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Passenger car steering pull and drift reduction considering suspension tolerances

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Passenger car steering pull and drift reduction considering suspension tolerances

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Abstract. Pull to side, Steering wheel misalignment and Drift leeward are handling anomalies affecting passenger cars travelling on straight paths. They represent a cost factor in the automotive industry, occurring in small but not negligible percentage of the overall car production. The present contribution is aimed at understanding which are their causes in terms of suspension tolerances, and at reducing their extent, in the specific case of vehicles with front Double wishbone suspension and rear Five arms suspension. The most influential parameters on handling irregularities have been identified through a design of experiment analysis. Then, after performing a sensitivity analysis by multibody virtual modelling, a correlation with experimental data from presetting and wheel aligner benches has provided sufficient information for setting tolerance thresholds, able to keep the handling anomalies under study within acceptable bounds. Pull to side and Steering wheel misalignment have been found to be mainly related to the set up phase of wheel angles (front camber angles influencing Pull to side, front and rear toe angles influencing Steering wheel misalignment), while the main cause of Drift leeward has been identified with (rear) ride steer.

1. Introduction

Among handling anomalies affecting passenger cars travelling on a straight path, the Pull to side (PTS, lateral deviations from straight trajectory with steering wheel correctly aligned), the Steering wheel misalignment (SWM, straight trajectory with steering wheel not aligned) and the Drift leeward (DL, lateral deviations due to the effects of uneven ground surface on the rear suspensions) are particularly relevant. Even though they do not constitute safety problems, however they represent a cost factor in the automotive industry, occurring in small but not negligible percentage of the overall car production.

Several studies are devoted to investigate the contribution of tyre characteristics on Pull to side and Steering wheel misalignment (also referred to as drift). Among them, [1] presents steering pull as an effect of asymmetrical tyre cornering; [2] describes a method for measuring residual aligning torque, as a predictor of tyre contribution to steering pull; tyre–induced pull and drift problems are respectively discussed also in [3–5], with special emphasis on plysteer, and [6–7]; while in [8] a specific analytical model is developed, aimed at studying the effects of tyre asymmetric characteristics during straight–ahead running.

On the other hand, the literature aimed at investigating the contribution of tolerances of suspension systems on Pull to side and Steering wheel misalignment is less extensive. The analysis presented in [9] is focused on a simulation–based dimensional tolerance optimization process, to minimize vehicle pulls by reduction of dimensional variation in a front suspension system. A computational method is proposed in [10] to evaluate the impact of dimensional variations on vehicle steering pull, in the specific case of front Mac Pherson suspension and rear Twist bar suspension. In [11] an analytical vehicle model and a full–vehicle model are considered, for studying the effects of suspension geometry on steering pull and drift (i.e. Steering wheel misalignment). A robust design optimization method to reduce steering pull phenomenon is presented in [12], considering tolerance of suspension system elements, such as hard points, spring, damper and bushings. Clearly, these issues also have an impact on the design of control systems, such as active front steering control [13], as well as on steering performance of particular classes of vehicles, like autonomous drive vehicles [14] and ultra–light cars [15-17].

The present contribution is focused on understanding which are the causes and on reducing the extents of PTS, SWM and DL as handling anomalies due to suspension component and assembly tolerances, in the specific case of vehicles with front Double wishbone suspension and rear Five arms suspension [18]. The vehicle assembly process is first analyzed in terms of errors and tolerances by means of a design of experiment analysis (DOE), aimed at identifying which parameters generate PTS, SWM and DL. A sensitivity analysis by multibody virtual modelling is then performed, aimed at understanding how and at which level the relevant suspension parameters can affect the straight path handling of the vehicles under study. Finally, the results of simulations are correlated with experimental data from presetting and wheel aligner benches, for setting tolerance thresholds able to keep the anomalies under study within acceptable bounds.

2. Design of experiment analysis of the assembly process

Two vehicle models have been considered, with suspension systems of the same typology. A design of experiment (DOE) analysis has been performed aimed at understanding the role of tolerances on specific parameters that can affect handling behaviour. More in detail, displacements of the suspension hardpoints with respect to their ideal position (in a chassis reference system) have been estimated as functions of combined tolerances due to both component tolerances and coupling tolerances.

