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EVALUATION OF A CONCEPTUAL VEHICLE STEERING SYSTEM FOR INDEPENDENT WHEEL CONTROL

Summary. This paper presents a brief description of an unconventional steering system involving electronic stability control and its influence on vehicle motion. The proposed configuration enables individual changes in steering angle for each single wheel, in contrast to the mechanical linkage solution. An analysis of vehicle behaviour during emergency braking on a heterogeneous surface is conducted, especially with regard to the undesirable rotation of the vehicle body. The benefits of using this active steering system, implemented in the steer-by-wire mode, are characterized, while the problems for further consideration and the potential benefits of such a solution are described.
Keywords: steer-by-wire, drive-by-wire, Ackermann geometry, independent four-wheel steering, toe angle, vehicle steering, cornering control

1. INTRODUCTION

The number of vehicles used across the world is constantly growing at a very fast rate. This causes several complications related to safety, infrastructure, environmental pollution, financial cost (purchasing, operating, recycling), social and medical problems. One of the most important issues is the active safety of a car. This area of research is still in the phase of intensive development among automotive manufacturers, given that customers constantly replace their vehicles in search of more state-of-the-art requirements.

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2. ACTIVE STEERING SYSTEMS

One of the most significant aspects of active safety involves the design of the steering system, which has undergone significant changes in recent decades. Among the changes has been power steering, which is commonly used nowadays. It allows less restricted adaptation of wheel geometry, self-aligning torque, tyre width (friction during rotation at standstill) and steering ratio over an entire or partial range. Some systems are able to facilitate self-manoeuvring (e.g., Autonomous Park Assist). Another implemented solution, albeit much less common today, is the possibility of linking the steering wheel with the rear axle, which can be done in a passive way. For example, the angle of the axis of rotation (connection to the structure) of the rear wheel's control arm can be designed in such a way that, when the forces resulting from the cornering occur (load down at the vehicle's external side, centrifugal force), the angle of the wheel remains appropriate. This solution is widely used in many commercial cars [6]. For the Porsche 928, a solution called the Weissach axle was used to control the angle of the wheel during cornering and decelerating in order to create a lateral force on the rear axle. Through such operations, an understeer gradient can be shaped in some situations. Obvious examples of passive steering are a trailer and an articulated bus. That said, in this paper, the focus is on vehicles with two axles. Currently, some systems available on the market are able to actively control the rear axis wheel's steering angle in a comparable way to that for the front wheels, e.g., those of Renault 4Control (Talisman, Laguna), Delphi Quadrasteer (Chevrolet Silverado) and Nissan HICAS, as well as solutions designed by Toyota and Honda. Typically, the actuator facilitates power steering in the front axis either electrically through a rack and pinion or hydraulically. At low speeds, for example, during a parking manoeuvre, the front and rear wheels twist in opposite directions. This reduces the turning radius of the vehicle and, most importantly, the necessary space in which to make a turn. While driving at higher speeds, all the wheels twist in the same direction, which improves overall stability because the car does not rotate so intensively around its vertical axis. The advantages of the active system, compared to the passive one, are as follows: a wider range of possible steering angles of the wheel, the possibility of adjusting the direction, and the value of turning to the current undesirable kind of slip (understeer or oversteer, specified by the electronic traction control and its work characteristics). The tendency to understeer or oversteer is varied due to factors that cannot be foreseen at the design stage, such as the state and geometry of the road surface, the characteristics of the tyres, the distribution and value of the vehicle load, the longitudinal force of each tyre (braking or accelerating), cornering and the dynamic state of the whole vehicle body, and the unsprung mass. Another possible steering modification is when the steering angle of the front wheels, resulting from the current angle of rotation of the steering wheel (rudder), adds or subtracts a certain value by summing the planetary gear. This can be used to implement the variable steering gear ratio depending on driving conditions and driver preferences and based on the data collected by the electronic stability control and a special algorithm, e.g., BMW Active Steering.

