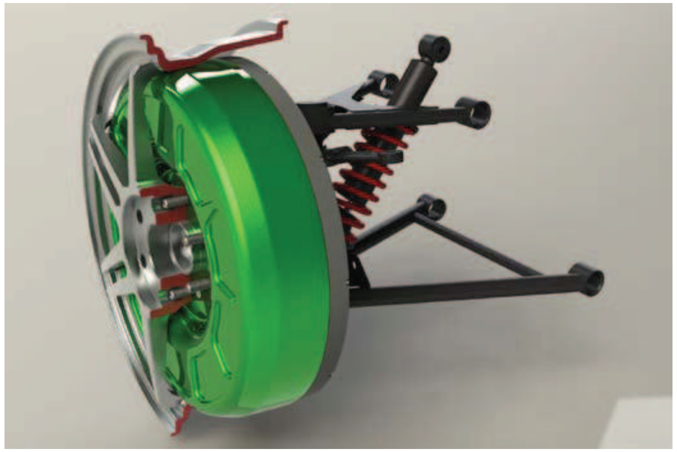
The Effect of Hub Motors on Vehicle Dynamics

The current interest in the development of EV and HEV vehicles has led to considerable discussion about the relative merits of chassis or hub mounted motors. Much of the debate has been concerned with issues of vehicle package, cost and driveline efficiency, however, the effect on vehicle dynamics has also emerged as a key factor, with apparently conflicting attributes making the advantage of one layout over the other difficult to define.

On the face of it, hub motors appear to offer real benefits over chassis mounted motors. However, the transfer of the vehicle's powertrain from the chassis to the hubs represents a significant shift in the ratio of sprung to unsprung mass and as every vehicle dynamics engineer knows, high unsprung mass is not desirable.

In the hub motor's favour, we have the advantage of independent control of drive torque to two or even all four wheels, without the cost, complexity and packaging implications of controlled differentials and driveshafts. This makes hub motors the obvious choice for torque vectoring control of the vehicle's response and stability, as well as four wheel drive traction. In addition, an EV's body package is freed from all requirements to accommodate the vehicle's powertrain, whilst a hybrid may retain the conventional IC powertrain package, with both EVs and HEVs needing extra space for batteries only.



The wheel and knuckle 'massed up' to replicate a hub motor

With such a powerful argument for the use of hub motors, Lotus undertook to conduct a unique study to evaluate the real world impact of the increase to unsprung mass.

Working with Protean Electric, Lotus took a mid segment sedan with class leading vehicle dynamics and replicated the unsprung mass and inertia characteristics of a range Protean's hub motor design by adding ballast to the wheels and knuckles.

Lotus then commenced a vigorous programme of benchmarking the vehicle dynamic performance of the 'massed up' vehicle. Lotus ride and handling engineers recorded subjective evaluations of the vehicle's steering, handling, stability, ride comfort and NVH, before collecting objective measurements of the same vehicle attributes. Finally, Lotus generated a comprehensive vehicle dynamics CAE model using their RAVEN software, and shadowed the physical benchmarking with a parallel virtual study.

A total of seven conditions were investigated, representing different levels of mass increase.

Initial subjective assessments identified four that were considered to offer sufficient separation in perceived performance to merit objective measurement.

Assessment Number	Front Hub	Front Wheel	Rear Hub	Rear Wheel
3	23kg	7.5kg	23kg	7.5kg
4	15kg	5kg	15kg	5kg
5	10kg	5kg	10kg	5kg
7	Std	Std	Std	Std

The vehicle was subjectively assessed for steering, handling and ride comfort, with detailed Vehicle Evaluation Rating scores given to different aspects of each category.

The standard vehicle was characterised by its overall very good steering attributes which lead the market sector and its good overall handling capabilities, which were considered to be responsive and well pitched within its target market. Ride comfort, whilst firm, was felt to be well controlled.

The increased unsprung mass brought about a small reduction in agility and a reasonable increase in overall steering efforts. Ride comfort with the highest unsprung mass was actually found to be as good as the standard vehicle for rolling comfort, but as expected unsprung mass shake was more apparent, which reduced the subjective rating for impact feel even though initial impacts were softer.

Contrary to expectations, the vehicle behaviour was found to exhibit the greatest degradation not when the unsprung mass was at its greatest, but at the intermediate conditions. Subsequent objective measurements would reveal the reason for this apparent anomaly.