A two–wheel steering vehicle travels on a straight path if the average of slip angles at the front axle is equal to that at the rear axle. Since slip angles differ from toe angles because of tyre deformation [19], in this study the crab angle (δ_t) of an axle is considered, representing the contribution to the axle slip angle given by the toe angles of the two wheels (say, δ_1 and δ_2):

$$\delta_t = (\delta_1 - \delta_2)/2 \qquad (1)$$

where δ_t takes the sign of δ_1. While on the rear axle the toe angles are imposed with respect to the mechanical symmetry axis (i.e. the axis passing by the front axle centre and the rear axle centre, which in general is not contained in the vehicle symmetry plane), the front toe angles are imposed with respect to the (rear) crab axis (defined by the rear toe angles), in order to reduce the differences between the front and rear axle slip angles.

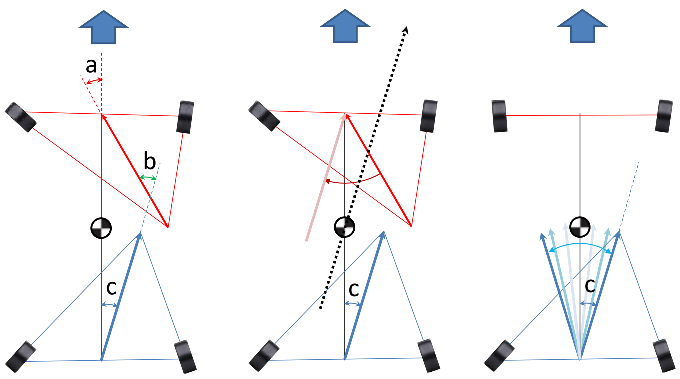

Figure 1. Crab axis (left: a = front crab angle; b = total crab angle; c = rear crab angle), SWM effect (centre) and DL effect (right).

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Clearly, PTS, SWM and DL are strongly related to the axle slip angles. PTS can occur only if the front and rear axle slip angles are not equal. SWM depends by different front and rear axle slip angles as well; in this case, however, the vehicle reacts to lateral forces due to the tyres by modifying the position of the front wheels until the front axle slip angle coincides with the rear one; consequently, the steering wheel changes its position, producing misalignment. DL can be evaluated as a dynamic variation of the rear axle slip angle, due to a vertical parallel excitation of the axle (figure 1).

The front and rear axle slip angles are also influenced by axle positioning on the vehicle's body during the mounting phase, and by different loads acting on the wheels of each axle. Therefore, vehicle's handling is affected by non–symmetric values (on the same axle) of toe angles, camber angles, lateral displacement of wheel centre, vertical loads acting on wheel, ride steer behaviour in vertical travel.
At the front axle the vehicles mount Double wishbone suspensions, as shown in figure 2 (left). During the assembly process, the anomalies that can be generated are: non–symmetric king pin axes; non–symmetric caster, camber and toe angles (the last two anomalies are generally adjusted in the final phase of the assembly process); non–symmetric lateral and/or angular (around a vertical axis) positioning of subframe with respect to chassis (compromising symmetry of the suspension mechanisms at the two sides of the same axle); different ratios between spring travel and wheel travel.

A DOE analysis has been performed on front suspension. The influence on suspension parameters of hardpoint displacements due to worst combination of tolerances are represented by histograms as those displayed in figure 2 (including numbered hardpoints, with displacements expressed in a chassis XYZ reference system; in the histograms, the percentages are defined with respect to the total variation of the parameter under study: ride steer or ride camber). Among the most influential parameters, ride steer (Fig. 3, top) is affected mainly by the Z (vertical) displacements of hardpoints 3 (lower control arm) and 2 (steering box), while the largest variation on ride camber is given by the Z displacements of hardpoints 7 and 8 (upper control arm).

