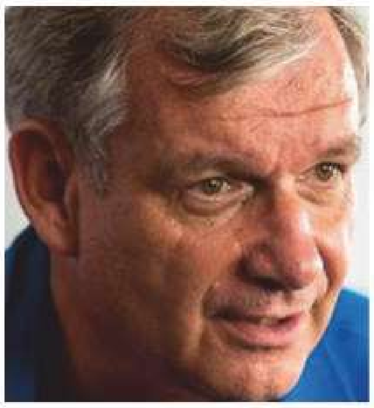

Braking new ground

OptimumG's lead engineer talks us though the braking zone in the new instalment in his key performance indicators analysis series

By CLAUDE ROUELLE

Continuing with our study of braking KPIs (key performance indicators) from the July issue (V29N7), this month we will look at vehicle stability under braking.

Stability represents the yaw moment acting against the natural rotation of the car per degree of body slip angle. It's quantified in Nm/degree of yaw moment per degree of body slip angle. This reaction moment acting against the body yaw should have a negative value.

In a practical setting stability can be looked at as the predisposition of the vehicle to stay in the directional state it is in, which can have direct effect on a driver's confidence in a vehicle. An unstable car will reduce confidence. We also need to mention that high stability is often (though not always) in opposition to fast response. Though good vehicle dynamics simulation shows that there are design and set-up choices that can give, if not both a good stability *and* a good response, at least better compromises.

Slip angle sensors

One of the most important areas to have a high stability will be under braking. Using a slip angle sensor, we can measure the true vehicle stability under braking. The slip angle sensor will record the angle between the direction the car is heading (car longitudinal axis) and the direction in which it is effectively moving. If we know the yaw inertia of the car, we can calculate the yaw moment using the derivative of the yaw rate sensor: *Yaw Moment = d(Yaw Rate)/dt * Vehicle Yaw Inertia.* Stability can then be measured as the change in the yaw moment divided by the change in the slip angle of the vehicle.

Slip angle sensor; the wheel force transducer measures all tyre forces and moments

While it would be ideal to run a slip angle sensor and determine the true vehicle stability under braking during every driving session, it is often impractical to run during a race weekend due to series rules disallowing this kind of sensor and/or the risk of damaging the sensor through contact with other vehicles, or the financial burden of purchasing the sensor to begin with.

But, for most circumstances we can correlate vehicle stability with yaw rate smoothness and steering smoothness anyway. Therefore, an alternative approach can be used to approximate the stability by looking at both the steering smoothness key performance indicator and the yaw rate smoothness KPI.

This approach will then be supplemented by showing how simulation can improve efficiency at the race track, by a presentation of the change in stability that can result from different set-up options.

First we need to determine the style of braking being used. To make things simple, the focus here will be on straight-line braking rather than trail braking (**Figure 1**). To differentiate our straight-line braking and trail braking, we will define a Boolean operation that returns a value of 1 when the vehicle is in a straight-line braking state, and 0 when it is not. First, we will sum the front and rear brake pressures into one channel. Then, we will combine the brake pressure with the lateral acceleration signal. A threshold of 0.2 lateral *gs* will be defined as the transition value between straight-line braking and trail braking based on a 10 per cent value of the average lateral acceleration that was generated on this course (2.0*g*). The 10 per cent value was chosen based on experience with the circuit and the vehicle sensitivity to cornering.

Residual pressure

We also need a test in the math function that shows if there is more than residual pressure in the braking system. To find the residual pressure for the vehicle the braking pressure can be read from an area on a long straight where there should be no braking input. In this vehicle, the residual pressure is being output as 0.2bar, so that will be the trigger. With the thresholds set, the straight-line braking channel will return the value 1 when the total brake pressure is higher than the residual pressure of the system, in this case 0.2bar, and the absolute value of the lateral acceleration is less than 0.2*g*. The trail braking function will return 1 when the absolute value of the lateral acceleration is equal or greater than 0.2*g*.

Table 1, below, summarises the math channels in MoTeC i2 Pro data analysis software. For a better context of the transition point we can now move on to compare the straight-line braking trigger to the total brake pressure and the lateral acceleration of the vehicle.