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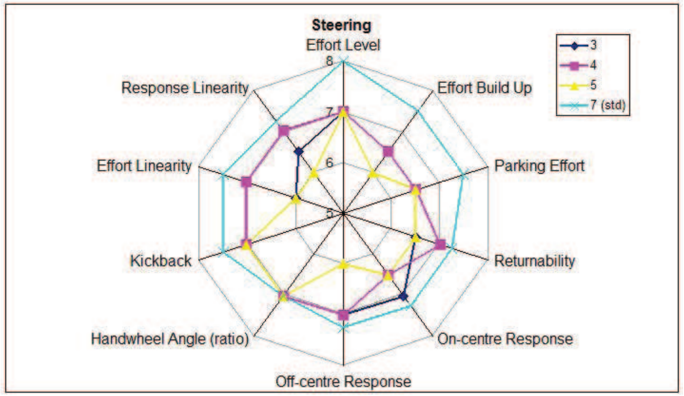
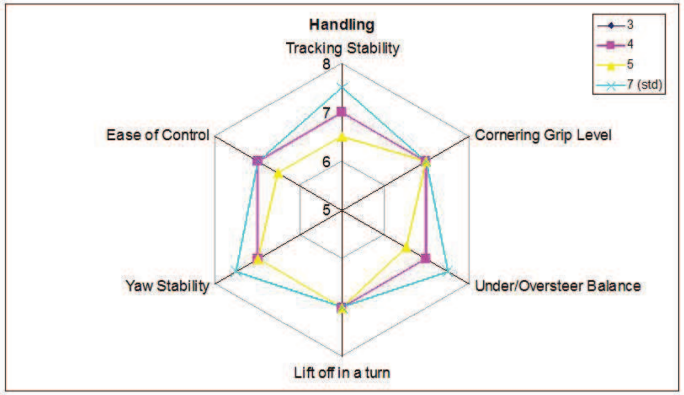
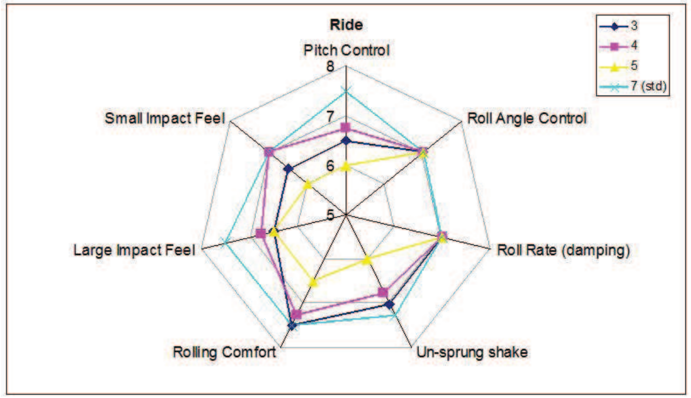
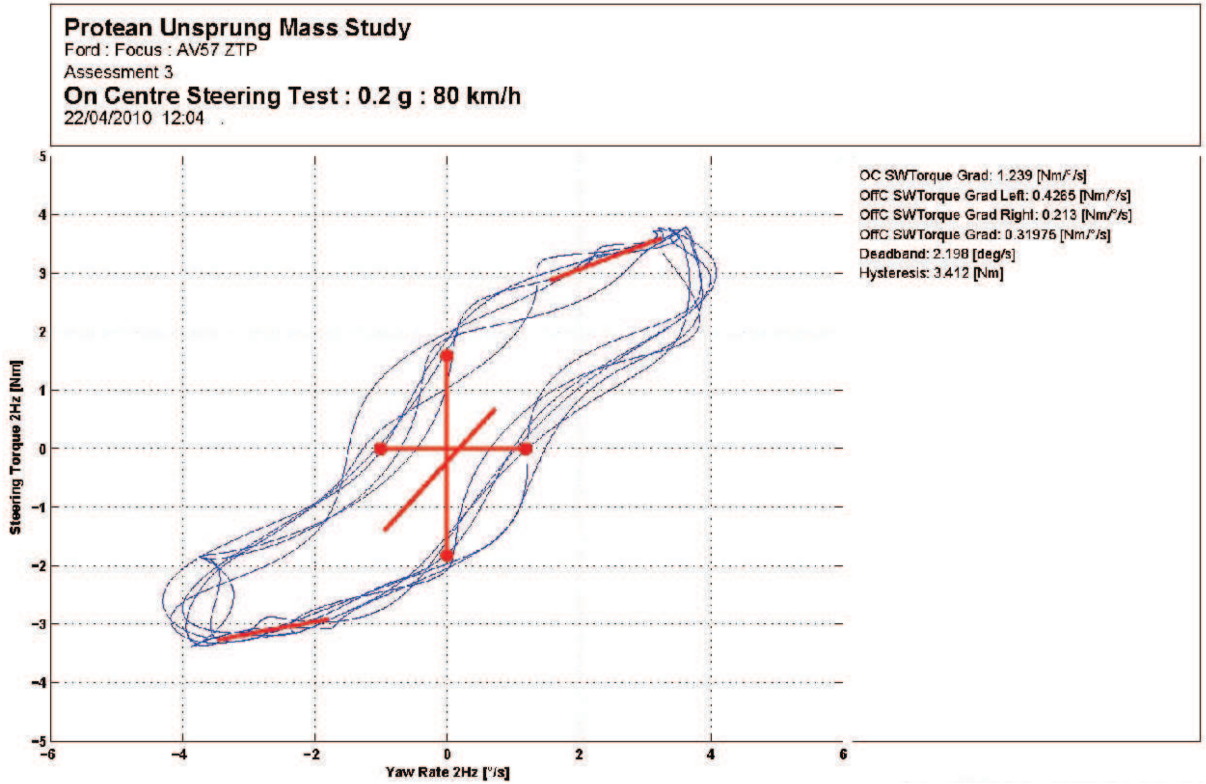






