4].

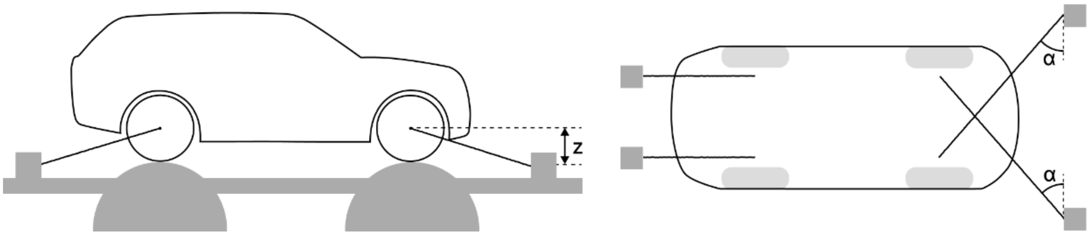
2.3.1. Test Equipment

For this investigation, a Range Rover Sport was used. The vehicle was fitted with supporting instrumentation and logging equipment to capture vehicle driveline fluid temperatures, powertrain torque, wheel and engine speed alongside tyre temperature and pressure. Table 1 below details the key vehicle attributes.

Vehicle Parameter	Test Vehicle
Vehicle Model	Range Rover Sport
Powertrain	Petrol Turbocharged Inline 6-cylinder MHEV
Driveline	4WD with fixed centre transfer case
Tyre Size	275/40 R22 108Y
Nominal Inflation Pressure	36 PSI
Vehicle Test Mass	2405 kg

Table 1 - Test Vehicle Details

The facility utilised for the investigation was a Climatic Wind Tunnel located at JLR Gaydon in the UK, with a schematic shown below in Figure 6.



Figures 6 - Chassis Dynamometer Side & Top Profile Schematics

As shown in Figure 6, the z-height between the floor anchor point and vehicle lower control arm mounting point can vary dependent on the vehicle that is being tested and the location of the suspension lower control arms. The specification of the vehicle chassis dynamometer can be seen in Table 2.

Facility Parmeter	**Facility Specification**
Roller Surface	Anti-Slip Coating
Roller Type	Twin Axle Single Roller
Roller Width	0.6 m
Roller Diameter	1.70 m
Maximum Wheelbase	3.20 m
Restraint Type	Floor Anchored Chains
Fan Nozzle Outlet Area	6.75 m^2

Table 2 - Climatic Wind Tunnel Dynamometer Specifications

2.3.2. Influencing Parameter Evaluation

Having reviewed surrounding literature and the physical vehicle installation, a number of key influencing parameters were identified as shown in Table 3 below [3][4][5].

Variable	**Constant / Varied**
Tyre Temperature	Constant
Tyre Type	Constant
Tyre Pressure	Varied
Dynamometer Roller Positioning	Varied
Restraint Tension	Varied
Ambient Temperature	Constant

Table 3 - Influencing Parameter Type

Tyre temperature, tyre type and ambient temperature were all determined to be constant as they would be expected to remain consistent between coast match tests. To evaluate the impact of each variable on the outcome of the coast match test, a fixed procedure was utilised as seen below in Figure 7.

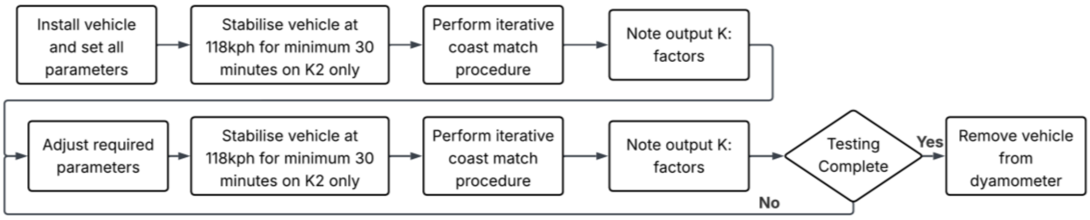


Figure 7 - Test Process Methodology

As in Figure 7, the procedure included a warmup duration of a minimum of 30 minutes at 118 kph to ensure consistent pre-test driveline fluid and tyre temperatures, aligning with standard JLR practices for WLTP type approval as per GBR-20171151 [6]. To ensure reliability of results generated, repeat testing was carried out for each test condition and an average of results taken with the exception of variation of the restraint tension whereby each test condition was considered individually. Table 4 below shows the test conditions evaluated.

