
Evaluation Criteria for AWD Vehicles System Analysis

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ABSTRACT

Handling behaviour is a very important aspect of modern cars, which need to reach high levels of lateral acceleration maintaining good stability and driveability. The presence of an AWD powertrain changes the response of the vehicle and then it is very important to qualify the car behavior in terms of perceived performances through objective indexes. The paper presents the development of evaluation criteria for AWD vehicles objective assessment; simulation tools and SW standard procedure has been optimised for AWD performances virtual evaluation and different architectures (locking, self-locking, visco-coupling, active differentials) are compared in terms of longitudinal, lateral and cross-coupling dynamics performances. Through the proposed methods it is possible to make vehicle system analysis using simulation model and standard procedures to classify different AWD architectures. It is also a powerful tool for target setting-deployment-achieving in order to traduce AWD vehicle performance in terms of architecture choice and component specifications. The same criteria could be used to support control strategies development and on road AWD systems experimental tuning through simulation analysis. In the paper the application of the method to a virtual upgrade of the Alfa Romeo car is also described: the AWD layouts of interest have been simulated on the virtual car, as a support to the choices of a new Fiat platform.

AWD VEHICLES PERFORMANCES ANALYSIS

Speaking about the handling performance of a car, it is necessary to distinguish between longitudinal, lateral performances and cross coupling (see figure 1).

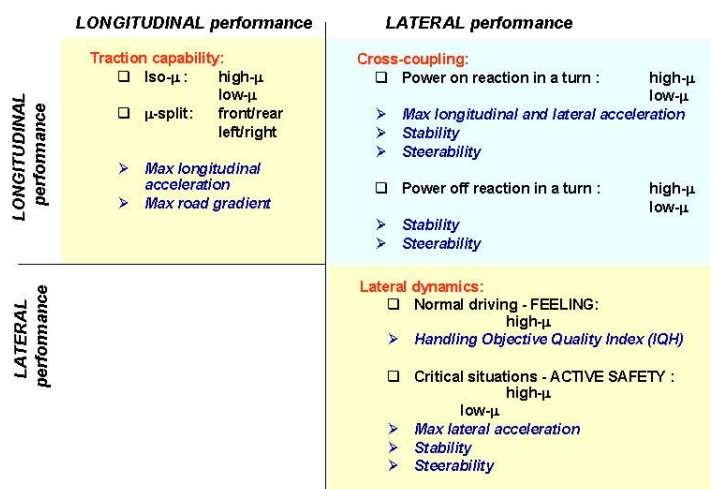


Figure 1: Handling performances of a car

LONGITUDINAL PERFORMANCE

The longitudinal performance regards traction capability in straight line (maximum acceleration) and the maximum road gradient which can be passed in different cases:

- Iso μ : the adhesion coefficient is the same under the four wheels: all the adhesion value are considered, from low (i.e. icy or snowy ground) to high (dry asphalt, good grip).
- μ -Split: the adhesion coefficient is different under the wheels. Depending on the archetype in study, it might be interesting to consider left/right split (it is the case of on axle differential), or front/rear split (central differential).

Taking in account of the pitch transfer load and of the geometry of the car (wheelbase, CG height, mass), the

maximum performance on iso- μ conditions of the car is described by $a_x = \mu$.

In order to quantify the performance loose with respect to the maximum one, the TCI (Traction capability Index) has been created, as difference between the area held by the ideal performance and the obtained performance. The upper limit is defined by the engine: considering the vehicle in 1st gear, knowing the gearboxes transmission rates and taking into account of the powertrain efficiency, it is possible to convert the maximum engine power into a maximum possible acceleration. In figure 2 the sketched blue area represents the TCI: the higher TCI is, the best the performance is.

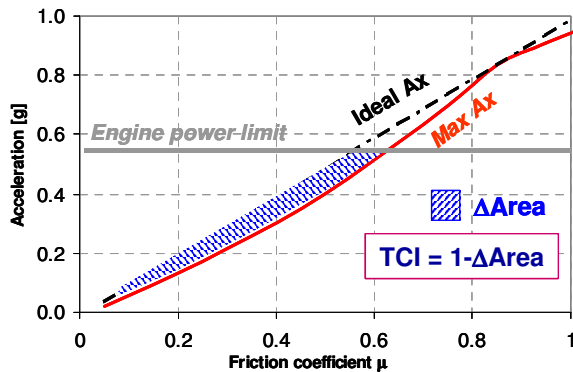


Figure 2: TCI definition

LATERAL DYNAMICS

The lateral dynamics performance must be seen from two different corners: normal driving (feeling area) and critical situations (car at limit, active safety).