Following on from the findings of the subjective assessment, objective steering and handling measurements were conducted using an "on-centre" steering manoeuvre. This test highlights the dynamic response of the vehicle to a continuous sinusoidal steering input, the test being run at different steering input magnitudes in order to highlight non-linearitys in the vehicle behaviour.

Small differences in lateral acceleration and yaw velocity response were identified, with a slight increase in yaw response phase lag. The changes were considered to be consistent with the increase in vehicle yaw inertia associated with the mass added at each wheel. The steering torque build up was found to be less linear with the increased unsprung mass. The initial rate of torque increase relative to yaw rate was increased, but then reduced off centre. The characteristic was considered to be consistent with the combined effects of the yaw response lag, increased steering friction and increased wheel and hub inertia about the steering axis.



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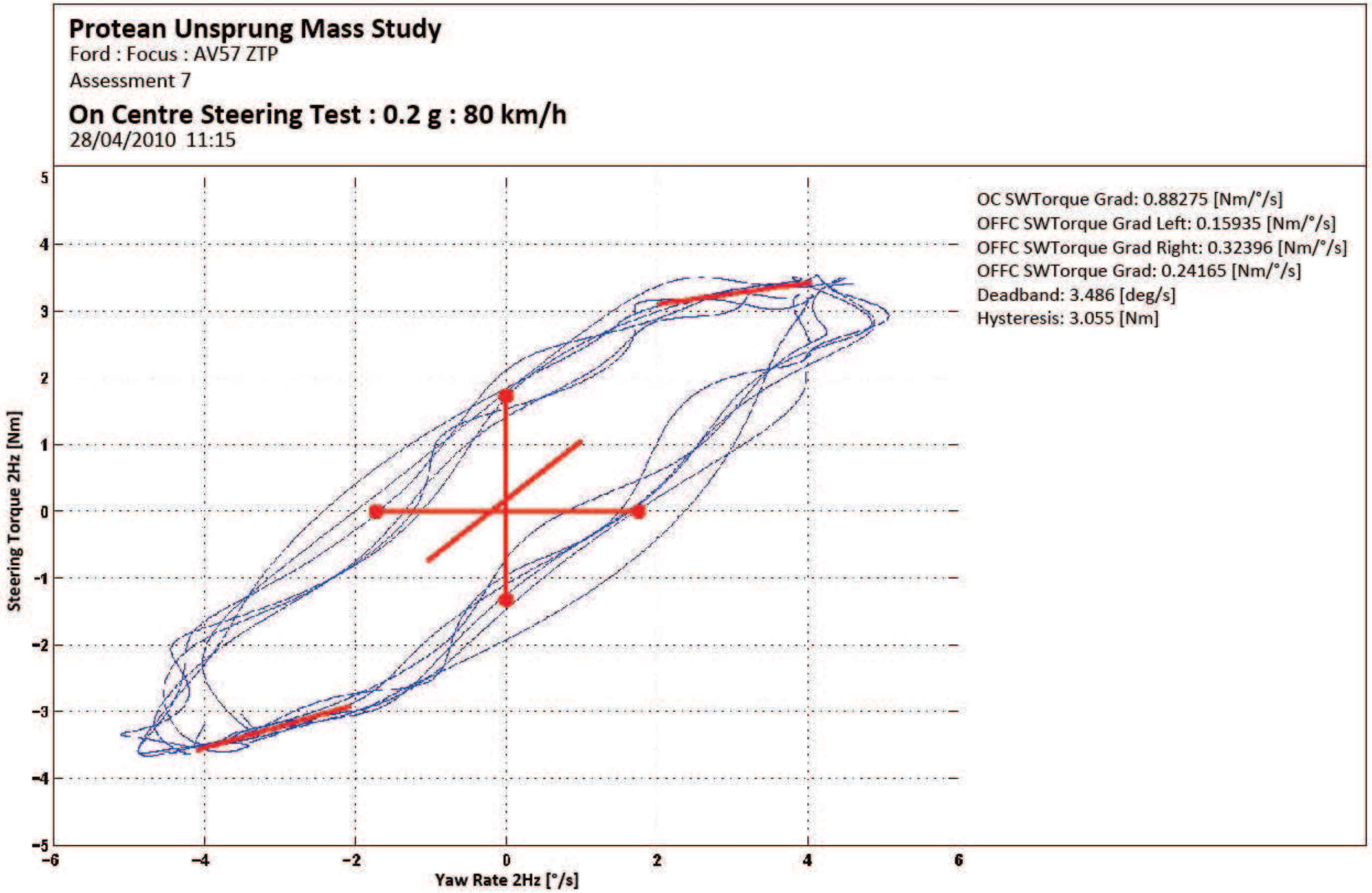
CAE models were used to better understand the dynamic mechanisms responsible for the observed differences in the vehicle responses.

