Unsprung Mass with In-Wheel Motors - Myths and Realities

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It has long been widely accepted that unsprung mass is an important parameter in ride and handling behaviour. In a wide-ranging study connected to feasibility studies for in-wheel motors, some specific and detailed measures for the sizes of the effects in play have been taken - and the reality is something of a surprise compared to what "everybody knows". Subjective, Objective and Predictive measures of ride & handling suggest that the modern development toolbox is easily capable of restoring dynamic performance and that the opportunities afforded by in-wheel motors in terms of packaging and vehicle dynamics control are of substantial interest to the vehicle dynamics community.

Driver-Vehicle Control, Vehicle Control

1. INTRODUCTION

Pressure on energy use for transport has led to a strong resurgence in interest in electrical machines as primary torque generators for ground vehicles. First used in the 1830s by Robert Anderson, electric vehicles were considered superior to steam until around the turn of the 20th century, with internal combustion engines barely more than a noisy curiosity with difficult-to-change gears.

Today, nobody imagines that electrical energy storage rivals that of hydrocarbons and the implementation issues with early IC engines have been largely solved. However, the supply of fossil hydrocarbons is unarguably finite (though many argue over exactly *how* finite). In order to decouple issues of energy supply from vehicle behaviour, an electrical architecture has many advantages, principally that it is entirely energy-source-independent.

Modern vehicle architecture is entirely dominated by the location of the IC engine. Vehicles are defined as “front-engined”, “mid-engined” or “rear-engined” among engineers, who view market segmentation as little more than window dressing on a fundamental platform design – correctly, in the authors’ opinion, when considering fundamental platform architecture decisions.

An electrical driveline notionally allows freedom from the consolidation of all torque generation to a single location in the vehicle, and offers the possibility of, for example, moving the motors to individual wheels. This is certainly not a new idea, with US patents recorded in 1884 discussing the concept and the Lohne Porsche of 1899 selling 300 copies of a vehicle with in-wheel motors, his ideas being studied intently for NASA’s successful lunar rover vehicle.

Recent conformity in vehicle architecture, with highly optimized versions of Alec Issigonis’ basic layout now dominating sales, has led to some complacency in viewing any other architecture as somehow inferior. This seems a little unreasonable as 50 years’ continual development has been applied to the base architecture, with electrical layouts only recently being dusted off again.

Protean Electric, a producer of in-wheel motors, has commissioned a series of wide-ranging studies into the effects and opportunities afforded by in-wheel motors. This includes driving experiments using real vehicles, test rigs and theoretical studies. These studies provide a comprehensive overview of the implications of in-wheel motors in mainstream applications. Two of the studies, specifically into unsprung mass effects, were carried out by Harty and Anderson. They worked in isolation and from very different perspectives, and the results are reported briefly here; conventional “you can’t get there from here” perspectives are severely challenged.

2. STUDY CONTENT

The studies were carried out using numerical models and real physical vehicles. Primary concerns with the addition of hub motors centre on:

i) degraded roadholding
ii) degraded ride comfort

In evaluating vehicle performance, it is unwise to become obsessive about a single measure. Instead it is good practice to consider a so-called “balanced scorecard” with a number of different indicators. These indicators can be expressed using numerical measures, whether formed from predictive modelling, measured data or subjective review in-vehicle with an expert assessor.

Ground vehicle dynamic performance can be broadly split into:

- **ride***: the ability of the vehicle to absorb disturbances
- **refinemen**t: the ability of the vehicle to attenuate noise and vibration
- a**ctive**** **safety**: the ability to stop and steer in emergency situations
- **driveability**: the response of the vehicle to the controls – steering, braking and drive - in normal situations

Exercises were carried out using subjective assessment, objective measurements and predictive analysis to review the impact on dynamic performance with increased unsprung mass.

3. SUBJECTIVE RESULTS

The use of subjective assessment has a rich history in vehicle development. Subjective methods were first developed in the aircraft industry, where the Cooper rating scale was used to rate aircraft in terms of the ease or difficulty in completing specific tasks. The Cooper scale is from 1 to 10, where 1 is the best (most easy to handle/least demanding) and 10 is the worst (most taxing for a pilot). Research has shown that achieving a score of 1 on the Cooper scale is associated with control delays of less than 100 ms and an absence of reversals / substantial delays / hysteresis in responses in control inputs[1].