Test Number	Tyre Pressure	Dynamometer Roller Position	Restraint Tension	Repeats
1	36 PSI	Centred	Baseline	4
2	36 PSI	-60 mm from centre	Baseline	2
3	36 PSI	-30 mm from centre	Baseline	2
4	36 PSI	-10 mm from centre	Baseline	2
5	36 PSI	+10 mm from centre	Baseline	2
6	36 PSI	+30 mm from centre	Baseline	2
7	36 PSI	+60 mm from centre	Baseline	2
8	16 PSI	Centred	Baseline	2
9	26 PSI	Centred	Baseline	2
10	46 PSI	Centred	Baseline	2
11	36 PSI	Centred	Configuration 1	2
12	36 PSI	Centred	Configuration 2	2
13	36 PSI	Centred	Configuration 3	2
14	36 PSI	Centred	Configuration 4	2
15	36 PSI	Centred	Configuration 5	2
16	36 PSI	Centred	Configuration 6	2
17	36 PSI	Centred	Configuration 7	2
18	36 PSI	Centred	Configuration 8	2

Table 4 – Repeatability Test Matrix

As seen in Table 4, to determine the repeatability of restraint tension, 9 technicians were chosen to set the restraint tension on the dynamometer as per normal setup process. This was captured in the baseline restraint tension and 8 subsequent restraint tension configurations.

2.3.3. Baseline Results

To assess baseline repeatability of the process without altering any test variables, four consecutive baseline tests were conducted. Analysis of the data collected indicated a baseline force variation, normalised by track road load, of ~0.4% - 1.2% over a range of 0-100 kph as shown in Figure 8, demonstrating low test to test force variation. Dynamometer position was then evaluated as shown in Figure 9.

Figure 8 – Baseline Testing Force Variation

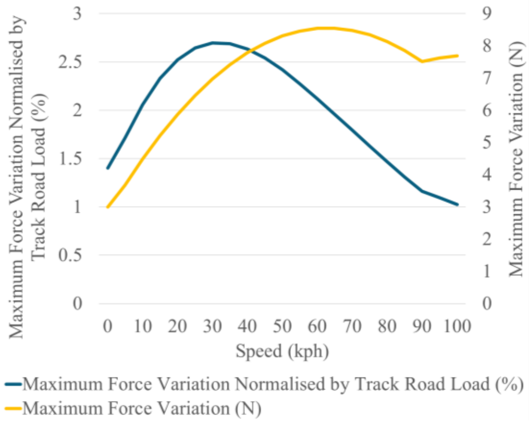


Figure 9 – Dynamometer Position Testing Force Variation

As seen in Figure 9, dynamometer position change of -60mm to +60mm from nominal led to a maximum force variation of 2.7% - 1.0% of track road load across a speed range of 0-100 kph. Whilst this was greater than the normal test to test variation, this was deemed of lower significance to overall load variation.

As shown in Figure 10, the evaluation of tyre pressure from 16 PSI to 46 PSI yielded a significant maximum force variation of 59.3% - 19.8% of the track road load over a speed range of 0-100 kph.

