Torque vectoring

MALCOLM BURGESS OF LOTUS ENGINEERING EXPLAINS HOW TORQUE VECTORING HAS THE POTENTIAL TO SIGNIFICANTLY REDUCE THE CONFLICT BETWEEN STABILITY AND RESPONSE YET ENHANCE RIDE AND FUEL ECONOMY IN ELECTRIC VEHICLES

Most people with an interest in vehicle dynamics will be familiar with the traditional quest for an ideal balance between conflicting attributes such as ride comfort, response, stability, and fuel economy. One emerging technique called torque vectoring is particularly suited to electric vehicles and has the potential to significantly reduce the conflict between two of these attributes, stability and response, while offering the opportunity to enhance the others. It is an area where Lotus has been evaluating and developing new systems and approaches.

When a driver turns the steering wheel, they expect the vehicle to change direction (yaw). The vehicle does not, however, respond immediately because tires take time to build up lateral forces, and the actual vehicle response may not be exactly what is required, or expected. Typically, the vehicle yaw rate response to a rapid steering input is seen in Figure 1.

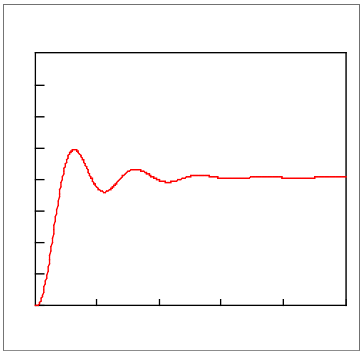


FIGURE 1: **PLOT OF VEHICLE YAW RATE RESPONSE TO A RAPID STEERING INPUT**

Particularly at high vehicle speed, after an initial delay period (a fraction of a second) the vehicle yaw rate can overshoot and oscillate before settling on a steady value. At very high speeds, or if the vehicle's suspension is poorly tuned, the oscillations can increase and the vehicle can go out of control. Even at lower speeds, the oscillations can make the vehicle feel less stable and the driver may find that they need to make multiple steering adjustments to follow the intended path through a corner.

Conventional vehicle suspension is tuned through bump steer, static settings, etc, to minimize the oscillations and to give a stable response at all vehicle speeds and loading conditions, but any increase in stability is at the expense of vehicle agility and the vehicle response can become dull.

This can lead to a compromise between vehicle response, stability, ride, and fuel consumption. For example, tire rolling resistance would be reduced if the suspension characteristics could be tuned to reduce tire scrub.

When a vehicle is fitted with a means of independently controlling the drive and braking torques to each wheel (for instance, electric hub motors), there is an opportunity to improve the vehicle yaw response. This is done by increasing the drive torque to the outside wheels, and creating an effective braking torque to the inside wheels. These drive torques are in addition to the normal drive torques required to control vehicle speed.

The ability to tune yaw behavior via torque vectoring can potentially eliminate compromise between response and stability. Suspension characteristics could be tuned to benefit ride and fuel economy, while torque vectoring generates the desired response.

Maximum turning moment (torque)

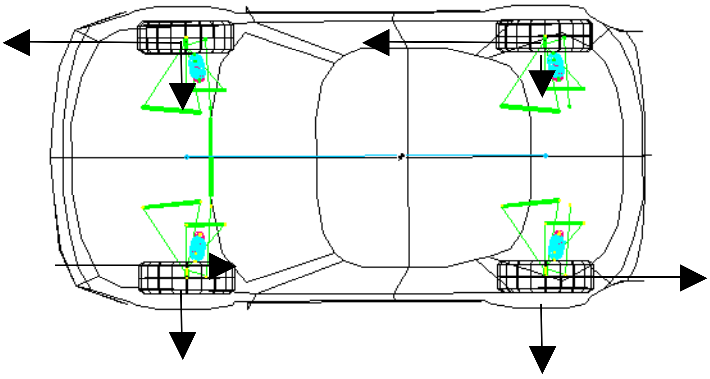
Independent of the steered angle of the wheels, a yaw moment is generated when the resultant of the tire forces is perpendicular to a line through the center of gravity. The resultant force is the combination of lateral force and driving/braking force. The maximum yaw moment (if required) is obtained when the resultant of the tire forces is perpendicular to a line from the center of the tire to the vehicle center of gravity.