In the ground vehicle industry, the so-called "Vehicle Evaluation Rating" (VER) scale is widely used. Like the Cooper scale it goes from 1 to 10 but unlike the Cooper scale, 1 is worst and 10 is best. It is applied not only to the completion of tasks but of more or less every way in which the operator interacts with the vehicle. In practice, grades 1 to 5 are used for unsaleable vehicles, with a rating of 1 denoting a vehicle that is unsuitable for further testing. A rating of 5 denotes a functioning vehicle but one that is not recommended for release to the market. Scores 6, 7 and 8 are used to denote vehicles that are acceptable, mid-class and excellent, respectively. Scores of 9 and 10 are reserved for vehicles and areas in which no improvement is imaginable and are thus rarely used. An example of a score of 10 would be idle refinement in which it is impossible to discern whether or not the engine is running except by looking at the tachometer.

It is hopefully obvious that the subjective evaluation of a vehicle is very much a review of its behaviour among its peers. Thus a vehicle rated 7 for ride will have different absolute levels of ride performance if it is in the so-called "supermini" segment rather than in the "extreme luxury" category.

For this reason the subjective review of vehicles is a skill that takes some time to acquire. Nevertheless skilled practitioners are available within the industry and their thoughts and perceptions are regarded as valuable despite the difficulty in reproducing them.

A test vehicle – a 2007 Model Year Ford Focus - was ballasted with 30kg additional mass at each wheel, distributed between rotating and non-rotating unsprung masses in a way which broadly reflects the Protean Electric PD18 product. No other changes were made to the vehicle, which is to say no development was performed for the purpose of this exercise; such activities are the subject of a later document. The ballasted, unmodified vehicle was subject to review under a range of circumstances and subjectively reviewed by a jury of expert assessors.

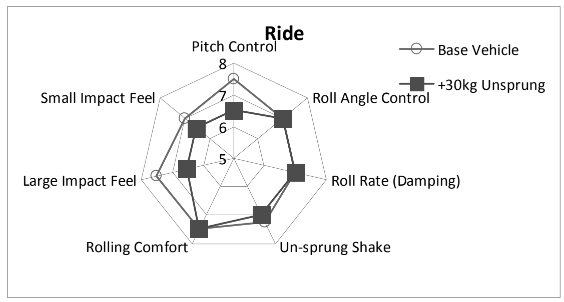

Fig.1 Subjective Results for base vehicle and +30 kg unsprung mass at each end – ride behaviour.

Figure 1 shows the subjective result "spider" plot for ride evaluation. Nothing about the impressions was described by the reviewer as being irrecoverable, merely in need of attention in order to return the vehicle to subjective performance levels of the standard vehicle, which is regarded as "among the leaders" in most areas of its behaviour.

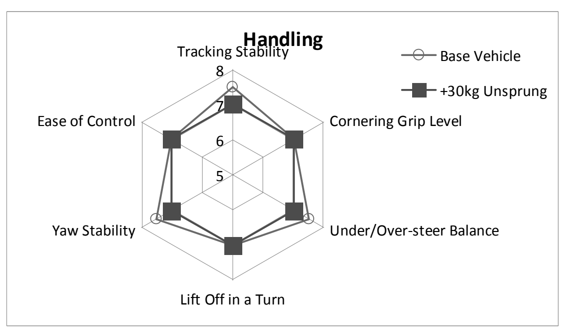

Fig.2 Subjective Results for base vehicle and +30 kg unsprung mass at each end – handling behaviour.

Figure 2 shows the results for the base and modified vehicle for handling behaviour. The behaviour is noted as being rather similar to the base vehicle; this was slightly surprising to the authors, who were expecting it to be somewhat worse.

Figure 3 shows the results for the base and modified

* Ride is often split into "Primary" – the whole vehicle body in motion on the suspension springs, quite slow – and "Secondary" – higher frequency motion of individual components such as wheels or powertrain masses.