- Feeling area: it is considered to be in the low-middle lateral acceleration values, on high μ . In this conditions the handling feedback to the driver is studied by IQH (Handling objective Quality Index) [1].
- Critical situations: in this case the car is near the limit, and maximum lateral acceleration reachable becomes very important, since they may really improve the active safety of the car.

The lateral vehicle dynamics can be detected with the collaboration of professional drivers, who could describe vehicle behavior through their sensations. A different engineering approach could be defined, finding a correlation between objective measurements during testing and subjective evaluations: this is the approach which has led to the development of IQH index. The application of the related methodology (collecting data in standardized ISO tests and analysing them in standard procedures) permits to evaluate the perceived handling quality of a car, in terms of:

- Steering wheel activity (IAV)
- Quickness of car response (IRV)
- Car feedback graduality (IPI)
- Roll motion (ICO)
- Roll motion velocity (IVC)

Usually the IQH ranking of a car is represented by a spider graph, like shown in figure 3.

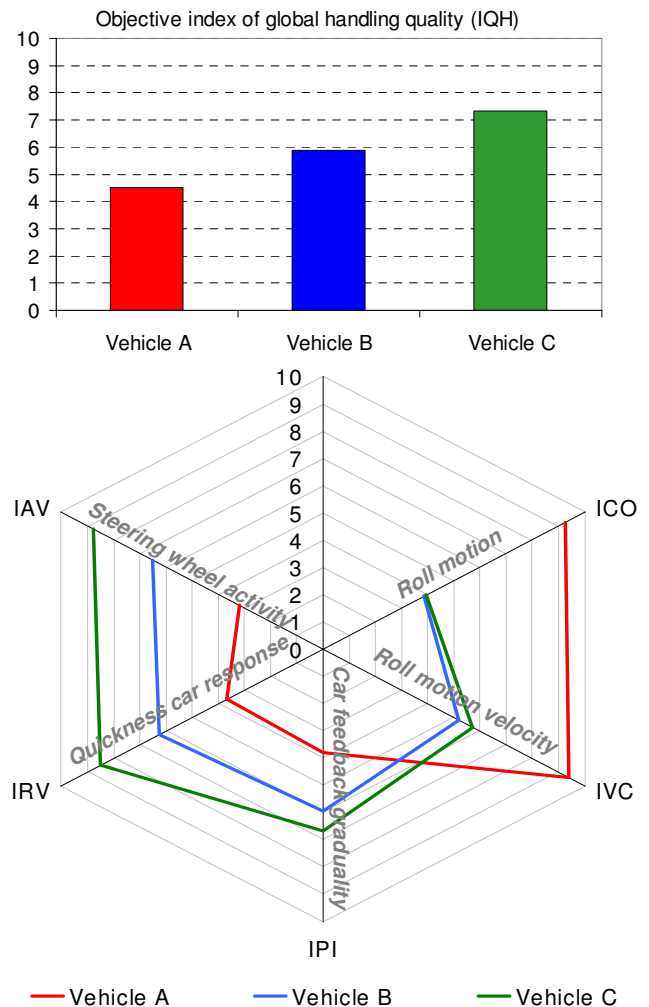


Figure 3: IQH ranking of three different cars

The IQH methodology is a powerful way to compare the different 4WD archetypes, in term of perceived handling quality of the car. The IQH methodology is based on a set of standard maneuvers: from the collected (or simulated) time histories a set of synthetic parameters is calculated, obtaining through statistical models and correlations the indexes of perceived quality. The set of maneuvers used in this approach is composed by:

- Steady state circular test, according to ISO 4138 [2]
- Step steering wheel input, according to ISO 7401 [3]
- Double lane change according to ISO/DIS 3888 [4]

To complete the analysis, frequency sweep (according to ISO 7401) are processed.