Table 1: Equations for braking stability using steering smoothness in MoTeC i2

Math channel name	Math channel equation
Total brake pressure	'Front Brake Pressure' [bar] + 'Rear Brake Pressure' [bar]
Straight line braking	choose('Total Brake Pressure' [bar]>0.2 and abs('G Force Lat' [g])<0.2, 1, 0)
Trail braking	choose('Total Brake Pressure' [bar]>0.2 and abs('G Force Lat' [g])>=0.2, 1, 0)

The slip angle sensor will record the angle between the direction the car is heading and the direction in which it is effectively moving

To generate the braking stability KPIs, we will want to look at the yaw rate smoothness, the steering smoothness, and the partial lock-ups during the straight-line braking segment defined above. The steering smoothness and yaw smoothness math channels have been addressed in previous articles, so they will just be given. If you wish to have a more detailed explanation, check out our article from the November 2018 edition (V28N11). **Table 2** summarises the math channels for slip ratio, partial braking lock-up, yaw rate smoothness, and steering smoothness which allow for the stability KPIs to be calculated.

The steering smoothness is being used to show how much additional steering wheel input the driver is adding when braking. This in turn suggests how the chassis slip angle or the yaw moment is changing, causing more driver corrective inputs. The yaw rate looks at how quickly the vehicle is rotating. Our KPI will look at the ratio between the steering smoothness and the yaw rate smoothness.

A greater difference between the smoothed yaw rate data and the logged yaw rate data suggests that the car is rotating much more aggressively than the driver might prefer, meaning that very little yaw moment is required to change the rotation of the vehicle. If we have a high ratio between steering smoothness and yaw rate smoothness, it indicates that more steering variation is required to induce a yaw rate variation. Therefore, for our KPI, a higher value indicates a more stable vehicle.

Table 2: MoTeC channels for slip ratio, lock-ups and stability

Math Channel Name	Math Channel Equation
Slip ratio (front left)	('Wheel Speed FL' [km/h]) - 'Corr Speed' [km/h])/'Corr Speed' [km/h]
Partial lock-up (front left)	choose('Slip Ratio (Front Left)'<-0.07,1,0)
Front partial lock-up Integral	Integrate('Partial Lockup (Front Left)'+'Partial Lockup (Front Right)','Partial Lockup (Front Left)'>0 OR 'Partial Lockup (Front Right)'>0,range_change("Outings:Laps:Track Sections:Braking Zones:Throttle"))
Rear partial lock-up Integral	Integrate('Partial Lockup (Rear Left)'+'Partial Lockup (Rear Right)','Partial Lockup (Rear Left)'>0 OR 'Partial Lockup (Rear Right)'>0,range_change("Outings:Laps:Track Sections:Braking Zones:Throttle"))
Yaw rate smoothed (deg/s)	smooth('Yaw Rate' [deg/s],0.5)
Yaw rate smoothness (deg/s)	abs('Yaw Rate' [deg/s]-'Yaw Rate Smoothed' [deg/s])*100
Steering smoothed	smooth('Steering Wheel Angle' [deg],1.0)
Steering smoothness	abs('Steering Wheel Angle' [deg]-'Steering Smoothed' [deg])*100
Steering stability	integrate('Steering Smoothness' [deg],'Straight Line Braking' == 1,range_change("Outings:Laps:Track Sections:Braking Zones"))
Yaw rate stability	integrate('Yaw Rate Smoothness' [deg/s],'Straight Line Braking' == 1,range_change("Outings:Laps:Track Sections:Braking Zones"))
Stability KPI	'Steering Stability'/'Yaw Rate Stability'

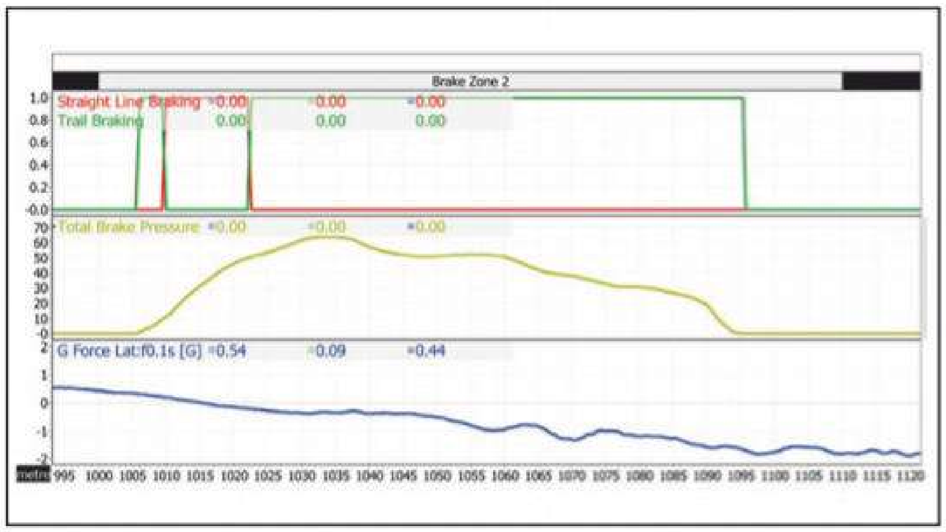

Figure 1: The red section corresponds to where the driver was within the bounds for straight line braking analysis, green is where it's within the bounds for trail braking