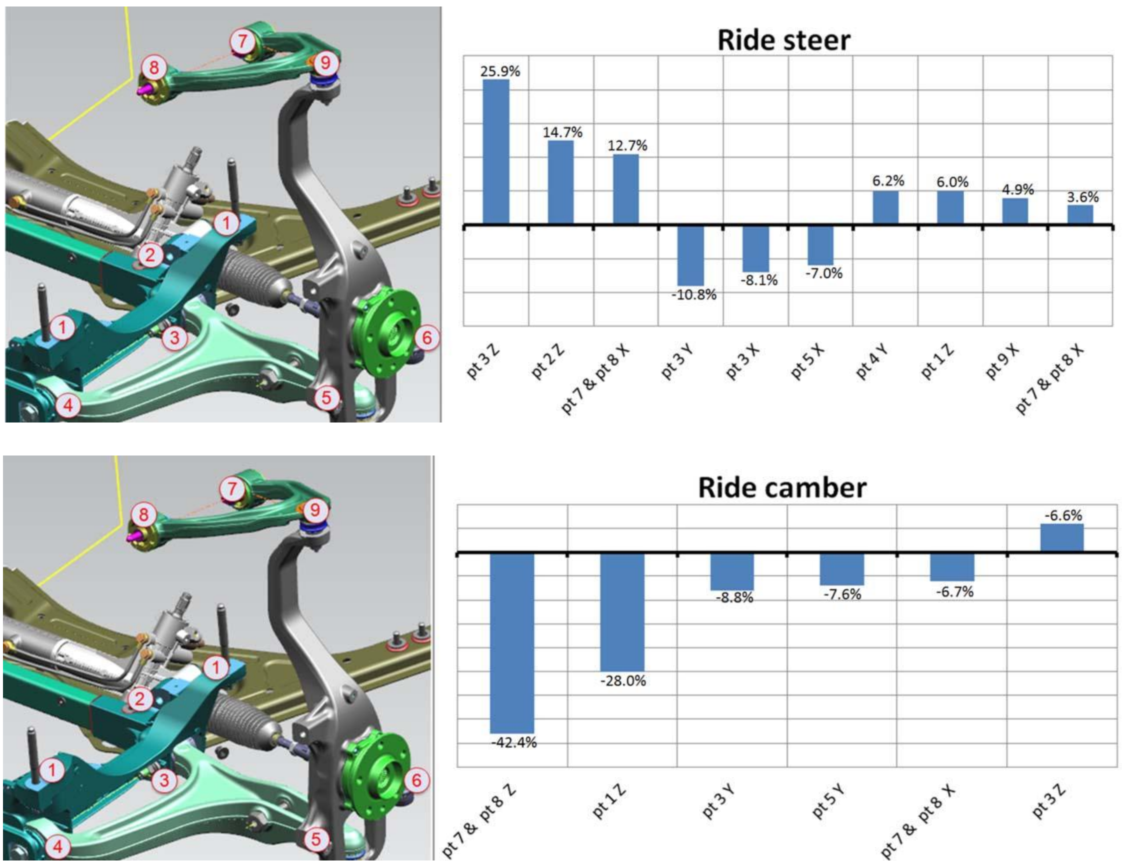

Figure 2. Front suspension: ride steer (top) and ride camber (bottom).

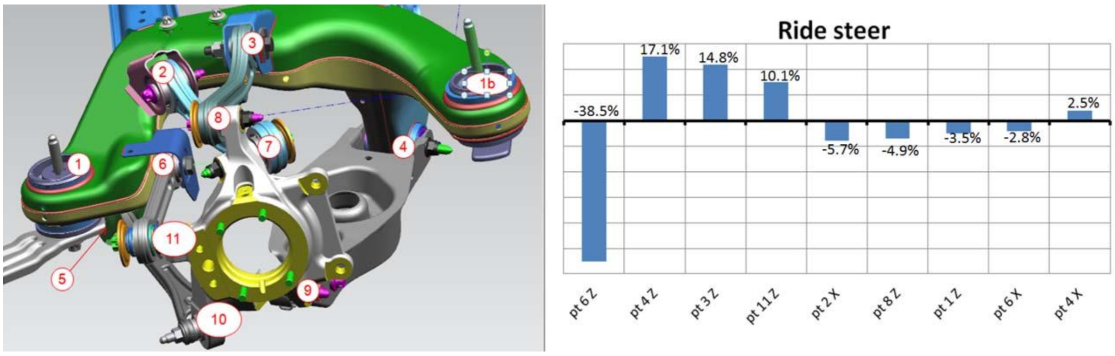

Figure 3. Rear suspension: ride steer.