LATERAL DYNAMICS IN CRITICAL SITUATIONS

At high lateral acceleration the IQH methodology is not applicable, and the point is not the good feeling from the car, but the active safety. The car should reach great values of lateral acceleration without strong oscillations, permitting its control by steer wheel. In general, two aspects become really important: stability and steerability. The car must be stable, without spin phenomena (stability), and must respond to driver's steering input (steerability). These conditions guarantee a good safety near the limit of the car, i.e. in a critical situation like an obstacle avoiding at high velocity. The tests usually used to evaluate the limit are:

- Step steer input at high steering angle values (ISO 7401)
- Slow ramps (according to ISO 4138)

In figure 4 the time histories of two cars are superimposed, in a step steer input at limit. The vehicle "A" has stronger oscillation than vehicle "B", with high amplitudes and low damping.

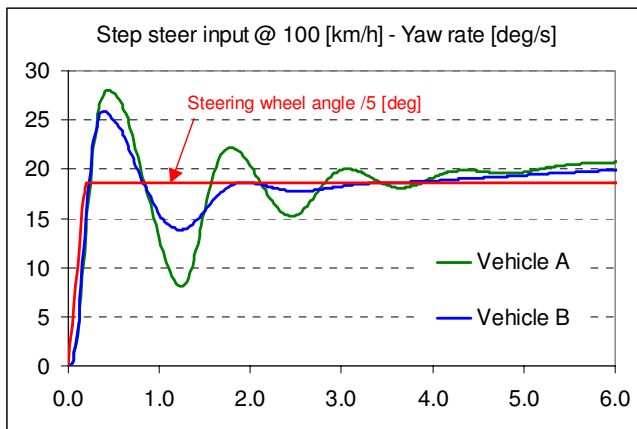


Figure 4: Step steer input at limit

The results coming from the analysis of slow ramps are understeer and side slip curves. The vehicles are compared in terms of maximum lateral acceleration taking into account of the sideslip angles values and of the understeer curve. An all wheel drive powertrain could strongly change the limit of the car, especially if the same components are controlled (i.e. C.R.F.

CYMENTO© [5] active differential or electromechanical coupling). In particular, the rear active differential of C.R.F. is able to split a certain amount of torque regardless of the torque coming from the engine and the relative speed of the output shafts.

CROSS COUPLING

When the cross coupling is studied, both longitudinal and lateral performance have to warrant a good reaction of the car: this is the case of power in or power off in a turn. The car could follow the path increasing or decreasing the radius, with yaw and sideslip oscillations. At the same time if the car has to be powerful during a power in, the maximum performance is required not only in X-direction, but also in Y-direction. To investigate this behaviors, the test usually done are:

- Power on/off in steady state cornering (according to ISO 9816 [6])
- Steering pad on constant radius (R=10-40-100 [m]) with constant acceleration/deceleration

To qualify the reaction of the car during the power off, the ISR index will be used. This index takes into account the yaw and sideslip response after the throttle transient, and the higher is the index value, the better is the response of the car in terms of deviation from its original path.

SIMULATION TOOLS

The all wheel drive layouts in study are evaluated as described below (see figure1) by the use of softwares developed at Centro Ricerche Fiat, each of them dedicated to particular performances (figure 5).