There are two main advantages in using these resultant forces to control vehicle yaw (as opposed to purely tire lateral forces):

- The resultant force can act at a greater lever arm, increasing the maximum moment available.
- Yaw rate can be controlled without requiring any steering.

If the forces are correctly controlled, the vehicle can be made to respond more quickly to a steering

FIGURE 2 (RIGHT): **SHOWS DRIVE TORQUES HELPING THE VEHICLE TURN LEFT. THIS IS CALLED TORQUE VECTORING AND IS DEFINED AS: CREATING A DIFFERENCE IN THE BRAKING OR DRIVING FORCES AT EACH WHEEL TO GENERATE A YAW MOMENT (TORQUE) WITH THE INTENTION OF CONTROLLING YAW RATE**



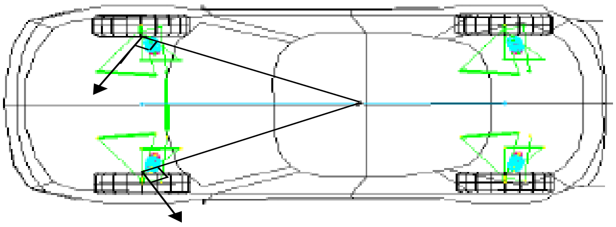


FIGURE 3: **MAXIMUM MOMENT ABOUT THE CENTER OF GRAVITY**

input and instability can be reduced. To do this, the control of the wheel torques needs to consider:

- Increasing torque on the one side must be balanced by a reduction on the other side to avoid unnecessary acceleration.
- Vertical load on each wheel – particularly as the vehicle corners, the vertical load on the inner wheels reduce and drive/braking torque may cause wheel spin or wheel lock-up.
- The addition of drive or braking torques at the rear may result in loss of rear grip – leading to loss of control.
- Any response must be safe and predictable.

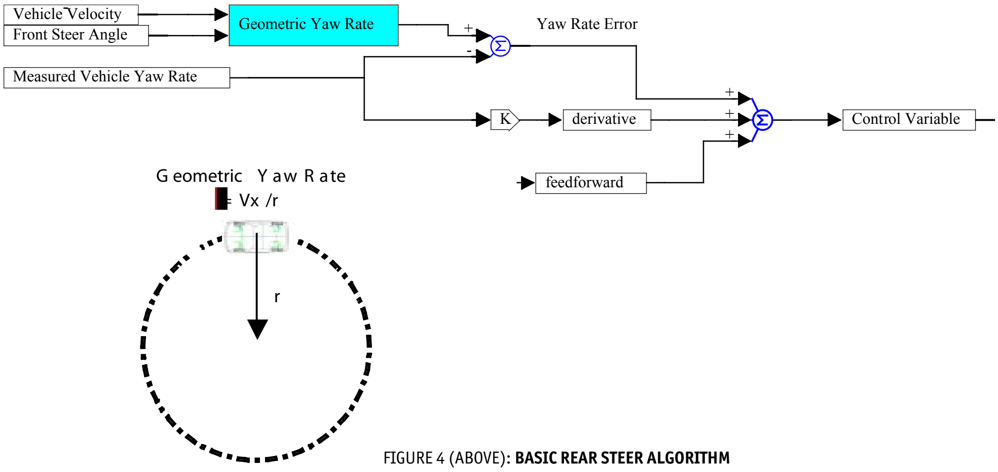


FIGURE 4 (ABOVE): **BASIC REAR STEER ALGORITHM**

The challenge is how to control the torque to achieve improved yaw response and stability. For example, simply distributing the torque based on steering wheel angle would achieve more yaw response (for the same steering input), but it would not create any improvement in stability. It could even make the vehicle less predictable.

Controlling the torque via feedback control

One method to achieve rapid yaw response and improved yaw stability is to use Lotus's rear steer algorithm which Lotus developed on rear steer vehicles based on yaw rate feedback.

The same algorithm can be adopted to control yaw rate using torque vectoring as a controlling variable, i.e. using the signal from the algorithm as a signal to control either front or rear wheel torques.

For any steer angle and forward velocity, an ideal yaw rate can be calculated by assuming no tire slip, and using the wheel geometry to approximate the turn radius.