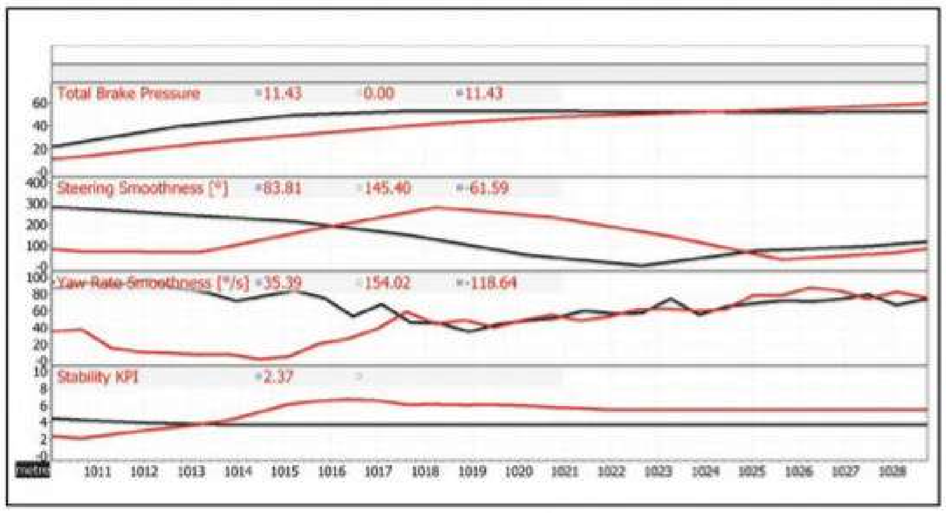

Figure 2: A comparison of steering stability and yaw rate stability for two drivers in straight line braking. The black trace shows a greater variation in steering approach

Partial lock-up

A partial braking lock-up is any instance where there is a difference between the vehicle speed and individual wheel speed beyond the peak slip ratio. We can determine the slip ratio of the vehicle by creating a math channel to find the ratio between the wheel speed and the vehicle speed. We can create a trigger when it surpasses the ideal slip ratio. For this vehicle, the ideal slip ratio was determined using an anti-lock braking system (ABS) which was set to regulate the slip ratio of the vehicle. The slip ratio that corresponded to the highest longitudinal acceleration was used as the upper bound for slip before the slip could be considered a partial lock-up, as after the ideal slip ratio the tyres are now sliding more than they are allowing the vehicle to slip, as shown in **Table 2**. The partial lock-up is being used in this case to filter out any instances of high vehicle stability due to vehicle lock-up. In this case we are looking at the duration of time the lock-up occurred by using the integral function. With the channels generated, the three parameters can now be plotted and compared between two drivers. **Figure 2** shows the stability KPIs on a section of the track for two different drivers.

We will start by looking at two drivers of similar level but different driving styles running the same vehicle and similar set-ups going into an area of straight-line braking. In this braking zone, we see the black-trace driver had greater variation in steering input, indicating a higher steering smoothness. At the same time, the yaw rate stability was equally high for this driver, suggesting the car has a lower tendency to rotate and was less influenced by the steering inputs. When we combine the smoothness results into our KPI, we can now see that the red driver had a higher vehicle stability than his competitor.

We can consider the effects or partial lock-ups on stability negligible in this corner. Based on the stability KPI we can infer that the red driver was more stable than the black. Depending on the circumstances within a weekend we can now either make a set-up change or coach the first driver to use a more gradual braking method to keep the car more under control and mitigate some of the instability seen in the data trace. In this case we will consider that time is available to make a set-up change and that we do not want to have the black-traced driver change braking style, so we will look at this as a set-up change analysis. But before we start looking at set-up changes we will want to make sure that the issue was not related to the tyres or brakes not being uniformly up to temperature.

We will now look at the six-lap average for the stability KPI and partial lock-ups to see if the

In order to use the traditional definition of vehicle stability we will need a tyre model that accounts for the tyre slip

stability was related to the tyre or brake temps. If the instability was temperature related, the number of partial lock-ups and the magnitude of the stability KPI should decrease with lap count. If it is set-up related, we can expect to see little trend between the stability KPI, partial lock-up quantity, and lap count.