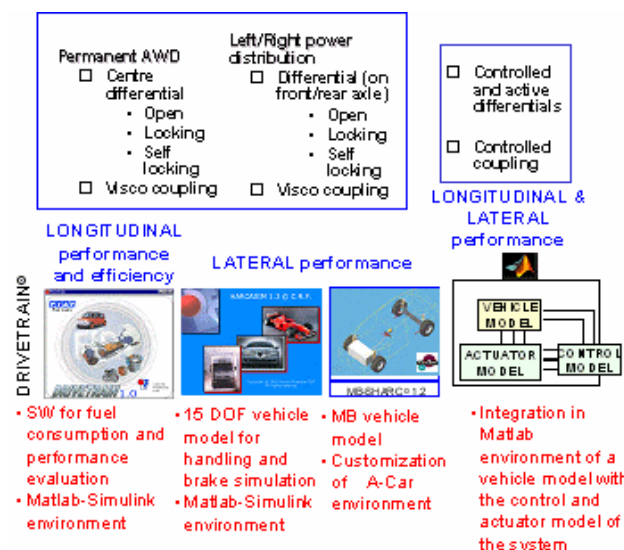


Figure 5: Simulation tools

DRIVETRAIN© is a software of Centro Ricerche Fiat, written in Matlab environment. Its goal is to estimate longitudinal performances and fuel consumption of a car. Harcasim© code is a 15 DOF model to simulate the lateral dynamics in Matlab/Simulink environment. It is under constant development at Centro Ricerche Fiat. All maneuvers necessary to evaluate IQH index are available in Harcasim© code, so starting from the vehicle general data (dimensions, weight, suspensions characteristics, tyres characteristics), a complete simulation can be done. MB SHARC© is an integrated handling and ride comfort environment based on multibody vehicle modelling, born like a customization of Adams/Car, containing all the IQH maneuvers. These tools are very useful to examine the AWD archetypes to provide a ranking: with DRIVETRAIN© it is possible to optimize the torque distribution (front/rear or left/right) and the locking factors to obtain the best longitudinal performance. Then, by HARCASIM© code the impact of this choice on the lateral dynamics is evaluated. If a zoom on a vehicle subsystem is needed, MB SHARC© multibody vehicle models are usually used. Nowadays, the application of active systems in all wheel drive archetypes is more and more diffuse, so the integration between actuators/controls and the vehicle model is necessary. Matlab has been chosen to melt together these aspects, providing an integrated environment to evaluate the active subsystem contribution to the handling behaviour of the car, once the actuators models and controls algorithms are known. This task in particular is described in this paper: two layouts with active rear differential are compared to the same passive ones.

ALL WHEEL DRIVE SYSTEM ANALYSIS: APPLICATION

This example regards an application to a virtual upgrade of an Alfa Romeo car, the characteristics of which are represented in figure 6.

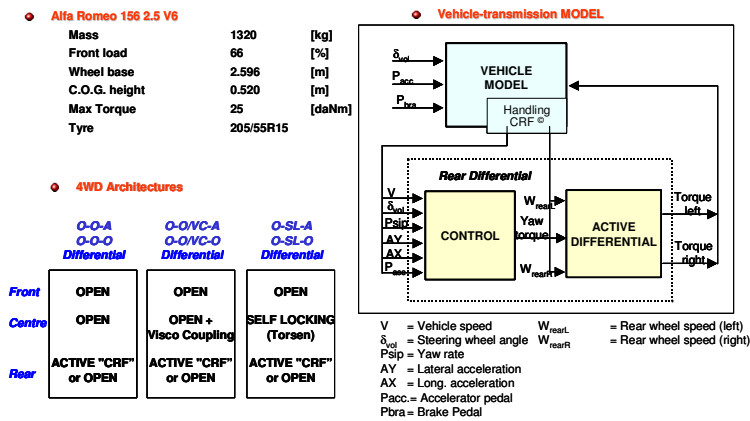


Figure 6: Application of system analysis - layouts

The reference vehicle is front axle drive and both suspensions and tyres characteristics are known. The

first layout upgrade is to consider the vehicle as a 4x4 one, with three open differentials or the active differential on the rear axle. The second layout presents a visco coupling at center and open or active on the rear, then the last has a self locking (Torsen) on the center and an open or the active on the rear. Since the active differential is composed by actuators and controls, the integrated Matlab environment has been necessary to do the analysis (as shown in figure 8 and explained below). The first task examined has been the traction capability by DRIVETRAIN © software, as shown in figure 7.