** "Active" safety in this context means the ability to avoid a collision through manoeuvring the vehicle. It is distinct from "Passive" safety, which is the ability of the vehicle to protect the occupants in the event of a collision and includes so-called crumple zones and airbag technology. It does not specifically imply the presence of electronic or other control systems.

vehicle for steering behaviour. It can be seen that there are typically small deficits in the modified vehicle.

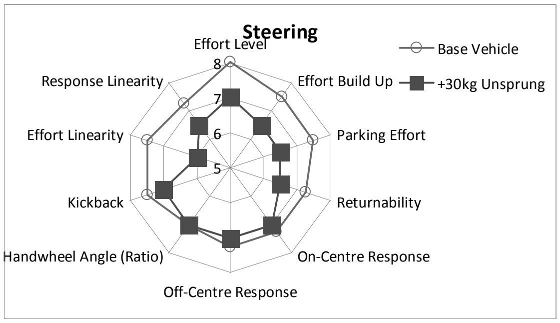

Fig.3 Subjective Results for base vehicle and +30 kg unsprung mass at each end – steering behaviour

The largest deficit concerns the effort in the steering, which is noted as becoming somewhat heavier under a large range of circumstances.

The addition of the unsprung mass with no further development activities can be expected to introduce some degradation, but performance is no worse than that which might be expected in the middle of a normal development programme and gives no particular cause for disquiet.

4. OBJECTIVE MEASUREMENT RESULTS

As well as the subjective reviews carried out, objective measurements were made of steering, handling and ride behaviour.

On both front and rear suspensions, tri-axial accelerometers at the strut top and on the wheel, and vertical accelerometers on the damper rod were added to the vehicle. A normal set of vehicle state measurements (yaw rate, lateral acceleration, vehicle speed) was also taken, as well as handwheel ("steering wheel") input.

Steering tests were carried out "on centre" – at less than 0.2g lateral acceleration with detailed datalogging to understand this most subtle of steering regions. Handling was reviewed with a variety of tests including a disturbance rejection test over an obstacle while travelling in a curved path. Ride testing was carried out on a bumpy ride road, typical of UK roads with repeated resurfacing over an undulating base giving a typically strong secondary ride input; it is referred to as a "shake road". A harmonic forced excitation test was also carried out on a static shake rig with additional instrumentation to discern the motion of the suspended powertrain.

The so-called wheel-hop mode of vibration, in which the unsprung mass (wheel, tyre, brake rotor, etc) is in motion on the tyre stiffness, is reduced in frequency from around 14 Hz on the standard car to around 10 Hz with the additional unsprung mass.

It is clear in figure 4 that although the frequency of the wheel hop mode is obviously modified there is no substantial change in the level of response. There is no clear evidence that vibrations at 10 Hz are any more or less noisome than vibrations at 14 Hz; thus it may be concluded that ride behaviour is not substantially altered over the surfaces tested.

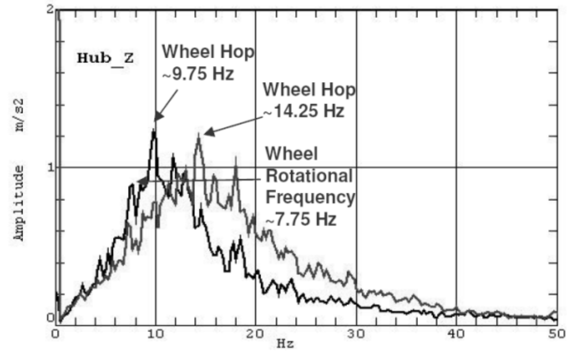

Fig.4 Calculated spectra for vertical wheel hub acceleration showing the 14 Hz wheel hop for the standard car and 10 Hz for the modified car, processed from shake road data.