Figures 3 and **4** refer to the vehicle stability and the time that the driver locked up the front wheels. With the six-lap trends we see that the partial lock-up did not have a strong correlation to the stability KPI, especially during the earlier portions of the session. We do see that the black trace did become more stable later in the session, but given the large partial lock-up time during the third lap we can assume that after this the black-trace driver decreased the braking aggression. The lack of correlation to lap progression indicates that the stability issue was set-up related, probably not temperature related. To aid in the determination of which element to choose, we can go beyond standard practices of using driver feedback and data and introduce simulation tools to give a better idea of the magnitude of change.

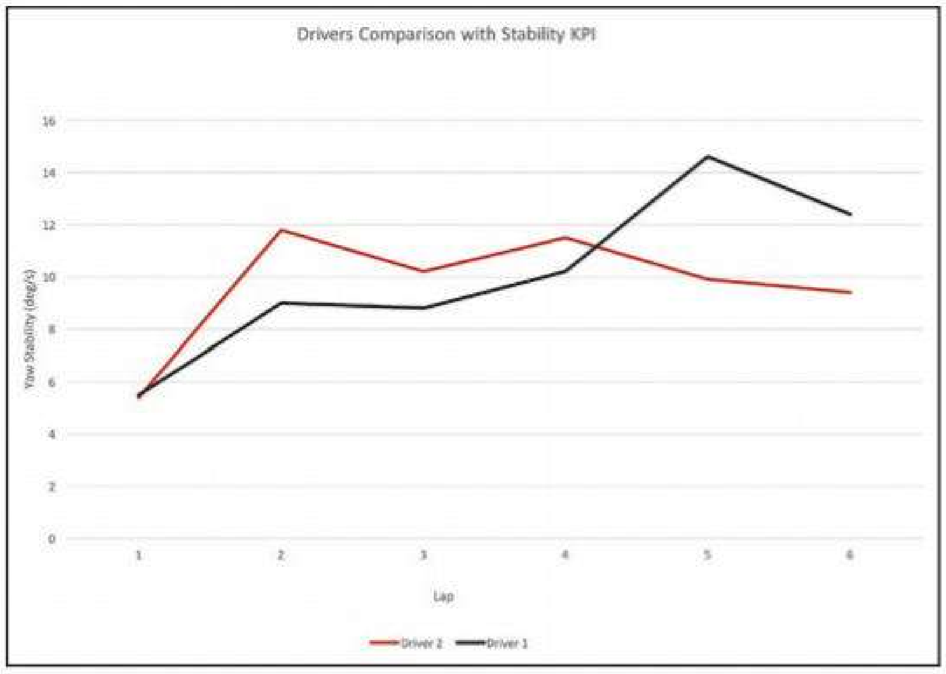

Figure 3: Driver stability trend across six laps. Black trace shows more stability later on

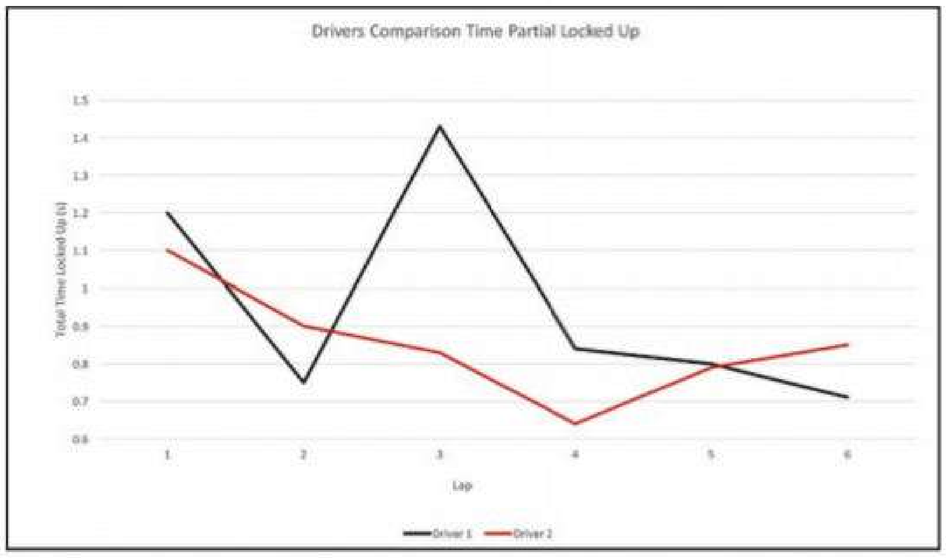

Figure 4: The driver lock-up trend across six laps. The data points to a car set-up issue