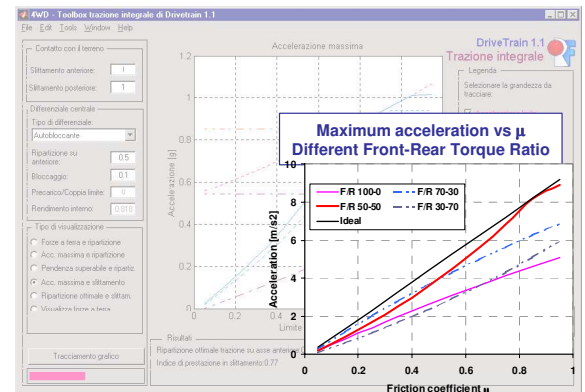


Figure 7: Traction capability: front/rear torque transfer

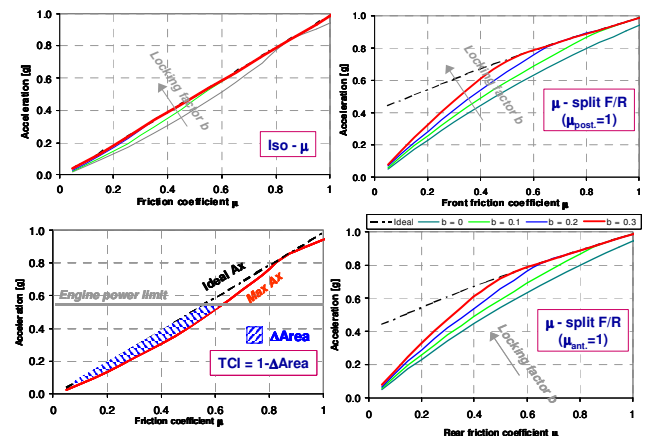


Figure 8: Traction capability – Central differential locking factor (torque rate = 50%)

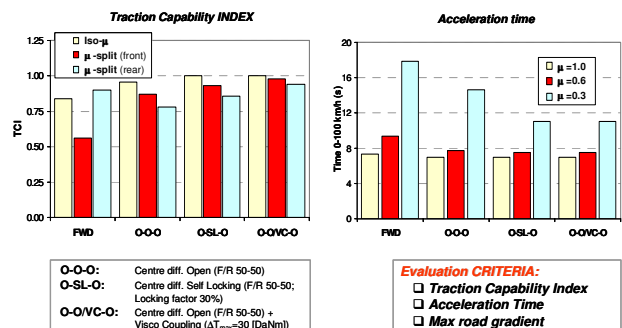
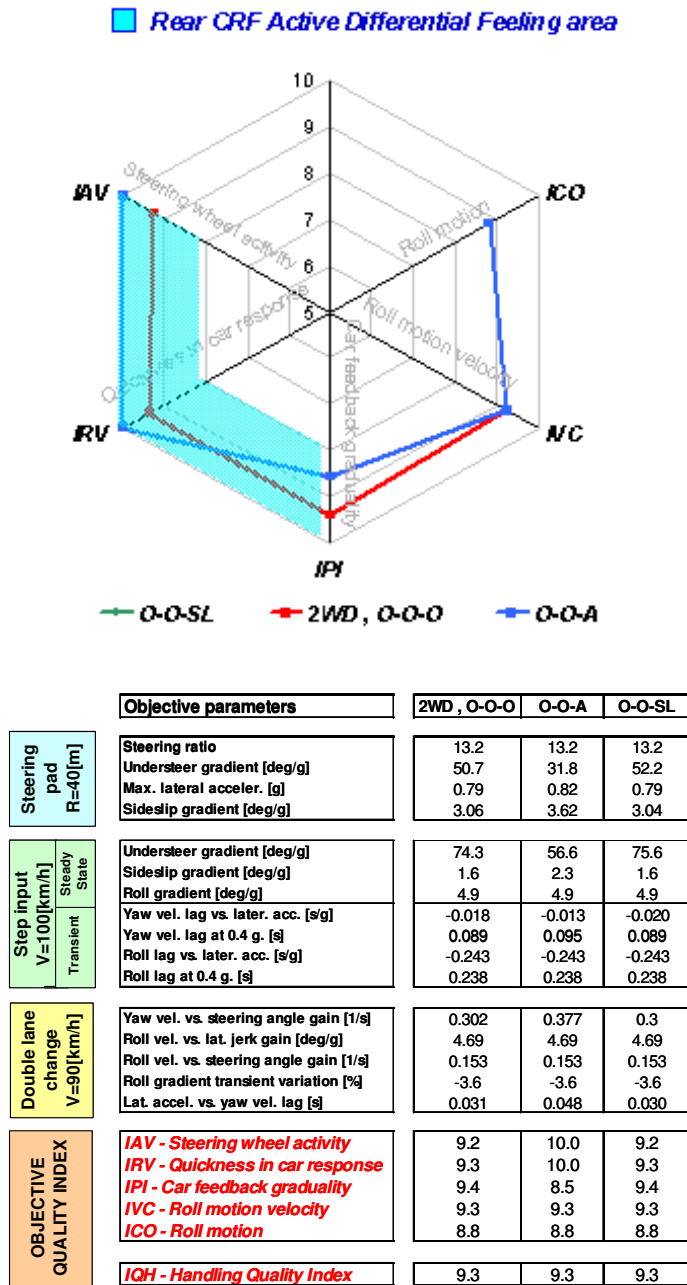