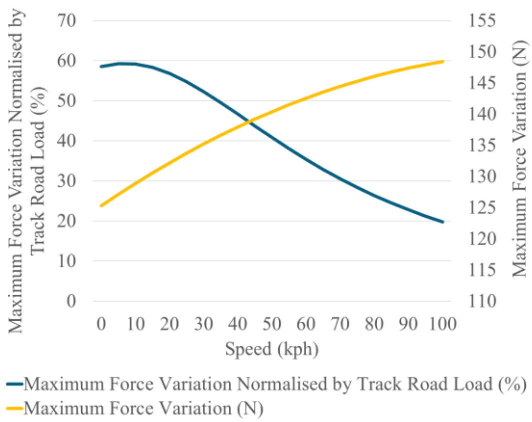


Figure 10 – Tyre Pressure Testing Force Variation

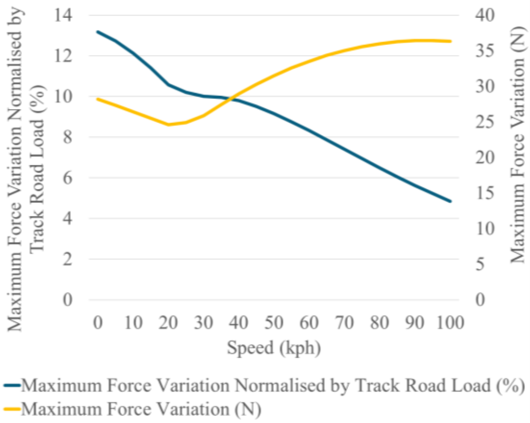


Figure 11 – Restraint Tension Testing Force Variation

To evaluate the effect of restraint tension, the force applied through the restraints was varied, with the vehicle maximum force variation shown in Figure 11 above.

This was achieved by asking nine technicians to each follow the normal installation process, whilst keeping the chain mounting location on the vehicle consistent.

The effect of varying chain tension through the normal installation process led to a variation in force of 13.2% - 4.5% over a speed range of 0-100 kph. This was deemed a significant variation in force applied to the vehicle between vehicle installation conditions. The combined results of the maximum force variation normalised by track road load over a range of 0-100 kph can be seen in Figure 12 below.

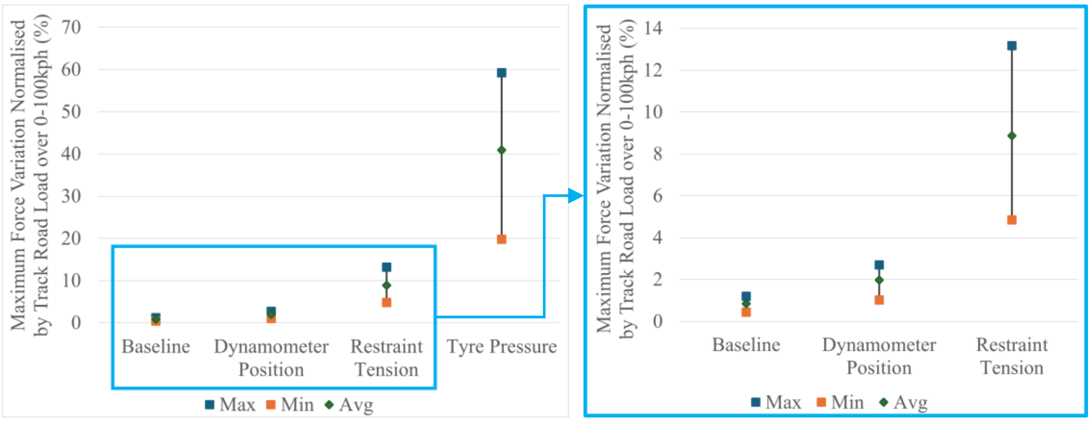


Figure 12 – Combined Maximum Force Variation

Overall, the initial results indicated that tyre pressure and restraint position had the most significant influence on tractive force applied to the vehicle. Additional plots can be seen in Appendix A – Baseline Test Results.

3 Control Measures

Having conducted baseline testing, a series of control measures were proposed to reduce to the variability in force between coast match tests. In line with facility best practice, a process to ensure tyre pressure and dynamometer positioning consistency between tests was implemented. To address dynamometer restraint forces applied, a more novel solution was required.

3.1 Restraint Tension Control Methodology

A series of z-axis load cells, commonly used in lifting applications, were proposed to be implemented at the floor anchor point of the vehicle restraint system. This would allow measurement of the axial forces imposed on the restraint system chains and ensure the user could replicate a previous coast match installation. For this application, Applied Measurements Z-Beam load cells and IPEtronik measurement equipment were chosen [7]. Figure 13 below shows the implementation of the load cells at the base of the restraint system.