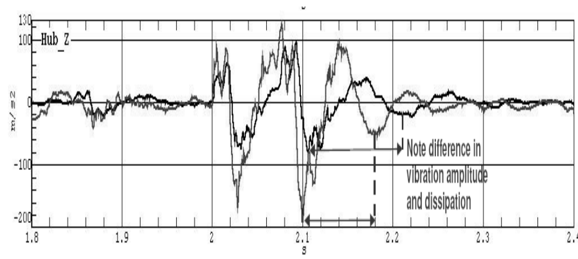

Fig.5 Measured results for vertical wheel hub acceleration over a large single disturbance for the standard car (black) and with additional 30 kg unsprung mass (grey).

The results in figure 5 show that over isolated single disturbances the modified vehicle gives measurably poorer behaviour (higher, multiple impacts) compared to the base car – giving a reduced VER score by a full point.

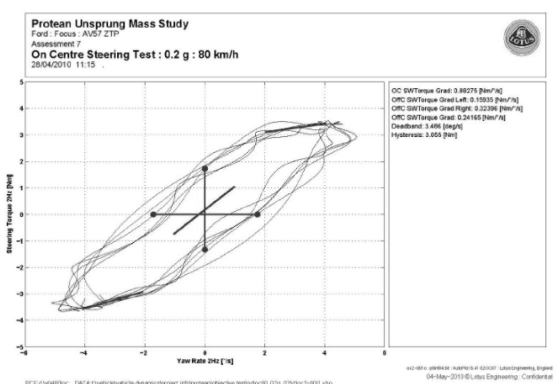

Fig.6 Measured results for on-centre behaviour – standard car.

Steering behaviour is shown as lightly modified between fig. 6 & 7, consistent with the subjective results compiled by an expert driver; not every aspect of steering performance was measured and so a direct comparison with every aspect of the subjective review is not possible but it is clear that some difference in steering character has been wrought.

While the differences in performance are measurable using sophisticated engineering techniques, none of the differences are beyond normal deviations from target in a typical vehicle development programme.

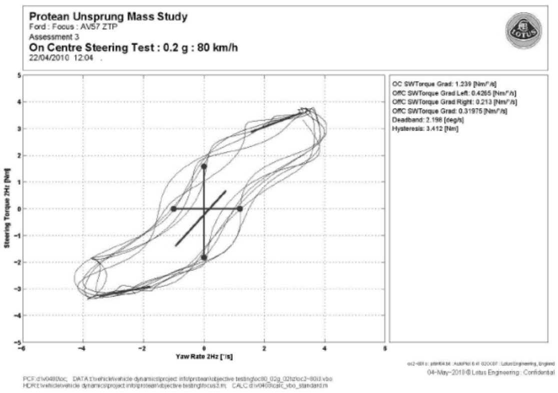

Fig.7 Measured results for on-centre behaviour – modified car.

5. NUMERICAL ANALYSIS

A sample application was evaluated numerically. Results are calculated for a wide range of possible corner loads and are thus applicable to a variety of vehicles including passenger cars such as the Focus previously described and also commercial vehicles such as a typical European panel van.

Table 1 : Parameters Used in the Study

Parameter	Laden	Unladen
Sprung Mass	1060 kg	310 kg
Unsprung Mass	50-80 kg	50-80 kg
Spring Rate	25-75 Nmm^{-1}	25-75 Nmm^{-1}
Damping Coeff.	0.5-10 $Nsmm^{-1}$	0.5-10 $Nsmm^{-1}$

The resulting vehicle characteristics are shown in table 2, below.

Table 2 : Resulting Characteristics

Characteristic	Laden	Unladen
Primary Ride Frequency	0.77 Hz – 1.34 Hz	1.43 – 2.48 Hz
Primary Ride Damping Ratio	3%-97%	5%-180%

When using predictive models, performance can be expressed using so-called Key Performance Indicators (KPIs). In general, KPIs are arranged such that they are a "more is better" number and also scaled to allow relatively easy assimilation. For this reason they are not always in common engineering units, although they are always traceable to more normal engineering quantities. The scaling of KPIs is such that 0 represents rather poor performance and 10 represents rather excellent performance, however it is entirely possible for computed KPI values to fall outside the 0-10 range.