At the rear axle the vehicles considered in this analysis mount multilink suspensions (Five arms), as shown in figure 3 (left). The rear suspension assembly process is a delicate matter: regulation button-holes are necessary to correctly complete the marriage procedure. A more complex DOE than that performed for the front suspension lead to histograms like the one represented in figure 3, showing the contribution of rear suspension tolerances on the ride steer (percentages defined with respect to the total variation of ride steer). The latter parameter is affected mainly by Z (vertical) displacement between hardpoints 6 and 11 (tie rod hardpoints).

Chassis, front and rear subframes are the main subsystems composing a full vehicle: they are connected together during the marriage, or coupling phase. Chassis can be affected by mass distribution anomalies (generating non–symmetric downforces on the wheels on opposite sides of the vehicle) and by geometric anomalies (twisting and bending; only the former is relevant within the present analysis, since it can cause different preloads on the opposite wheels of the same axle, and consequently different travel positions of the two suspensions). During subframe assembly process, there are two critical phases, potentially generating the anomalies under study: marriage and wheel alignment (last phase of assembly process, in which a vehicle complete in all its parts is positioned on the wheel aligner bench for setting the toe and camber angles of the front and rear axles). If the chassis is symmetric and not twisted, possible errors during marriage can lead to axle centre out of the chassis symmetry plane and non–parallel axles in lateral direction. On the other hand, during wheel alignment, possible errors can originate from incorrect wheel scanning on the aligner bench (the laser scanning process identify the wheel centres, along with toe and camber angles; from wheel centres, the positions of the two axles are determined, and consequently the vehicle mechanical symmetry plane, which, depending on the marriage phase, not necessarily coincides with the chassis symmetry plane). During the final setting of toe and camber angles, attention must be paid in avoiding any possible contribution yielding preloads on the elastic components, which after regulation would affect the setup.

3. Virtual simulation

After DOE analysis, a virtual sensitivity analysis has been performed using a multibody code (MSC Adams Car), aimed at understanding how and at which level the relevant suspension parameters can affect the handling on a straight path of the vehicles under study. Straight line manoeuvers have been simulated at an imposed vehicle speed of 100 km/h. Both a perfectly flat ground surface and a standard highway surface profile have been considered, the latter for taking into account vertical excitation due to irregularities of the ground. For PTS contribution, the steering wheel has been locked to 0°; while for SWM contribution, the steering wheel has been set free to rotate.

To evaluate the effects of asymmetry involving toe angles (front toe with respect to crab axis), camber angles, and lateral displacement of wheel centres, different hard–point configurations have been considered, in each case imposing the maximum tolerance differences found by DOE analysis; for vertical load asymmetry, different preloads have been imposed on the springs of the same axle; for different ride steer on the two wheels of the rear axle, the worst case evaluated with DOE analysis has been considered (largest error due to component tolerances), yielding different hard–point positions, and consequently different elasto–kinematic behaviours of the two rear suspensions.

Vertical load asymmetry on the front axle suspensions has been simulated by imposing a 6% difference in nominal preload on the two front springs, causing a displacement of centre of gravity from the symmetry plane, and consequently a lateral deviation of the vehicle (less than 5 mm over a 300 m travel) and a rotation of the steering wheel (lower than 2%). Asymmetry due to front subframe marriage errors has been simulated by imposing lateral displacements of lower control arms, and consequently of wheel centres (notice that after creating this asymmetry, camber and toe angles have been perfectly regulated), resulting in very small effects on PTS and SWM.