Figure 9: Traction capability – Ranking

Considering the (μ, ax) charts and the TCI index as indicators of the performances, the different layouts have been compared. When the central diff is a self locking,



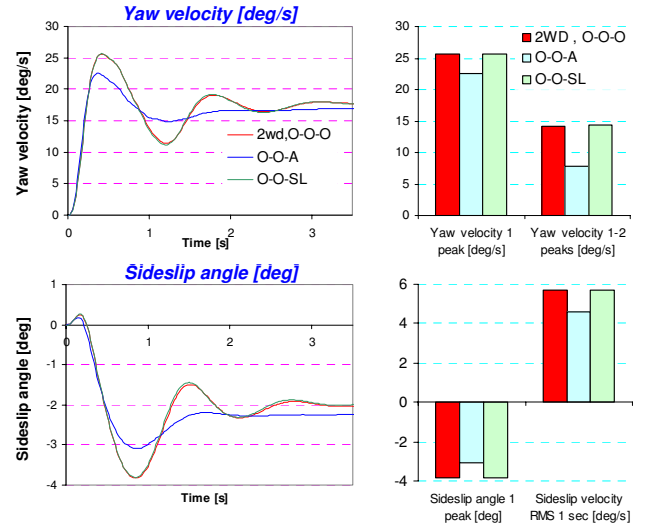
Evaluation CRITERIA:
☐ IQH values **IQxx Finger Print**

Figure 10: Lateral dynamics - IQH approach

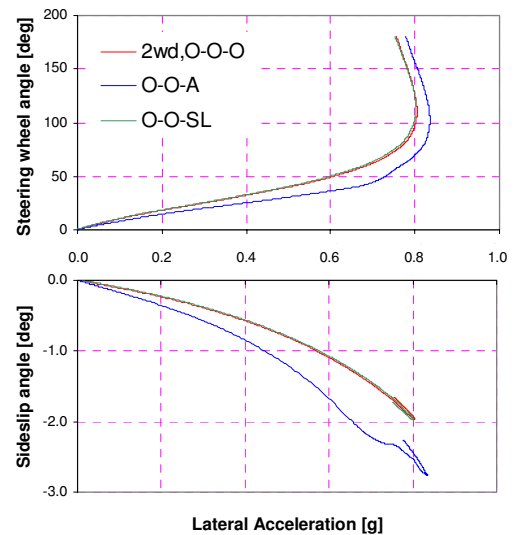
the 50% torque rate is decided, based on the weight balance and the geometry of the car, and the locking factor can be optimized for this mission: in figure 10 a comparison with different locking factors is shown. In the (μ, ax) graph, it is shown that increasing the locking factor is useful to reach higher performances, both on iso- μ conditions and μ -split ones. Also the TCI index (see figure 9) and the acceleration time (0-100 km/h) show a strong increasing as the locking factor increase.

When the visco coupling is present at the center, TCI index is the best in all situations, while the layouts with active rear differential are expected to be more powerful in lateral and cross coupling situations. Thus, basing the performance evaluation on the TCI index and acceleration time, once known the future mission of the car (sport car, sport utility vehicle etc..) the first tuning of

Step steer input at high lateral acceleration



Slow ramp steer



Evaluation CRITERIA:
 > Slow ramp steer: steerability, maximum lateral acceleration, maximum sideslip angle
 > Step input: peaks values, peaks values ratio, RMS values