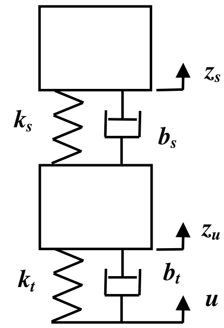

Fig.8 Abstract Model of the type used for numerical prediction – a two degree-of-freedom ride model implemented in Matlab/Simulink.

5.1 Ride

Primary Ride is enumerated using RMS sprung mass vertical acceleration filtered to pass 0-3Hz using a 4 pole Butterworth filter with zero phase shift:

$$KPI = \left(5 - \sqrt{\frac{\int_0^t \left(filt(\ddot{z}_s)\right)^2 dt}{t}}\right) \cdot 2 \qquad (1)$$

Secondary Ride is very similar, but filtered to pass data above 3Hz and scaled differently:

$$KPI = \left(3 - \sqrt{\frac{\int_0^t \left(filt(\ddot{z}_s)\right)^2 dt}{t}}\right) \cdot \frac{10}{3} \qquad (2)$$

Note that the ride measures are scaled such that a score of 1 is approximately at the 1 hour exposure discomfort boundary for 50% of the population as defined in the ISO 2631 standard. While imperfect, these measures do at least give some sense of relevance to human exposure in a way that raw acceleration scaling simply does not.

Two vehicle mass conditions, laden and unladen, were investigated and two levels of road profile scaling, "smooth" and "rough". The rough road profile scaling is representative of a surface such as the MIRA Pavé (sometimes referred to as Belgian Block) and is a typical durability surface. As such it is quite a rough surface and it might reasonably be expected that a vehicle operator would reduce speed on it.

Note that the Primary Ride results in fig. 9 for the smooth road are more or less indistinguishable from a stationary vehicle, whereas those for the rough road are close to the discomfort boundary, with a KPI score close to zero.

As is very apparent in fig.10, the Secondary Ride on a rough road is very uncomfortable indeed, while even on a smooth road it can be close to the discomfort boundary if too much suspension damping is employed.

By far the dominant conclusion from both Primary and Secondary Ride KPIs is that the influence of unsprung mass is small compared to the spectrum of road surface roughness that exists.

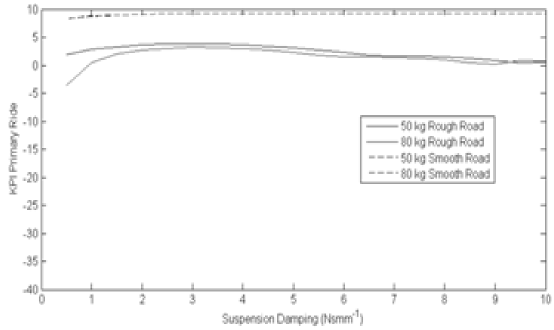

Fig.9 Primary Ride KPI scaled to allow easy assimilation with Secondary Ride KPI (fig. 10). For each pair of lines, 50 kg unsprung mass has the higher of the KPI scores.

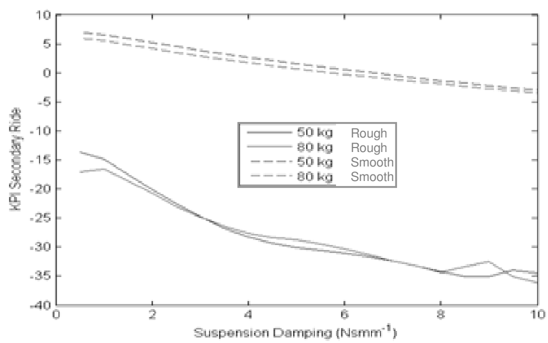

Fig. 10 Secondary Ride KPI scaled identically to Primary Ride results in fig. 9. For each pair of lines, 50 kg unsprung mass has the higher of the KPI scores.

5.2 Refinement

Refinement is enumerated with RMS sprung mass fore-aft acceleration using a two degree-of-freedom model similar in principle to the vertical model described above:

$$KPI = \left(3 - \sqrt{\frac{\int_0^t (\ddot{x}_s)^2\, dt}{t}}\right) \cdot \frac{10}{3} \qquad (3)$$

Increasing unsprung mass degrades the refinement KPI somewhat and may be expected to be readily noticeable in the vehicle over broken surfaces.