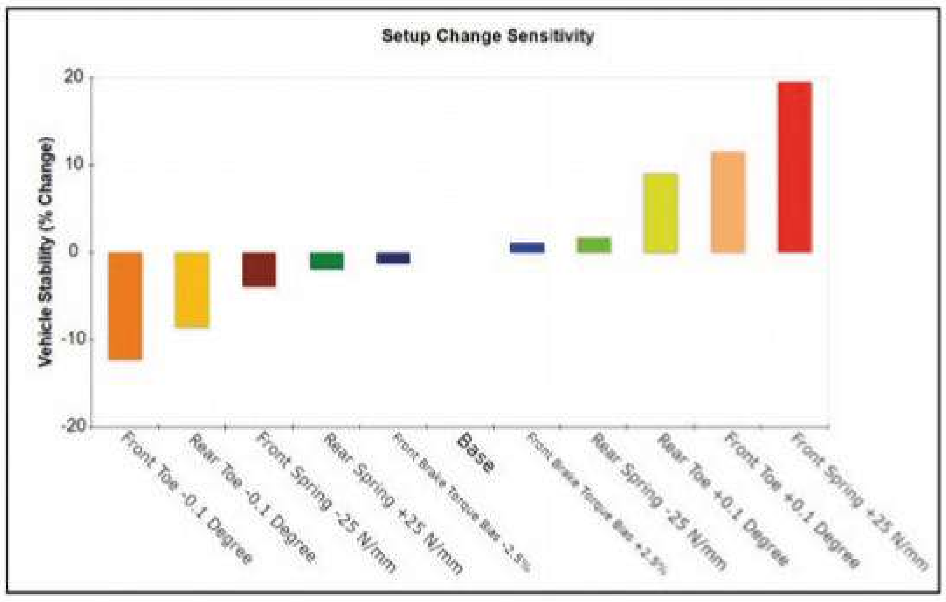

Figure 5: This graph illustrates racecar stability sensitivity to different set-up changes

Using simulation

For our simulation analysis, we will be using the full vehicle simulation tool OptimumDynamics to help determine adjustments to the racecar. OptimumDynamics provides the ability to iterate multiple set-ups and perform a full vehicle simulation using on-track data or an acceleration dependent simulation. For this analysis we will generate a sensitivity study by creating a yaw moment simulation with just one small car body slip (or yaw angle) input, no steering input, and our peak longitudinal deceleration capability. We will then track the maximum stability value (in this case in per cent change compared to baseline set-up) generated during the simulation for each set-up change.

In order to use the traditional definition of vehicle stability we will need a tyre model that accounts for the tyre slip. Unlike the steering smoothness and the yaw rate, we are looking for a higher value of vehicle stability in this simulation corresponding to a more stable racecar. The results are shown in the bar plot in **Figure 5**.

The sensitivity case study being analysed in this instance shows the relative change in stability caused by changing the front or rear toe 0.1-degree out (+0.1-degree) or 0.1-degree in (-0.1-degree) per wheel, increasing or decreasing the front or rear spring rate by 25N/mm, or by increasing or decreasing the front braking torque ratio by 2.5 per cent. Note that for this case analysis the relative stability change is higher than may be seen on other vehicles due to a lower initial stability value. The relative changes will vary for each vehicle and should not be considered catch-all values for the set-up changes being considered.

In this case, we know we want to increase the stability under braking but minimise the effects on other aspects of vehicle balance. Based on this, we will avoid making changes to the spring rates and increase the front toe-out. Just by using a simple single state vehicle analysis we now have a list of options and a strong gauge of how to adjust our vehicle to suit our driver's needs.

Conclusion

To sum up, by adding an analysis of steering and yaw rate under braking we can understand not only where a driver is braking but also how a vehicle set-up can be adjusted to suit the characteristics of a braking style by comparing the difference in driving styles using brake pressure and considering the variation in steering and yaw rate to gauge the stability of the vehicle in the braking state. With the braking stability KPI we can see how much the vehicle stability can vary for two different driving styles in a single lap trend and in a full session trend and how we can diagnose the problem even if the driver is not noticing the issue.

In combination with using simulation tools we can now have a better ability in predicting how the racecar changes are going to improve performance, and in diagnosing the issues the driver may face during an event.