The measured yaw rate is then used as feedback, giving a yaw error. A differential term (yaw acceleration) is included for damping. The output is used to control the rear steer. For torque vectoring, the same signal can be used to control the distribution of drive torque; i.e. for a left turn, an additional torque is applied to the right, with an equal braking torque applied to the left. These torques are in addition to the 'normal' drive torque that maintains the vehicle forward velocity.

Results from a step steer input are shown (Figures 5-7). It can be seen that with the feedback system there is an increase in lateral acceleration and yaw rate, and a quicker initial gradient for yaw rate. Responses are also less oscillatory and more stable.

A limitation to feedback control is that the system relies on measured yaw rate as an input signal. This measured response data will also include 'noise' (high frequency waves created by road inputs and general vibration). In order to use the signal, the signal must be filtered. This unfortunately creates a time delay in the signal, and the feedback becomes too late creating overshoot and oscillations in the response.

So an alternative approach is to use model-based control.

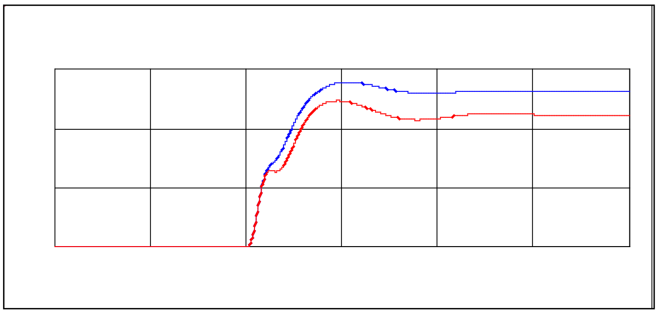


FIGURE 5: **STEP STEER LATERAL ACCELERATION RESPONSE WITH FEEDBACK CONTROL**

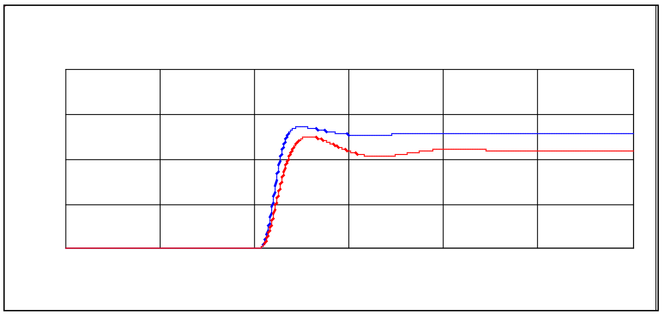
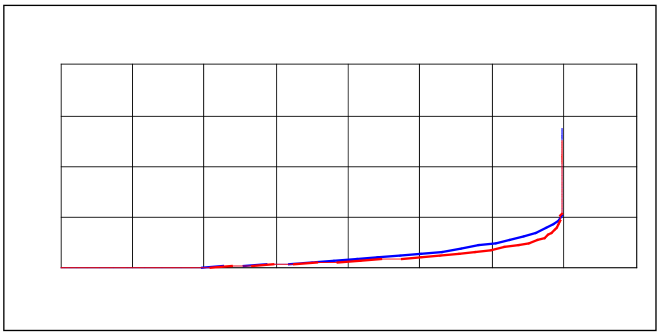


FIGURE 6: **STEP STEER YAW RESPONSE WITH FEEDBACK CONTROL**

FIGURE 7 (ABOVE): **CROSS PLOT OF YAW RATE AND STEER ANGLE SHOWS A SMALL IMPROVEMENT IN PHASING. PERFECT PHASING WOULD GIVE A STRAIGHT LINE OR LINEAR RESPONSE**



Model-based control

Model-based control does not require any feedback. Instead it uses a mathematical model to predict the required input to the vehicle (in this case driving and braking torques) to achieve a desired yaw rate. The desired yaw rate can still be calculated from the geometric turning circle (as in the feedback system) or alternatively it could be what is considered ultimately desirable, defined as a mapping.

The input to the model is therefore the desired yaw response of the vehicle (defined from the steering) and the outputs are the drive/braking torques that are required to achieve the yaw response. The mathematical model therefore represents an inverse of the actual vehicle system (Figures 8-9, right).