Steady state cornering analysis revealed a small reduction in the vehicle's lateral acceleration limit, whilst body roll and side slip were also found to increase as one might expect to result from a 132 kg increase in total vehicle mass, whether sprung or unsprung.

Steering input swept since analysis highlighted the differences in the vehicle's transient response as a function of input frequency. Here the CAE confirmed the slight yaw response delay observed in the objective vehicle measurements. The CAE models also allowed the effects of the increased unsprung inertia and gyroscopic torques to be quantified. It had been expected that these may have a significant effect upon transient steering efforts.

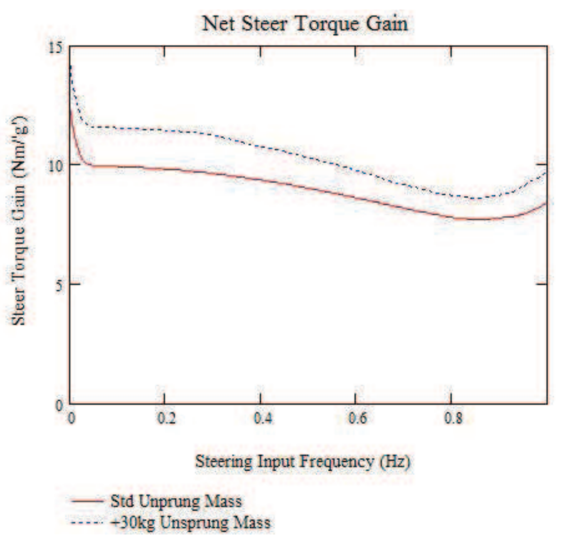
The steering torques generated by unsprung inertia are dependent upon steer velocity (the rate of change of steer angle) and wheel rotational velocity. Typical vehicle response to transient steering inputs has a bandwidth of around 1 Hz; beyond this frequency, vehicle response is completely out of phase with steering and is not within the operating range normally experienced by the vehicle user.

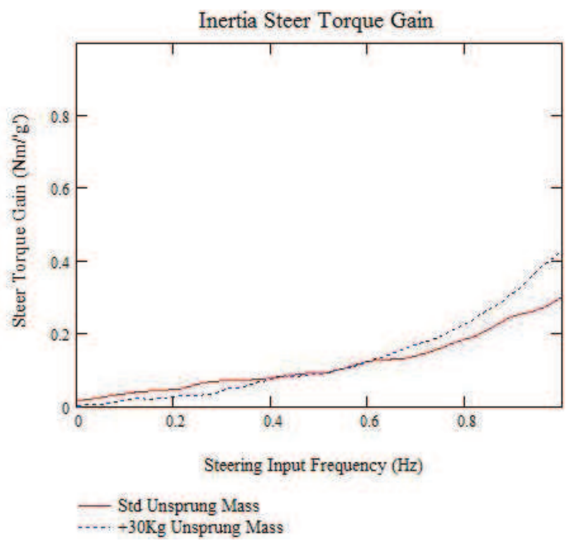
Steering wheel input rates may reach 750 deg/s in exceptional circumstances. With a typical steering ratio of 16:1, this relates to a peak roadwheel angular acceleration of 2.6 radians/s2 for a 0.5 Hz excitation. Even at this extreme steer acceleration, the transient resisting torque due to the unsprung mass inertia of a typical car is about 1.56 Nm. Reduced by the