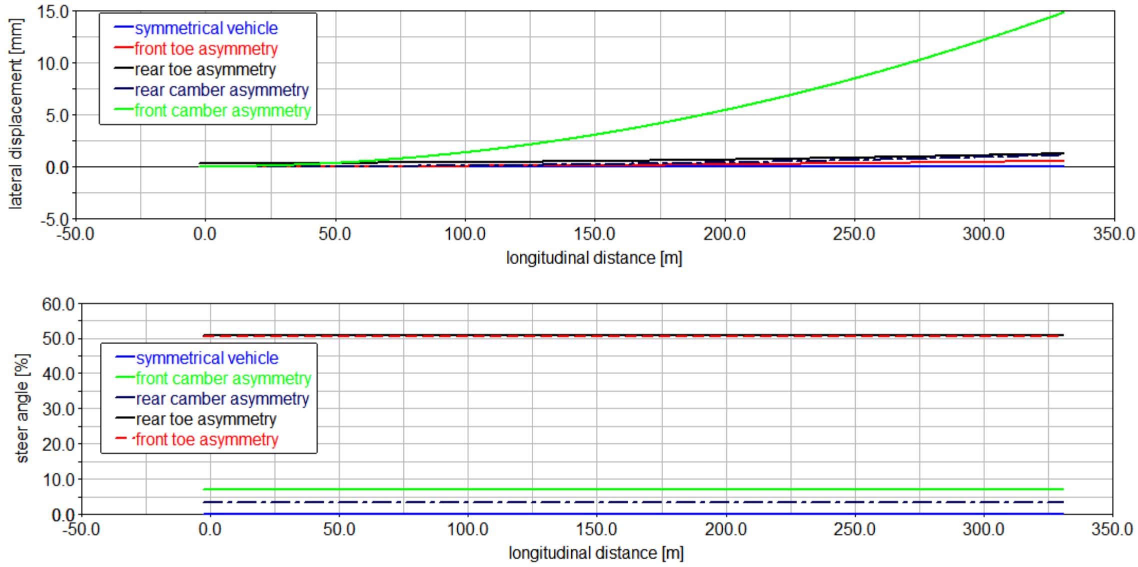

Figure 4. Effect of asymmetric camber and toe angles on lateral deviation (top) and steering wheel rotation (bottom).

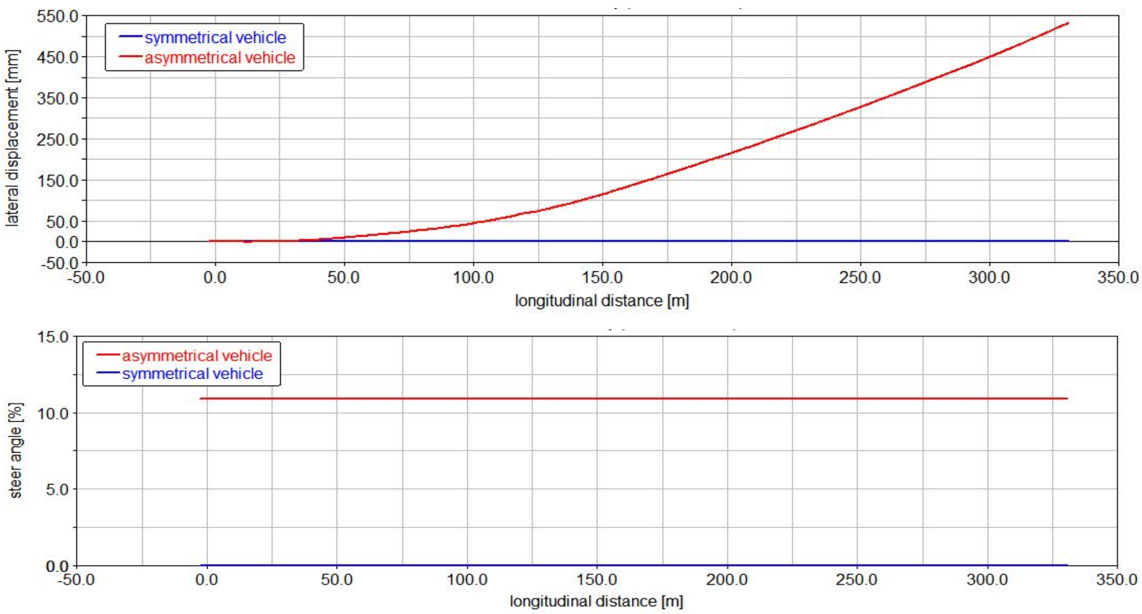

Figure 5. Effect of asymmetric rear axle ride steers on lateral deviation (top) and steering wheel rotation (bottom).