If the mathematical model is a good approximation to the inverse of the actual vehicle, the actual response of the vehicle will be a close match to the desired response, with no time lag or oscillations. Creating an inverse model of a complex system is sometimes not simple and sometimes not possible. Lotus has, however, created a highly realistic model that represents the inverse of a complex non-linear vehicle.

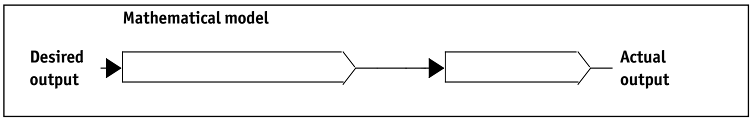


FIGURE 8 (TOP): **NO FEEDBACK REQUIRED**

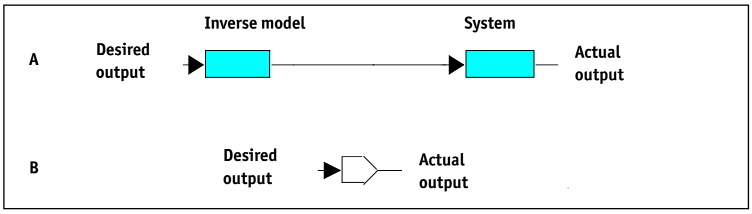


FIGURE 9 (ABOVE): **IDEAL OPEN LOOP CONTROL WITH A SIMPLE EXAMPLE MODEL** (A)**, WHICH IS THE SAME AS** (B)

A simplified representation of the system is shown in Figure 10 (below).

The actual system therefore responds to the 'actual' steer input. But the natural system will tend to overshoot, respond slowly or fail to achieve the desired output – as defined by the steering/yaw rate mapping.

The additional feed forward term (Figure 11, below) only controls the error between the desired yaw rate and the predicted yaw rate (note this is not the measured yaw rate). This is not steer-by-wire, but enhancement-by-wire.

Assuming the inverse model is an accurate representation of the actual system, the output response (to an input) is rapid, without having the overshoot and stability problems that feedback systems inherently have.

FIGURE 10: **INVERSE DRIVE BRAKE TORQUE MODEL**

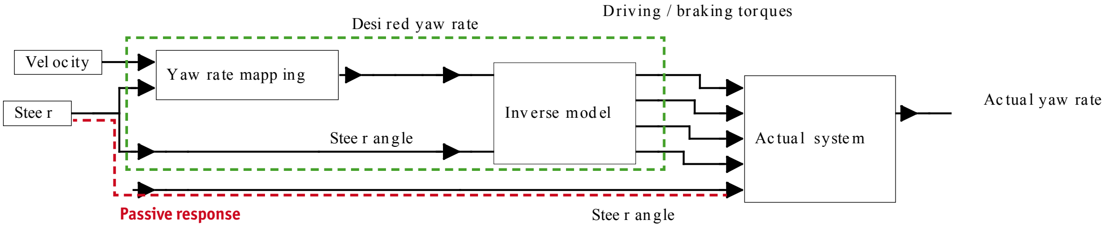
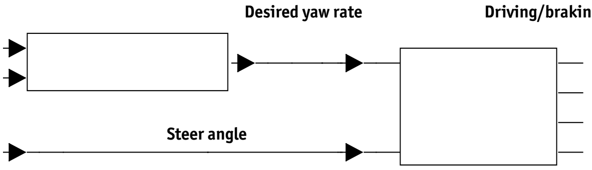