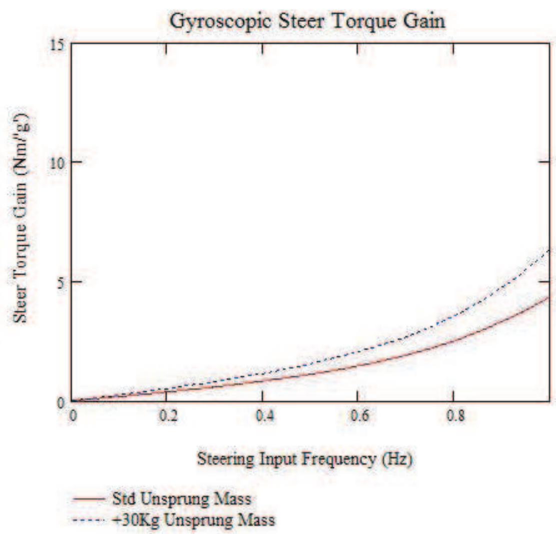


mechanical advantage of the steering gear, this results in just 0.1 Nm felt by the driver. With the added inertia of the heaviest hub motor, the contribution to steering effort from a transient steering input increases to 0.17 Nm, a figure which is still negligible compared to the total steering effort.

Gyroscopic torque is a function of both steer velocity and wheel rolling velocity. However, as wheel rolling velocity increases (with vehicle speed), steering angles and hence steer velocities reduce. Thus the typical contribution to steering effort due to gyroscopic effects rarely exceeds 0.75 Nm, whilst with the heaviest hub motor this value increases by just 0.25 Nm. So although the gyroscopic effect is greater than that of the increased inertia about the







steer axis, neither can be said to have a significantly detrimental effect on steering effort build up.

Ride comfort is the aspect of vehicle dynamics traditionally considered to be most affected by unsprung mass. Lotus conducted road measurements on surfaces deliberately chosen to excite the natural frequencies of the unsprung mass in order to emphasis any differences due to the unsprung mass increase. Accelerations were measured at the strut tops, damper rod and wheel hubs, to give a clear picture of vehicle body disturbance, as well as insight into the suspension behaviour.

The results showed a shift in the frequency at which peak hub acceleration occurred; this wheel hop frequency is primarily a function of unsprung mass and tyre radial stiffness. Although the difference in hub acceleration is clearly apparent, the resulting change in body accelerations is small and was subjectively assessed as being unlikely to be noticeable unless a direct back to back comparison of the standard and high unsprung mass vehicles were conducted.

Further testing was conducted on a concrete highway surface at higher vehicle speeds. This test highlights the vehicle's response to higher frequency excitation. From this testing it can clearly be seen that the higher unsprung mass reduces the acceleration response of the vehicle body at frequencies above the wheel hop frequency, giving improved higher frequency noise and vibration attenuation.

The final road testing used a purpose built double bump to measure the vehicle response to an impact event. The test clearly shows that the increased unsprung mass allows the suspension to absorb the bump impact better, resulting in reduced accelerations on the vehicle body.

Lab testing of the vehicle using two post rigs produced good correlation of the road measurement results, and clearly highlighted the shift in wheel hop mode frequency, from around 14Hz down to 10.5Hz. The measurements also showed the vehicle to have a powertrain vertical mode of 12.75 Hz. This provides the explanation for the subjective performance being worse for the intermediate unsprung masses rather than the highest unsprung mass. For the intermediate unsprung mass conditions, the wheel hop mode was close to the powertrain vertical mode, giving a coupling of the two modes. Normal powertrain mounting design practice would avoid coupling of powertrain modes with wheel hop frequencies.

CAE modelling was again used to correlate the findings of the physical testing, as well as providing Lotus with valuable insight into how tuning of suspension components could be use to mitigate the effects of

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the increased unsprung mass and recover the vehicle's performance.

Whilst it is true to say that the vehicle dynamic performance was degraded by the increase in unsprung mass, the degree to which this was noticeable was small and could be said to have moved the overall dynamic performance of the test vehicle from class leading to mid class. Further more, the understanding gained from this study has led Lotus to believe that the small performance deficit could be largely recovered through design changes to suspension compliance bushings, top mounts, PAS characteristics and damping, all part of a typical new vehicle tuning program.

Add the powerful benefits of active torque control and Lotus's findings make a strong argument for the vehicle dynamic benefits of hub motors as an EV drivetrain.

Source: Steve Williams, Lotus Engineering