A crucial issue is the shape of steering linkage geometry, which binds the rotation angle of one wheel (relative to the pivot angle) with an equivalent angle of the second wheel on the same axle. The starting point for further consideration is Ackermann geometry, which ensures the correct kinematics of the wheel, i.e., lines that are perpendicular to the free rolling direction of all four wheels (on the ground/road plane) starting at the points of contact that intersect with the ground at exactly one point. In fact, there are exceptions from this principle [7], especially due to a greater downward force on the vehicle's outer side during cornering, making it possible for larger centrifugal forces to transfer. The dependence of the lateral force generated by the tyre, which (in the absence of other excitations) is mainly the centrifugal one, depends on the wheel sideslip angle, that is, the difference between the velocity direction and the direction of free rolling. The maximum value of the lateral force, which is possible to transfer, increases with the vertical load exerted by the body of the car (gravity force and accelerations). The steering linkage geometry should be designed with respect to the above-mentioned issues and provide the widest possible range of steering angles in order to reduce the minimum turn radius. Usually, while tight cornering at low speed, kinematic inconsistency occurs, which results in a higher rolling resistance and increased tyre wear. The steering linkage geometry is always a compromise between many different desired characteristics. To find the optimum angle of each of the two steered wheels, at an arbitrary turning radius, it is necessary to know, among other things, the mass distribution of the vehicle, the state of its longitudinal motion (speed, acceleration, deceleration) and the dependence of the lateral force transmitted by the tyre from the vertical load and longitudinal force, as well as other characteristics of the suspension, its kinetics, including elastokinematics, the road profile and surface type. Not all of them can be predicted at the design stage, so it is proposed to consider a system that allows for the independent control of the steering angle of the left and right wheel. Such a solution is possible only in drive-by-wire architecture by implementing computer-controlled actuators, although physical connections can be preserved as required by the law [10].

While the literature describes the testing of prototype transporter robots and cars with a four-wheel swivel [2, 5], as well as prototypes built by big car manufacturers (Toyota Fine-T, Nissan Pivo), they mainly move at low speed, with their main advantage being manoeuvrability. The following discussion focuses on behaviour at high speed under real driving conditions.

3. EMERGENCY BRAKE WITH ACTIVE STEERING

An example of a situation in which an active steering system could bring some benefit is the breaking process of a car on heterogeneous surfaces. Figure 1 shows the top view of a car moving from left to the right, performing emergency braking. The left-hand side wheels run on the surface with lower friction coefficient $\mu1$, whereas the right-hand side wheels run with coefficient $\mu2$. Such a situation may occur during partial running onto a roadside covered with snow, when the central part of the road is dry. In the following discussion, a simplified model of the tyre was used, with the assumption that the sum of the longitudinal and lateral forces transmitted by the tyre have a constant maximum value, which is represented by the vector starting at a tyre-surface contact point and ending inside a delineated circle [4]. The circle radius represents the maximum possible friction force. In the presented situation, the driver (or autonomous driving program) attempts to maintain a straight-line trajectory until the vehicle comes to a complete stop of the vehicle. Each of the four forces depicted in Figure 1 is a source of torque around the gravity centre of the car. The radii of these moments are all the same, i.e., equal to half of the axis length. However, the value of forces that tends to turn the vehicle body anticlockwise (F_{RL} and F_{FL}) is smaller than the corresponding forces at the right-hand side of the vehicle, which strives to turn it clockwise. As shown, forces acting on the vehicle cause it to rotate relative to the centre of mass, which is obviously undesirable. The first method to counteract this is a partial reduction of the braking force, especially for the more adhesive wheels. This causes a reduction in the whole body-rotating torque and allows the tyres to transmit lateral forces, which counteract the rotation. However, in this case the braking distance is elongated. The presented situation is an important issue when creating an algorithm for the anti-lock braking system's (ABS') controller. Currently available systems use advanced computational methods in order to find the optimum configuration [8]; however, there are some general principles involved. In the case of front wheels, it is desirable to achieve a maximum braking force. In the case of rear wheels, seeking to reduce the braking torque on wheels with better traction makes it possible to reduce the rotating torque and transmit a lateral force with the wheel, whose grip is not fully utilized in the longitudinal direction. This helps to maintain the car's stability.