FIGURE 11: **FEED FORWARD TERM**



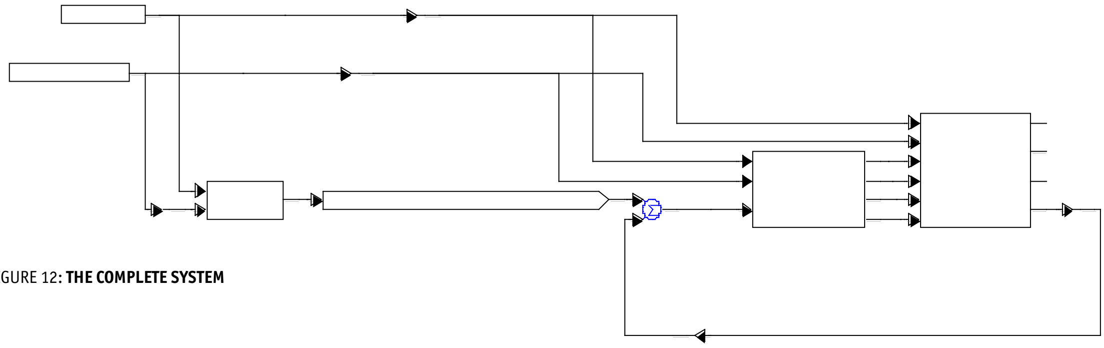


FIGURE 12: **THE COMPLETE SYSTEM**

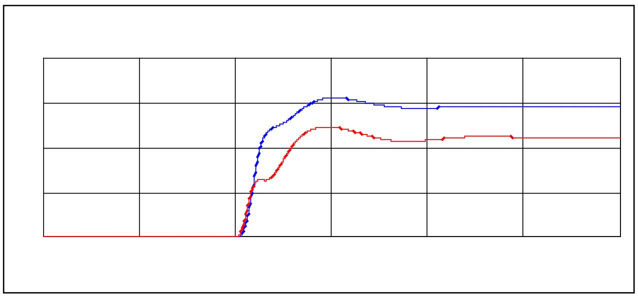


FIGURE 13: **STEP STEER LATERAL ACCELERATION RESPONSE WITH MODEL-BASED CONTROL**

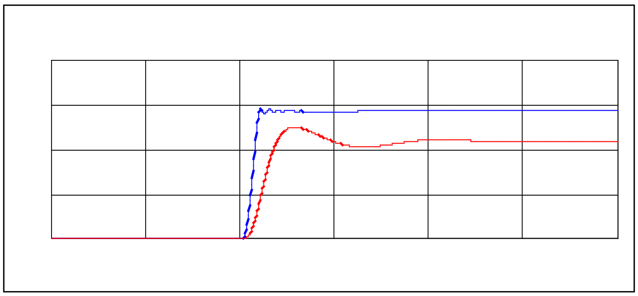


FIGURE 14: **STEP STEER YAW RATE RESPONSE WITH MODEL BASED CONTROL**

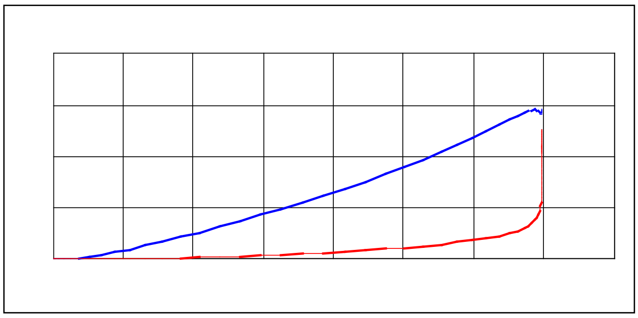


FIGURE 15: **YAW RATE/STEER ANGLE – CROSS PLOT**

Complete system

Since the mathematical model cannot not always match the vehicle/road system perfectly, a feedback loop can be included to correct for the difference between the desired yaw response and the actual yaw response. The complete control system therefore combines the benefits of rapid response from the mathematical model with the feedback providing fine tuning and improving accuracy.

From the results for a step steer input (Figures 13-14), it can be seen that with the model-based system there is an increase in lateral acceleration, and yaw rate, and a much quicker initial gradient for yaw rate. The yaw response matched the demand. The responses are also less oscillatory and more stable.

The cross plot (Figure 15) shows a dramatic improvement in phasing of yaw rate and steer. Perfect phasing would give a straight line or linear response. This dramatic improvement shows the capability of the system but is not necessarily the desired response. Mapping response to driver expectation would require further work.

So in conclusion, what is evident is that although feedback control shows improvements in vehicle response to the step steer, the model-based control approach has clear advantages. This approach has a dramatic improvement in step steer response, with yaw rate in phase with steering input, and elimination of yaw rate oscillations.

Torque vectoring using this approach has the potential to greatly improve response and stability, with the tuning of the control model enable vehicle behavior to meet driver expectations. Not only can future electric vehicles have clear environmental advantages, but with the torque vectoring their drive systems allow, they can potentially be both safer and fun to drive.