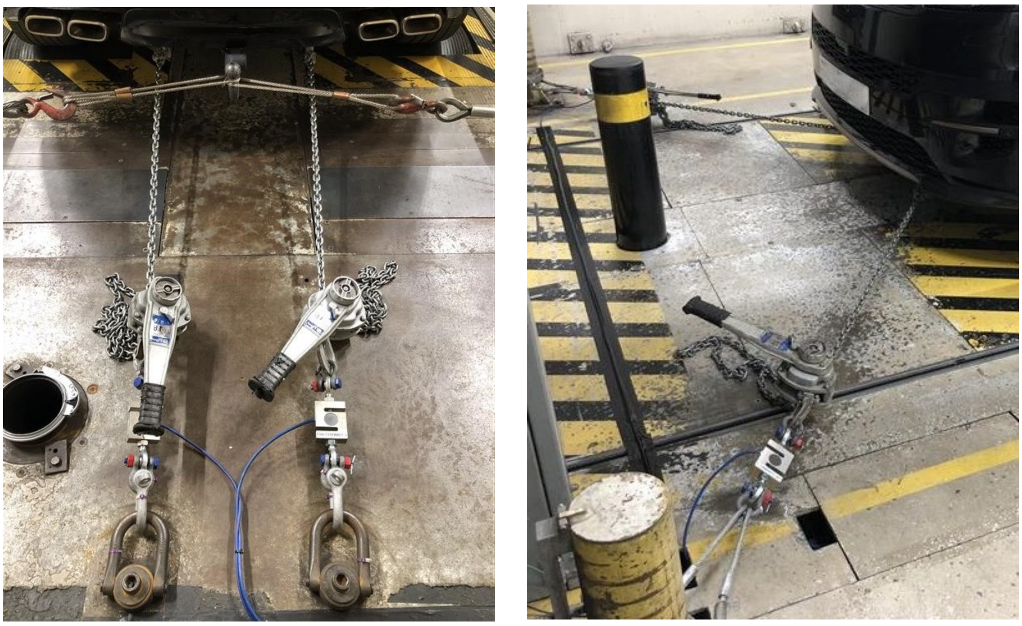


Figure 13 – Z-Beam load cells fitted at the anchor points of a chassis dynamometer restraint at the front and rear of a Range Rover Sport.

As can be seen in Figure 13, the load cells were located at the anchor point of the chassis dynamometer restraints. The axial force imposed on the restraint system could be decomposed as the combination of the vertical and longitudinal applied loading to the vehicle.

To ensure that the measurements from the load cells could be utilised to control the vertical loading applied via the restraints, an iterative process for vehicle installation, aiming to match the initial installation force, was devised as seen in Figure 14,

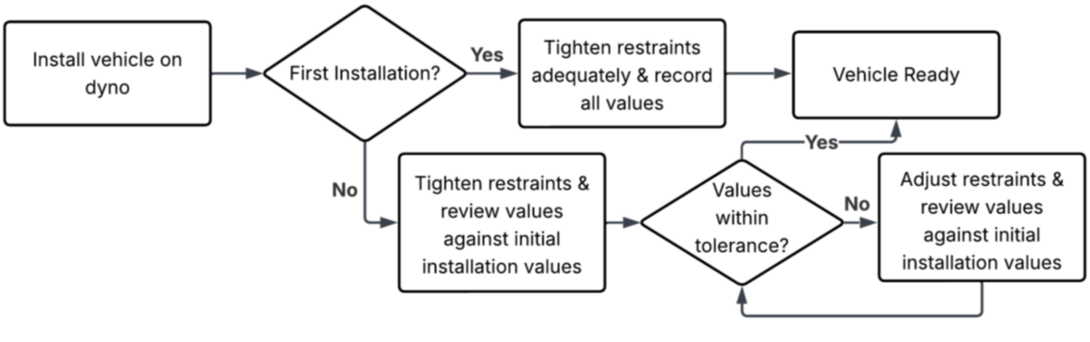


Figure 14 – Vehicle Installation Process Flow

To determine the process tolerance, an exercise was conducted with several facility technicians to ascertain an achievable tolerance within the tight timeframe required to install a a vehicle. The result of this exercise led to an agreed achievable tolerance of ±0.5 kN per restraint. Subective feedback from the technicians involved in the activity was that this tolerance could be more easily achieved by setting slightly higher tension in the restraints during the initial installation. This was deemed acceptable due to the low effect of restratint tension on vehicle wheel slip [8].