Asymmetry in wheel angles setup phase (camber and toe) is the most important one for investigating the anomalies under study. As shown in figure 4 (top), an asymmetrical regulation of the front camber angle produces the highest PTS effect on the vehicle (in fact, at low slip angles, camber variations are particularly effective on tyre lateral forces). As regards SWM, the front and rear toe angles have been recognised as the most influential parameters, as shown in figure 4 (bottom).
Different ride steer on the two wheels of the rear axle has been simulated by imposing the largest errors on hardpoint positions due to component tolerances (presetting process), while keeping camber and toe angles perfectly regulated (perfect static wheel setup). In this case anomalies occur only in presence of vertical oscillations of the suspensions (figure 5).

4. Experimental tests on presetting bench and wheel aligner bench

The vehicle assembly process has been improved by considering separately presetting bench regulation for reducing rear ride steer, and wheel aligner bench for reducing camber and toe static anomalies.

Scope of a presetting bench is imposing the correct position between rear subframe and uprights; if the components are all in tolerances, once that their relative positions are correct, also the arms will be correctly positioned. On the presetting bench only the position of part of the mechanism members is fixed, for allowing the regulation of camber and toe angles at the wheel aligner bench.

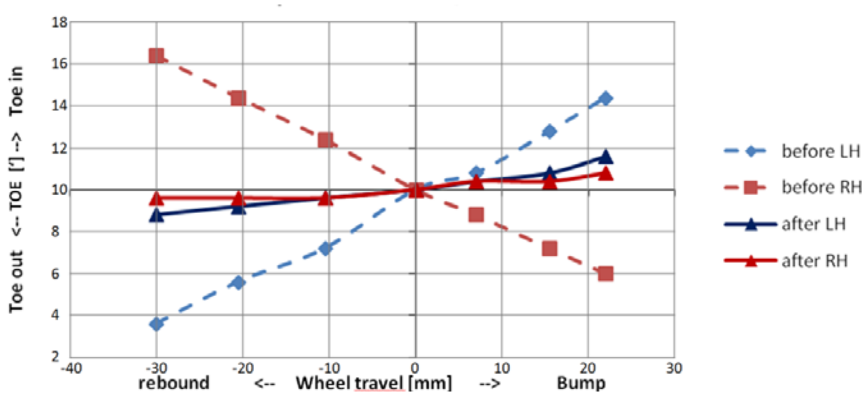

Figure 6. Toe angles [′] comparison before/after presetting regulation.

By testing some vehicles affected by DL, strong asymmetries in toe angles were detected, as shown in figure 6 (dashed lines). To evaluate whether this anomaly was related to the mounting phase or to the component tolerances, the components were disassembled to make again the mounting phase on the presetting bench. As a result, ride steer differences were strongly reduced. On some vehicles, presetting analysis was sufficient for reducing DL within acceptable bounds. On other vehicles, however, presetting analysis was not sufficient to correct this anomaly, which was caused by structural components. Consequently, a tolerance analysis has been performed for identifying the components out of tolerance.

The regulation of camber and toe angles at the wheel aligner bench is the most delicate phase during a vehicle set up. During this study, two critical aspects have been identified: correct positioning of laser scan columns on the bench, and correct locking of wheels on their supports. Regarding the first issue, it is important that the laser can scan a great surface of the tyre sidewall, in order to identify the closer point and to define correctly the centreline of the tyre. By improving sensor positioning, the reading errors of the lasers have been significantly reduced. The last phase which has been analyzed is locking of wheel supports: ideally the vehicle should be completely free, for reducing to zero bushing preloads; in practice the vehicle is locked for improving safety and reducing set up time. The improved procedure consists of locking the rear wheels while regulating the front wheels, and then locking one side of the vehicle for regulating the opposite rear wheel (in the existing procedure adopted for the production line under analysis, the front left plate was always locked, with the disadvantage of increasing preload on front bushings).