Figure 11: Lateral dynamics – active safety (limit)

the powertrain can be done. Next step is to evaluate the influence of the chosen layouts on the lateral dynamics. As explained below, this can be done by IQH index (see figure 10). In the spider graph, it is shown that the passive layouts cannot change the feeling area: in fact, the 2WD vehicle has the same handling perceived quality of the passive 4WD car with three open differentials or with a self locking on the rear axle. This is because the engine torque required to complete the IQH maneuvers is just a little amount of the maximum one,

so the differentials cannot transfer torque enough to create a significant yaw momentum. This results in a similar behavior between 2WD car and passive 4WD. The presence of the active differential on the rear allows to obtain different perceived handling and, depending on the control algorithm, all the filled area of the spider graph can be modified. This is because the device is able to transfer torque from one to the other rear wheel, regardless the engine torque, and this results in a significant yaw moment which can heavily modify the perceived behavior of the car. The same effects are shown at the limit, where the 4WD active vehicle has different response with respect to 2WD or passive 4WD (see figure 11). In the step steer at limit, it is clear that the active vehicle has the lowest amplitudes and frequencies of yaw oscillations; sideslip peak value is lower than the 2WD's one. This is because the passive layout cannot create a yaw momentum, as the active layout can do. The 4WD active vehicle has the highest values of lateral acceleration, but the higher values of sideslip angle too. In conclusion, at the limit the passive 4WD vehicle is really similar to 2WD one, in term of oscillations, maximum lateral acceleration and maximum sideslip angle values. If the active differential is mounted on the rear axle, the vehicle behavior could heavily change, and the changes may be optimized by the tuning of the active system control. When the cross coupling behavior is in study, two are the interesting tasks to study: the traction capability and the reaction of the car in a tip in/out in a turn. In this application, the first

than 0.6 [g]). If the car were 4WD with three simple open differentials, the performance would increase strongly: understeer became lower and limit lateral acceleration higher than in the first case.

The same performance were obtained if a central visco coupling were used. Passing to an AWD active layout, the understeer still decrease and lateral acceleration reaches the highest values when the central differential is a self locking one. This analysis shows that a great improvement of performance could be obtained passing from 2WD to a simple AWD layout. If the AWD architecture became more complicate, then the performance could be improved. To quantify the traction capability, the lateral acceleration at maximum longitudinal acceleration is usually calculated. Speaking about power off in a turn, the layouts in study have been compared as shown in figure 13. In the upper part of it, the time histories of yaw rates are shown, consequently to the power off. The 2WD car time history has a peak and then a drift, both due to the power off. The passive layouts shows the typical reaction to the throttle release: the car tends to reduce the bend radius. This behavior becomes more and more critical when the car is four wheel drive, in particular if a self locking differential is mounted at the center, as shown by the ISR index.

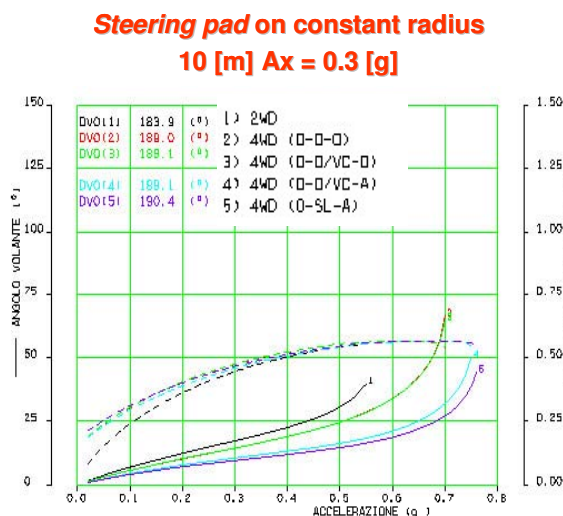


Figure 12: traction capability in a turn

task is studied through steering pad on constant radius, with constant acceleration. This particular procedure consists in performing a quasi static analysis at constant radius with a constant (positive or negative) longitudinal acceleration. This approach is very useful to simulate the cross coupling, even if it is not suitable during track tests. Figure 12 shows four AWD layouts compared to the 2WD car in a 10 meters steering. The dotted lines represent the steer wheel torque required, while the solid ones represent the steer angle vs lateral acceleration. The 2WD vehicle has the highest understeer and the lowest lateral performance (maximum value of A_y is less