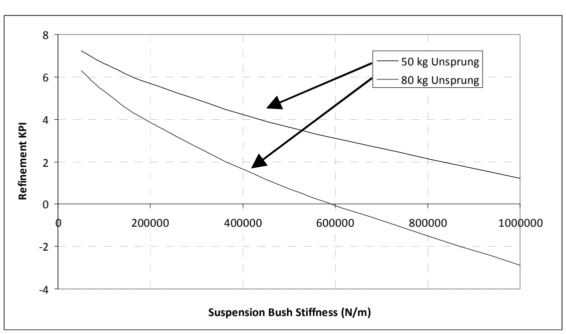

Fig.11 Influence of suspension bushing aggregate fore-aft stiffness on refinement KPI.

To offset the degradation the fore-aft stiffness characteristics of the suspension bushings were evaluated. In a vehicle without a typical powertrain installation there is nothing to prevent the resonant frequency being lowered since there are no suspended powertrain modes with which to couple.

It can be seen in fig. 11 that a reduction in bush stiffness will replace the lost refinement. This changes the suspension fore-aft resonant frequency from around 18 Hz to around 10 Hz and will require a good deal of detailed work to retain acceptable kinematic performance.

5.3 Active Safety

Active Safety uses RMS Load variation at tyre contact patch from the two degree-of-freedom vertical model under a reference road profile; load variation reduces effective grip due to asymmetry of relaxation length between loading to unloading:

$$KPI = \left(1 - \frac{\sqrt{\frac{\int_0^t (F_z - F_{z0})^2\, dt}{t}}}{\frac{F_{z0}}{\sqrt{2}}}\right) \cdot 10 \qquad (4)$$

Individual results for a sweep of unsprung mass and damping coefficient show clearly that there is an optimum damping level for minimum load variation. There is no substantial difference in character between laden and unladen, smooth and rough road – only a difference in scaling.

The degradation of effective friction can be supposed to be substantially linear with load variation. Going from KPI 7 to KPI 5.5 (50 kg to 80 kg unsprung mass on smooth roads, points A and B respectively in fig. 12 represents a difference of about 0.05g in whole vehicle friction performance – far less than the difference that may be wrought by fitting budget tyres. KPI 7 is achieved with around 2 $Nsmm^{-1}$ with 50 kg unsprung; KPI 5.5 is achieved with around 3 $Nsmm^{-1}$ with 80 kg unsprung.

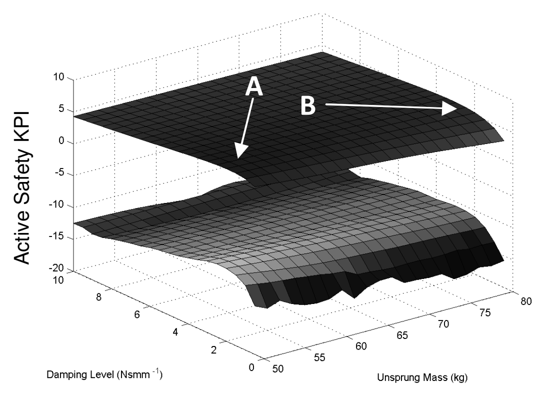

Fig.12 Unsprung mass and damping effects on Active Safety KPI for smooth (upper) and rough (lower) roads.

When the KPI scores for the different scenarios are compared with each other it can be seen that by far the largest influence is the roughness of the road, and again it can be seen there is no obvious “no go” point in terms of unsprung mass; note that the degradation of active safety on rough roads is acute, bringing the KPI well below zero for any value of unsprung mass and damping coefficient used in the study.