5. Results and discussion

Virtual analysis put in evidence that PTS and SWM are mainly related to the set up phase of wheel angles. In particular, both anomalies can be explained by the contribution that vehicle geometry gives to the sideslip angle. Front camber angles influence PTS, while front and rear toe angles influence SWM. Main cause of DL has been identified with (rear) ride steer, which in turn can be generated by components out of tolerances or/and presetting variation.

By improving all the set up process (presetting bench and wheel aligner bench) on a whole production line, the number of vehicles affected by PTS, SWM and DL was strongly reduced: from 3% down to about 1% of the production. Clearly, further improvements are still needed for correcting the anomalies of the residual 1% of vehicles.

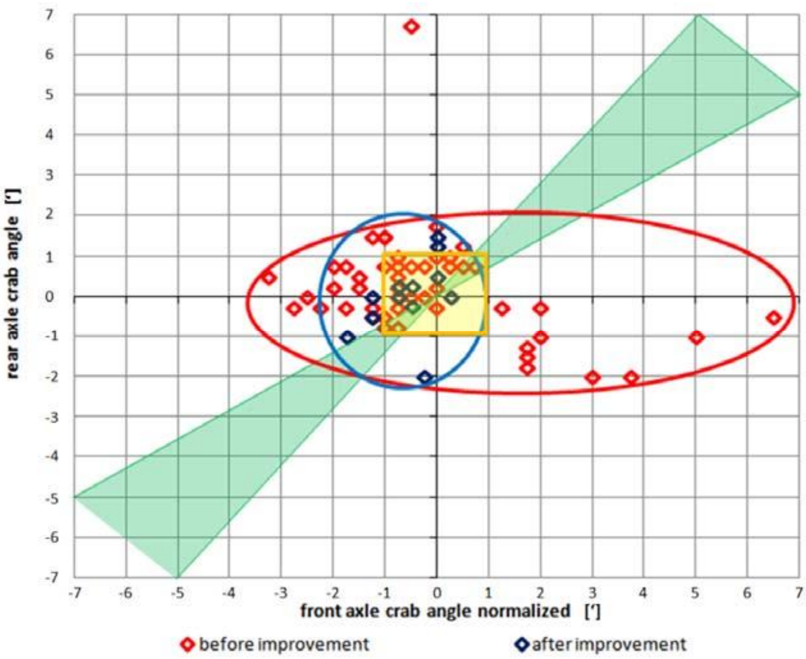

Figure 7. Crab angle [′] variation analysis.

The plot in figure 7 synthesizes the results of the present analysis, displaying a comparison of front and rear crab angles before and after process improvement, where especially the front crab angle variation has been strongly reduced. The yellow central rectangular area identifies the bounds for acceptable values (in terms of handling behaviour) of front and rear crab angles. In the diagram, the points on the first and third quadrant diagonal (equal front and rear crab angles) are acceptable in terms of handling behaviour (the vehicle travels on a straight trajectory); actually, also points close to these diagonals are still acceptable (green triangular areas).

6. Conclusions

In this study three relevant handling anomalies affecting passenger cars travelling on a straight path have been studied: Pull to side, Steering wheel misalignment and Drift leeward, in the specific case of vehicles with front Double wishbone suspension and rear Five arms suspension.

After analyzing the vehicle assembly process in terms of errors and tolerances to identify which parameters can actually generate these handling irregularities, sensitivity analysis by multibody virtual modelling, and subsequent correlation with experimental data from presetting and wheel aligner benches, has provided sufficient information for setting tolerance thresholds, able to keep the handling anomalies under study within acceptable bounds.

In conclusion, it can be stated that Pull to side and Steering wheel misalignment are mainly related to the set up phase of wheel angles. Front camber angles influence Pull to side, while front and rear toe angles influence Steering wheel misalignment. Main cause of Drift leeward has been identified with (rear) ride steer, which in turn can be generated by components out of tolerances and presetting variation.

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