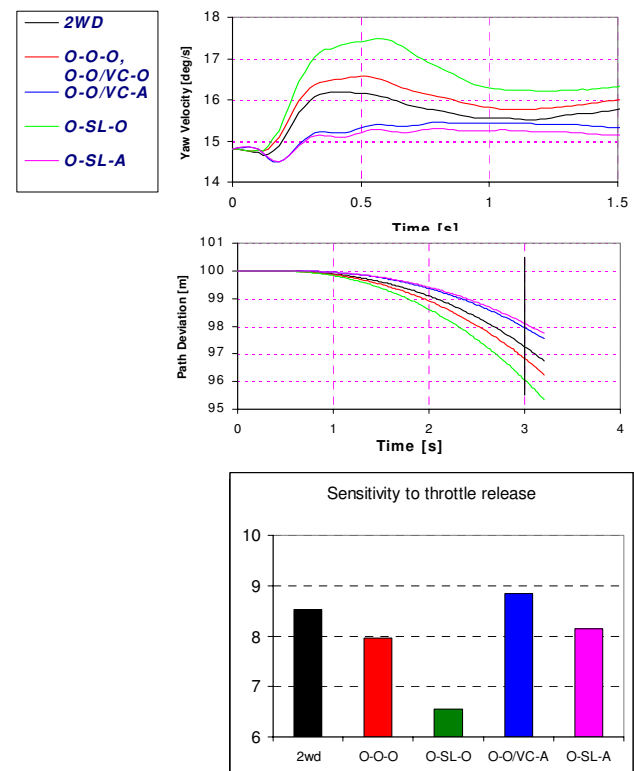


Figure 13: Power off in a turn

If the car has three open differentials, the locking is impossible and the handling of the car is similar to the 2WD's one. In fact if a visco coupling is present, since no slip is detected the car behaves like a 4WD with three open differentials, or, in other words, like the 2WD car. If an active differential is present on the rear axle, the car behavior is heavily changed, as shown in figure 15, by

the tuning of the active system parameters. In the lower figure 15, the radial change in radius due to the throttle release is shown: the plot helps to quantify how the passive 4x4 cars follows a different path with a smaller radius than the 2WD, while the active archetypes show particular reactions, due to the control setup.

APPLICATION CONCLUSIONS

The analyzed archetypes has been classified in terms of longitudinal, lateral and cross coupling behavior, through the described performance indexes and the final ranking is shown in figure 17. With respect to the 4WD-three open differential, the analysis has shown:

- Longitudinal performance:

The presence of a self locking or visco coupling on the center allows better performances in all conditions (except in left right split, because of the layout). If the central device is a free differential or a self locking, the performances in the left right split are increased because of the device torque transfer in such conditions.

- Lateral performance on high grip:

Only the presence of the active device on the rear allows to change both the normal driving feeling and the active safety. In particular, this device permits a tuning of the vehicle response, based on the control strategies. If a central self locking is present, the performance at high lateral acceleration becomes worst, because of a loosing in stability, due to locking phenomena.

- Cross coupling:

The central self locking increases the power on performance, but the reaction in power off becomes worst. The active device increases a lot steerability (power on), stability (power off) and permits to personalize the car response.

CONCLUSIONS

A methodology for the comparison of longitudinal and lateral performances of two AWD vehicles, in terms of maneuvers and significant parameters, has been developed. Software standard procedures for AWD performances virtual evaluation has been created. These results help to start up and optimize:

- Vehicle system analysis using simulation model and standard procedures to classify different AWD architectures;
- Target setting-deployment-achieving in order to traduce AWD vehicle performance in terms of architecture choice and component specifications.

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AWD Configurations positioning vs O-O-O

		O-SL-O	O-OVC-O	O-O-SL	O-O-A
LONGITUDINAL Performance	Iso - μ	+	+	=	=
	μ -split (F/R)	+	++	=	=
	μ -split (L/R)	=	=	+	+
LATERAL Performance	Normal driving FEELING	=	=	=	++ Feeling personalization
	Critical situations ACTIVE SAFETY	=	=	-	++ Higher lateral acceleration Increased stability & steerability
CROSS COUPLING Performance	Power on in a turn	+	=	+	++ Higher lateral & long. performance Increased steerability Power on vehicle response person.
	Power off in a turn	-	=	-	++ Increased stability Power off vehicle response person.

Figure 14: Performance comparison