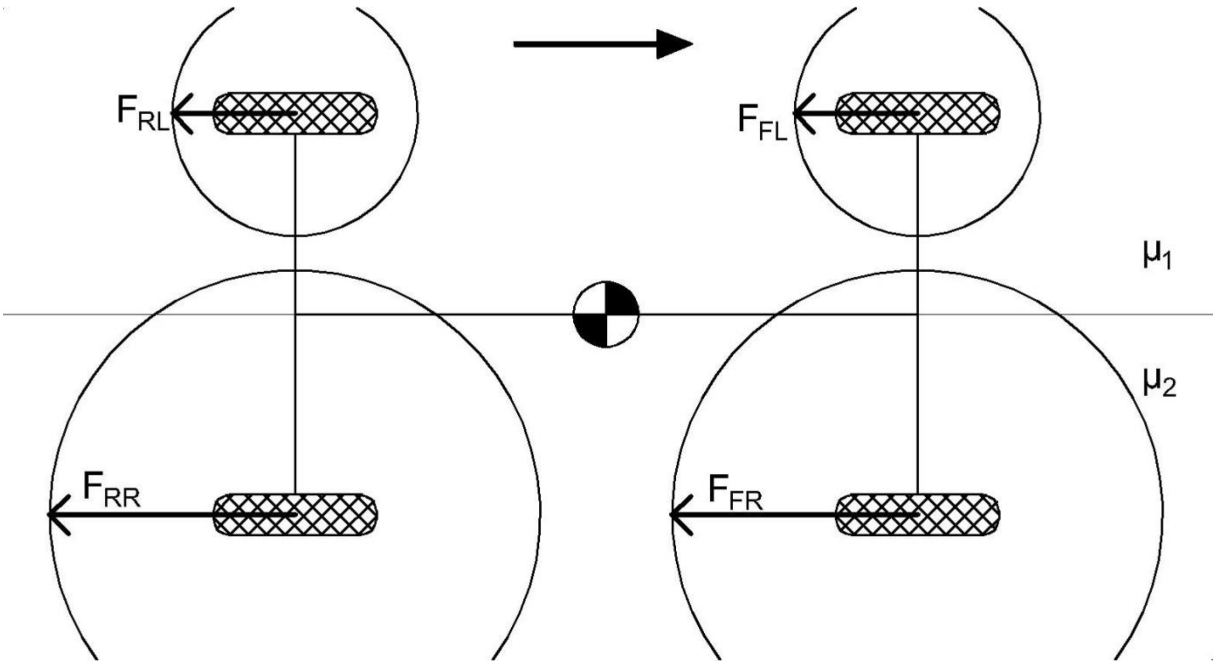

Fig. 1. Braking with a conventional system

Figure 2 shows a possible configuration of wheels in the same situation as described above, which involves the possibility of independently adjusted steering angles. In this case, the front-right wheel is set at an angle, in which the force F_{FR} is generated. It can be decomposed into the longitudinal component $F_{FR}(x)$, which causes deceleration, and the $F_{FR}(y)$ component, which counteracts the rotation relative to the gravity centre of the vehicle body. The first step is to determine the direction of force F_{FR} and thus the ratio of longitudinal to lateral forces. This should be done in a way that does not reduce the deceleration too much, while simultaneously achieving a significant contribution to the balance of torques in relation to the gravity centre. A tyre, whose direction of motion is not identical to the free rolling direction becomes a source of force $F_T(y)$. After the direction of force F_{FR} is designated, a lateral force dependence relative to the angle of sideslip for the specified tyre type and operation conditions should be used to find this angle. The camber, castor, scrub radius, forces, kinematics (including elastokinematics) and other important design features should be taken into account, as well as their current value and change during the rotation around the pivot axis. As force $F_T(x)$ results mainly from the operation of the brake system, it should be correctly set, for example, by components of the ABS and the electronic stability program in order to achieve the maximum overall wheel reaction. The total force generated by tyre F_T is of course equal to force F_{FR} acting on the vehicle body. A two-dimensional model was used, while the vertical dynamics related to the action and kinematics of suspension, were omitted. The next stage of the development, according to the presented concept, is a system with four-wheel (as opposed to only two-wheel) independent steering, in which the rear axle can be used in a similar way. The main advantage of the described solution is a significant reduction or elimination in the torque, which rotates the car's body. Such an effect may also be achieved in other ways. One possibility is an appropriate driver response, causing the steering wheel to rotate in the correct direction to counteract the rotation of the vehicle. A second solution involves the negative scrub radius shown in Figure 3, with the cross marks indicating the points where the pivot axle crosses the road level. In this situation, when the central point of application for the decelerating force generated by the tyre is not in the axle pivot, this causes a torque in the steering system, which tends to turn a wheel. If this value on both sides of the vehicle is not equal, the rotational force on the steering wheels appears in the direction of counteracting the rotation of the car [7]. This has a dual effect: firstly, the driver may need to correct the position of the steering wheel; secondly, it may cause some wheel geometry changes, as an effect of elastokinematics, which, in a predicted way, counteracts rotation, although this kind of action is obviously limited.