5.4 Driveability

Driveability in the lateral (steering) sense looks at Dynamic Index (DI) variation from baseline; low DI promotes feeling of agility or nervousness and high DI promotes feeling of dullness or stability. The base vehicle DI presumed well matched to its intended use and any variation is therefore regarded as degradation:

$$KPI = ABS(DI_{base} - DI_{test}) \cdot 100 \tag{5}$$

Driveability in the longitudinal (accelerator pedal) sense is rated using acceleration rise time; low time gives immediacy, times of 0.5 sec or greater feel very sluggish. 50 msec is a 10:

$$KPI = \frac{0.5}{t_{rise}} \tag{6}$$

In lateral driveability KPI, the DI change resulting from the addition of the motors alone is around 0.01 and therefore the overall KPI score is 9. Note that the battery pack has been used to offset the increased DI from the motors alone. In comparison, the effect of loading the vehicle drops the KPI for the standard vehicle to -15; the influence of the motors is small compared to the variation with vehicle payload.

Longitudinally, the potential for in-wheel motors to improve perceived performance is high. In a typical IC driveline, the response to a change in throttle demand is slurred first by inlet manifold transit time, then by the need to wind up the engine on its elastic mounts and finally by the need to wind up the driveshafts before the torque is delivered to the wheel. A final, minor source of lag is the delay while the wheel changes speed to deliver a different slip ratio at the contact patch, but this is normally short. Typical road car drivelines can take up to 300 msec to respond, particularly with automatic gearboxes; in-wheel motor response times are typically a few milliseconds to a change in torque demand – so fast that the delays remaining in the system are essentially imperceptible. This is a powerful modifier to perceived response; the KPI changes from 2 (auto transmission) or 5 (manual transmission) to 10.

6. OTHER REMARKS

While it is tempting to compare the KPI values from 1 to 10 with those from the VER scale this is not very fruitful; as previously mentioned the VER scores are evaluated on a scale that takes into account the market in which vehicles will be sold and therefore it is not absolute like the KPIs discussed above. Also for most saleable vehicles the VER scores will be between 6 and 8; thus there are issues of both sensitivity and offset when attempting to compare the two scales.

The preceding body of work suggests that the addition of some 30 kg unsprung mass to a typical vehicle installation is less challenging from a vehicle dynamics perspective than might be expected. The challenge has been examined from a practical, experimental and theoretical viewpoint and the conclusions are broadly identical – “you can get there from here” – and are remarkable mainly for how unremarkable they are.

The addition of separate, highly controllable motors in distributed locations in the vehicle offers a substantial opportunity for improved vehicle dynamics through the manipulation of longitudinal wheel slip and its consequent impact on lateral force capacity at individual wheels. For agility, fidelity of behaviour and high speed yaw damping, such techniques have an excellent potential to strongly manipulate vehicle behaviour[2]. That they have been largely forgotten due to misplaced reservations about increased unsprung mass seems to have been throwing out the baby with the bathwater.

7. CONCLUSIONS

The obvious impact of implementing in-wheel motors on a vehicle is to increase its unsprung mass. Slightly less obvious effects are to increase the yaw inertia and to improve the torque response rate. Popular reservations around increased unsprung mass centre on degraded ride and grip performance.

These aspects of performance have been examined in detail and can be summarised thus:

- **ride overall:** difference in road roughness results in very large differences in scores compared to influence of unsprung mass
- **primary ride:** no discernible difference on smooth roads, slight degradation in rough road performance
- **secondary ride:** slight degradation in both rough and smooth road performance may require detail changes to seat or suspension components
- **refinement:** some change in suspension component detail may be required to recover small loss in refinement behaviour
- **active safety:** noticeable but not severe loss in smooth and rough road grip levels; slight increase in damping levels may be required to optimise performance
- **driveablity:** slight changes to suspension components may be required to restore agility

While perceptible differences emerge with increased unsprung mass, on the whole they are small and unlikely to be apparent to an average driver. The nature and magnitude of the changes appears to be nothing that cannot be overcome by the application of normal engineering processes within a product development cycle. Conversely, the promise of individual wheel motor control shows good potential for substantial improvements in vehicle behaviour.

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[1] Pratt, R, “Flight Control Systems: Practical Issues in Design and Implementation”, IEE Publishing, p.131.

[2] Harty, D, “Brand-by-Wire” – A Possibility, Aachener Colloqium 2002, pp. 1009-1024.