4 Control Testing & Results

To determine the impact of the addition of the vehicle restraints control process, a test matrix was devised, utilising test cases 10-18 of Table 4. As per the original baseline testing, 9 fitters were utilised, with the first vehicle installation being utilised to generate the reference restraint loading and the subsequent installations targeting a tolerance of 0.5 kN per restraint. Carrying out the test process as described in 2.3.2 yielded the results shown in Figure 15 below.

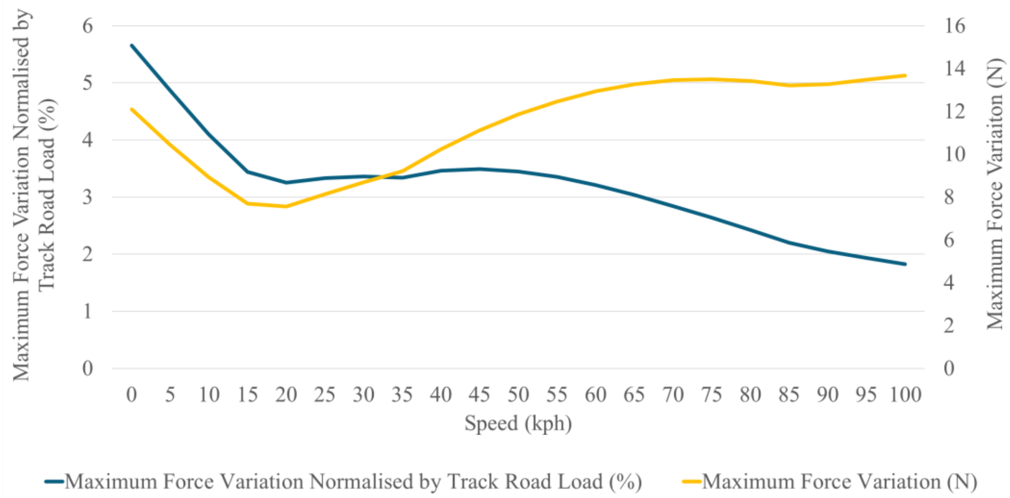


Figure 15 - Restraint Tension Control Process Force Variation

As can be seen in Figure 15, the implementation of the restraint tension control process yielded a maximum force variation of 5.6% - 1.8% of the track road load over a speed range of 0-100 kph. This result was compared to the initial baseline test results for restraint tension control test cases 8-18. The comparison showed a reduction of force variation between 3.0% - 7.0% of the track road load over a speed range of 0-100 kph as seen below in Figure 16.

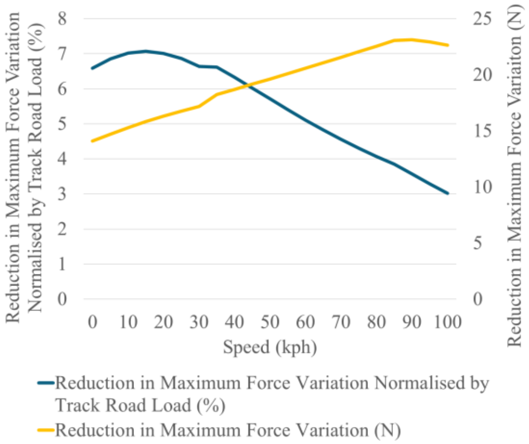


Figure 16 – Restraint Tension Baseline to Control Process Force Variation Change

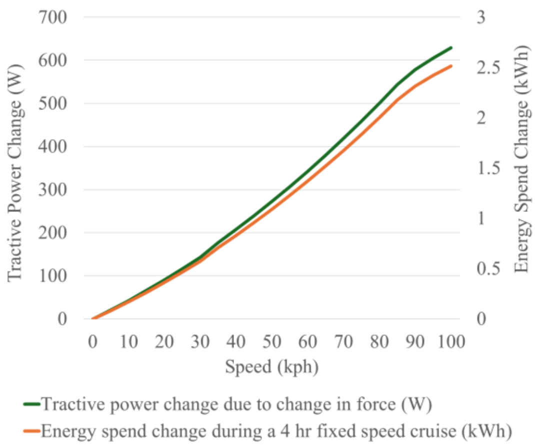


Figure 17 – Power & Energy Change between Baseline and Control Process

The effect of the force reduction shown in Figure 16 was applied to a 4-hour cruise cycle, where the resulting change in vehicle force was reflected in the change in power and energy consumption as seen above in Figure 17.