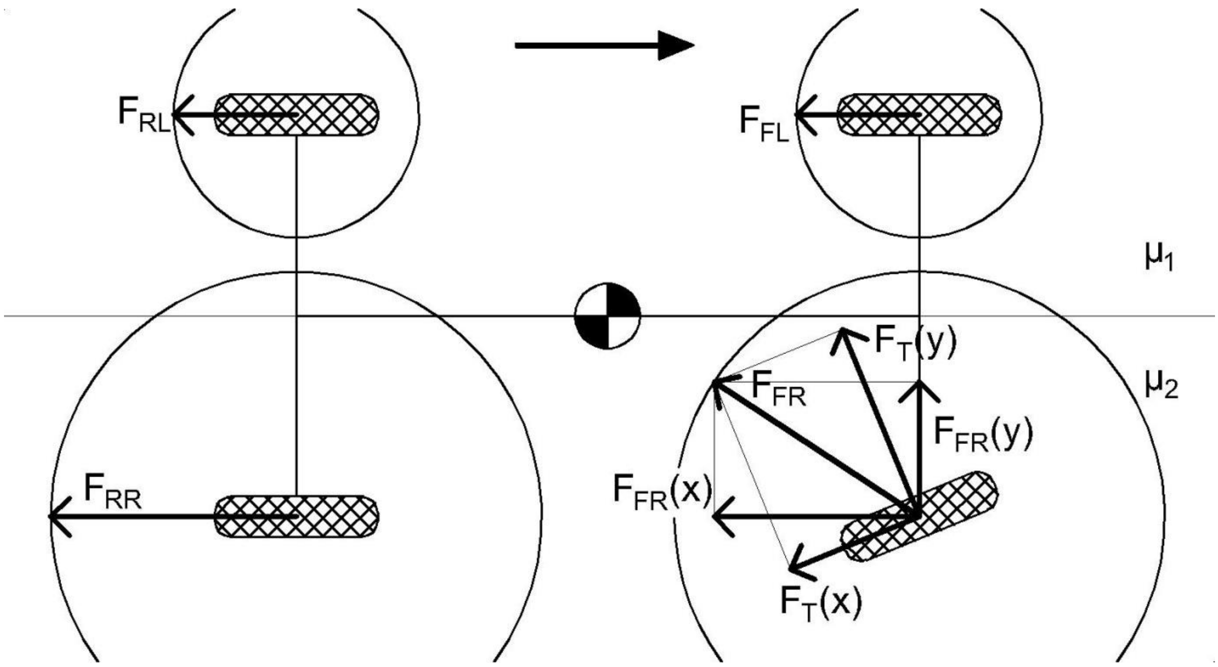

Fig. 2. Braking with an independent front-wheel steering system

As mentioned before, the advantage of the fully independent left and right steering system is to maximize the use of the longitudinal grip of the wheels on the surface with a lower friction coefficient. For a conventional steering linkage solution, the wheel with less traction also transmits lateral forces, causing a decrease in the longitudinal force maximum value, which intensifies the undesirable car torque relevant to the gravity centre. In the presented case, the steering wheel angle will be in the range of about 0-20°, given that, for standardized tyres, in this range of tyre sideslip, an increase in the lateral force up to its maximum occurs [1].

In fact, the maximum total force transmitted by the wheel as a function of this force direction is not constant, as assumed above (circle in Figs. 1-2); rather, in most cases, it has a shape that is more similar to an ellipse than a circle (higher force $F_T(y)$), as shown on the graph, which actually increase the positive effect of the proposed solution. The value of F_{FR} in Figure 2 could be greater.