The implementation of the control process for restraint tension demonstrated a reduction in tractive power of up to 628 W at 100 kph, which applied to a 4-hour cruise use case would result in an expected reduction in tractive energy of ~2.5 kWh.

5 Conclusion & Recommendations

Overall, an investigation was conducted to assess the variability of tractive force applied to a vehicle when influenced by normal operating parameters of a climatic wind tunnel with a floor anchor restraint system. Baseline testing yielded results indicating a significant variance in tractive force due to changes in restraint tension applied to the vehicle. A novel solution was proposed to implement restraint tension monitoring equipment and a process devised to ensure consistent vehicle restraint tension upon installation of a vehicle into a climatic wind tunnel. Validation testing of applied control techniques demonstrated a reduction in variability of axle loading normalised by track road load from a range of 13.2% - 4.5% down to 5.6% - 1.8% across speeds of 0-100kph. As applied to a 4-hour cruise use case at 100 kph, a change in tractive energy of up to ~2.5 kWh was noted for a Range Rover Sport with the reduction in tractive effort.

Overall, the process implemented provided sufficient confidence in the repeatability of the installation process to allow all thermal performance and feature development testing to be carried out with a singular coast match test, without the requirement for subsequent coast match tests. This improvement in operational efficiency was estimated to save ~20 hrs of climatic wind tunnel time per ICE vehicle test programme and ~190 hrs per BEV vehicle test programme. Deployment of the control process demonstrated an active improvement in facility operational efficiency with negligible impact on vehicle installation time and facility maintenance requirements.

Overall, the author recommends that climatic wind tunnels utilising a floor anchor restraint system adopt the methodology described in this paper to reduce variability in axle loading due to restraint tension, allowing optimisation of facility time and reduction in environmental impact of vehicle development. Going forward, the author recommends further work to review the tolerance value associated with the use of the restraint monitoring process and to define if any further reduction in installation variability can be achieved through a tighter tolerance.

6 Reference list

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7 Appendix A – Baseline Test Results

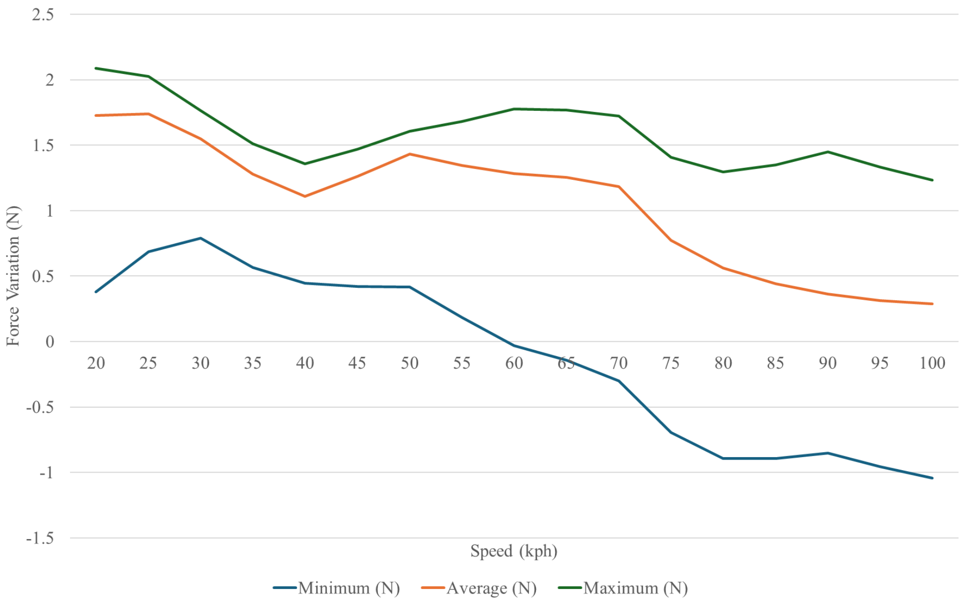

Figure 18 - Baseline Testing Force Variation Min, Max, Avg

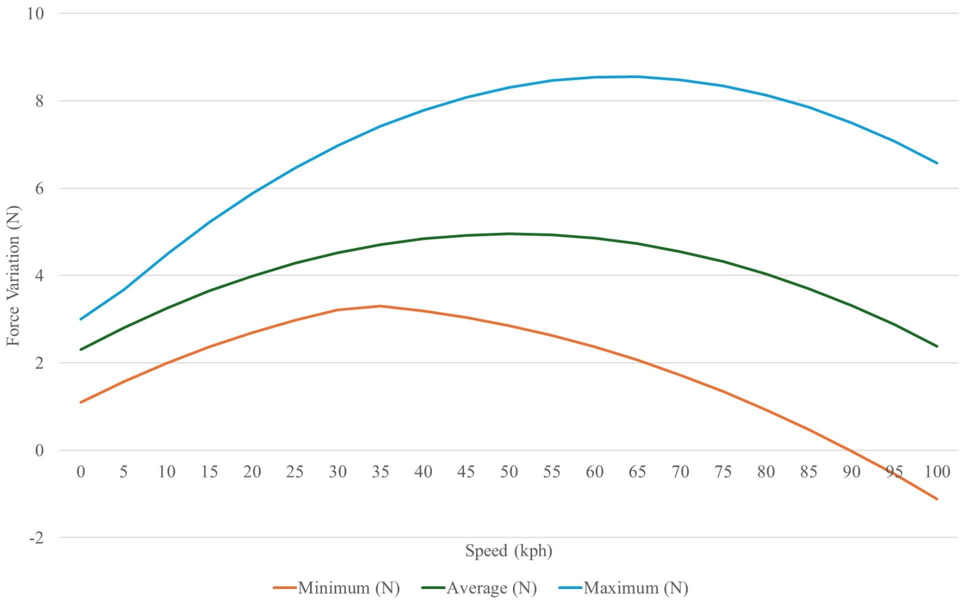

Figure 19 - Dynamometer Position Testing Force Variation Min, Max, Avg

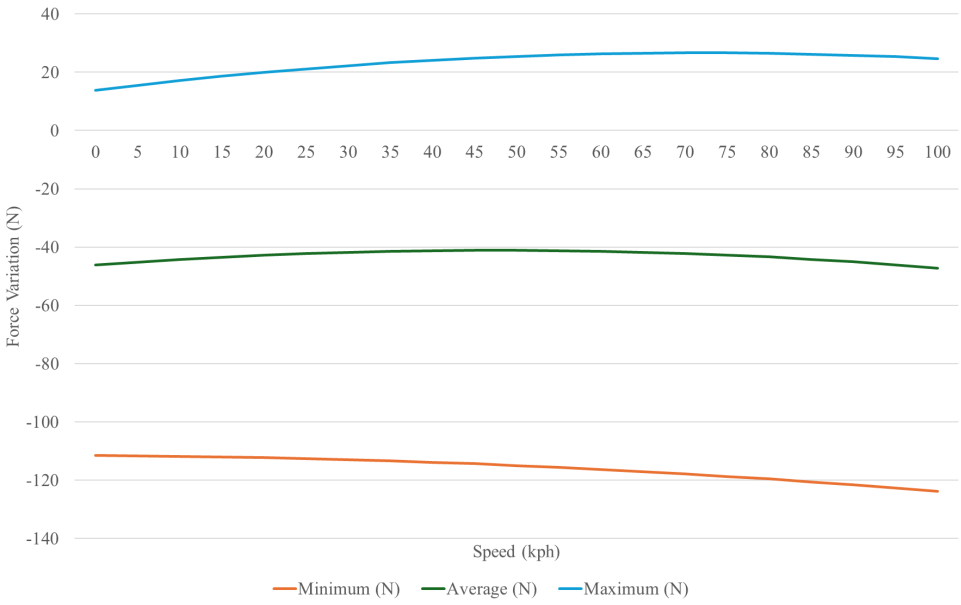

Figure 20 - Tyre Pressure Testing Force Variation Min, Max, Avg