The forces presented in Figure 1 are twice as strong at the vehicle's right-hand side, while the friction coefficients are also obviously 1:2 to each other. After the introduction of modifications shown in Figure 2, the torque relative to the gravity centre disappears. The moment of forces generated by the right-rear wheel and that emanating from the two left wheels are balanced. Torque from the front-right wheel is zero because of the angle (in line with the gravity centre). Therefore, it behaves in a way that is theoretically perfectly, maintaining the desired vehicle position. In the case of four-wheel independent steering, there is a possibility of changing the proportion of forces counteracting the rotation between axes. Algorithms to control this aspect should be similar to those implemented in traction control systems. The proposed system should be integrated with other systems of the car, especially the anti-lock braking. In real situations, the flexibility of components, including tyres, should be taken into account. As a result of using active independent steering, the toe angle can be constantly modified without limitation. In emergency situation, this feature, together with skid steering, can be used to safely stop the vehicle. This technique can also be used to maintain control in the case of the failure of one or more of the actuators responsible for wheel twisting, in which braking force is applied to individual wheels [9]. Currently, steer-by-wire systems are in the phase of development, including in relation to changing views, needs and limitations on the part of the driver, for example [3]. In a car with four-wheel independent steering, this is seems to be much more important issue, due to the car's less intuitive behaviour. This is not a problem in autonomous vehicles, where the proposed system could bring significant benefits. Independent steering can be used to automatically compensate for the bump and roll steering effects, which allow for more freedom when shaping the geometry of the connecting rods.

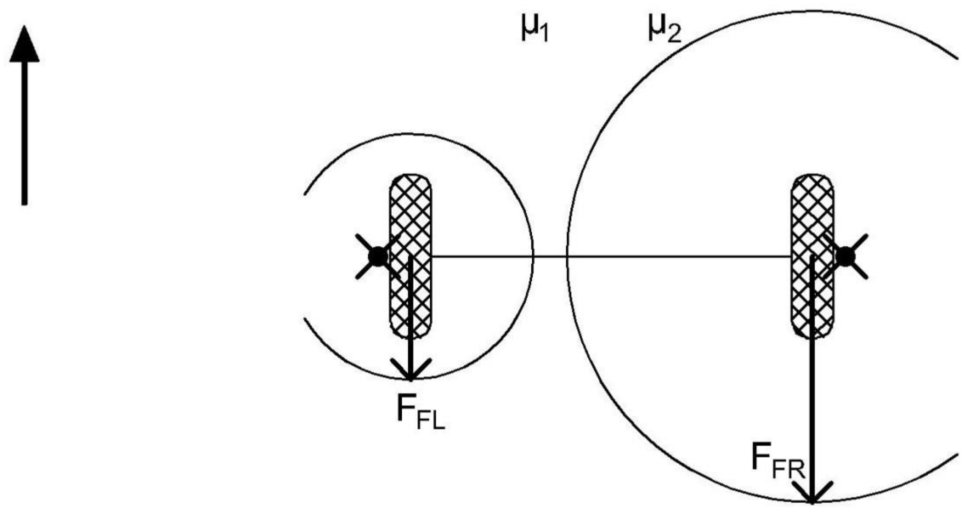

Fig. 3. Negative scrub radius

During cornering in a car with two independent, actively steered wheels of the front axle, there is a limited possibility of adjusting the position of the vehicle body's centre of rotation in the longitudinal direction with a suitable shaping of the sideslip angle at every wheel, which results from setting two controlled wheels. In the case of four-wheel steering, the centre of rotation can be chosen freely, with the only limitation being the speed of steering and the maximum steering angle. The proposed system can be combined with other systems allowing for the geometry of the wheel to change while driving. Active independent steering can be used to improve the behaviour of the car during manoeuvres at high speeds, while providing profit due to the significant enlargement of autonomous parking system limits. Systems with four-wheel steering offer, among other things, every advantage of vehicles with rear-axle steering implemented in any method, in particular, limiting the rotary movements of the body during cornering at high speeds. Another important issue is the process of entering into a turn, when the vehicle body starts to lean outside; as such, the steering angle of every wheel could be properly set at every moment to obtain a response to the road situation and vertical forces. In conventional steering, the linkage with the mechanical stability of the structure usually remains. In the proposed system, this aspect may cause some problems, but this should be considered according to tyre grip characteristic, as well as the directional and rotational stability.

4. CONCLUSION

Nowadays, in the era of the automation and autonomization of transport processes, safety should be a priority consideration. The obvious limitation, which results from the law of physics, cannot be avoided, but can be shaped in a sophisticated way. According to a number of practical problems connected with the proposed solution, the effects resulting from independent steering can only be partially used in order to slightly improve vehicle behaviour. As shown above, this could bring some benefits when correctly controlled. Therefore, further numerical calculations and experimental validations should be conducted.

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