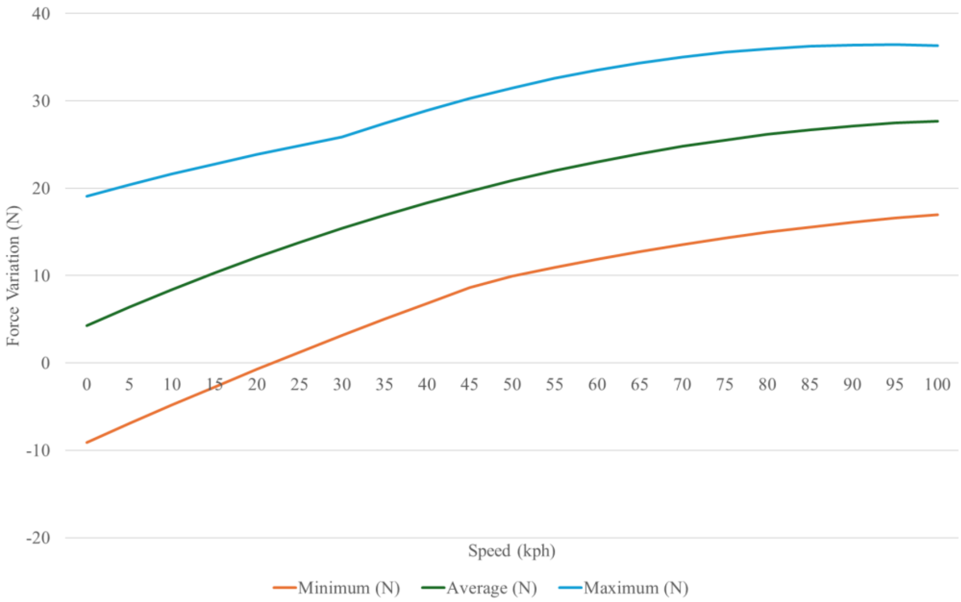

Figure 21 - Restraint Tension Testing Force Variation Min, Max, Avg

8 Appendix B – Control Process Test Results

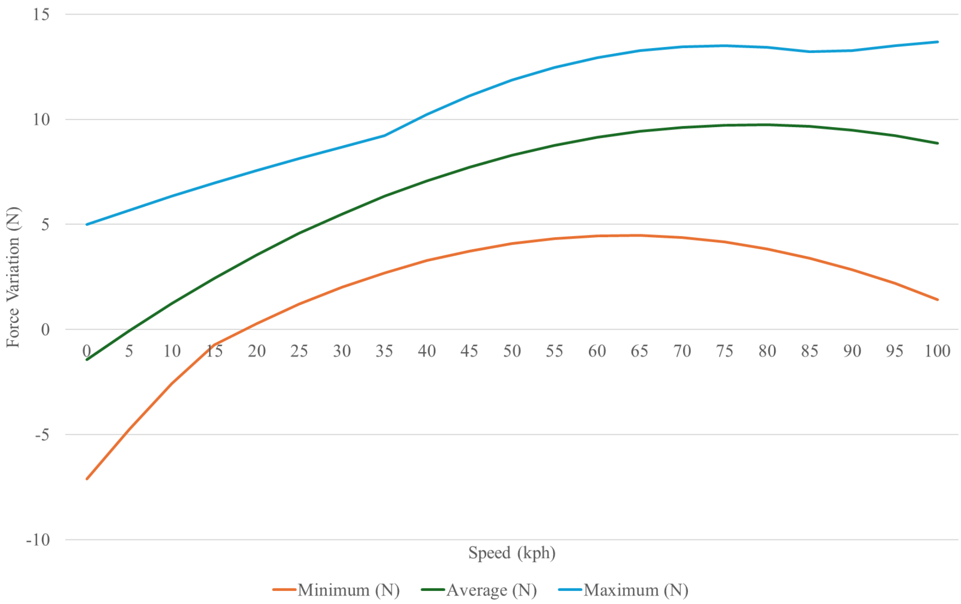

Figure 22 - Restraint Tension Control Process Force Variation Min, Max, Avg