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Reducing energy consumption of a power steering system using wheel individual electric drives and an optimized chassis concept

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Summary

Modern electric drive trains provide a variety of new features besides propulsion. We design a novel power steering system for electric vehicles using wheel individual drives. Using a suitable chassis and control system, the drive train can induce a specific steering torque into the steering system. Hence, the power steering system becomes part of the drive train. Our novel power steering system reduces the overall energy consumption of electric vehicles in many driving situations compared to vehicles with conventional power steering systems. With the optimized chassis concept presented in this paper, the power consumption reduction can be further improved.

Keywords: electric drive, energy consumption, power steering, powertrain, simulation

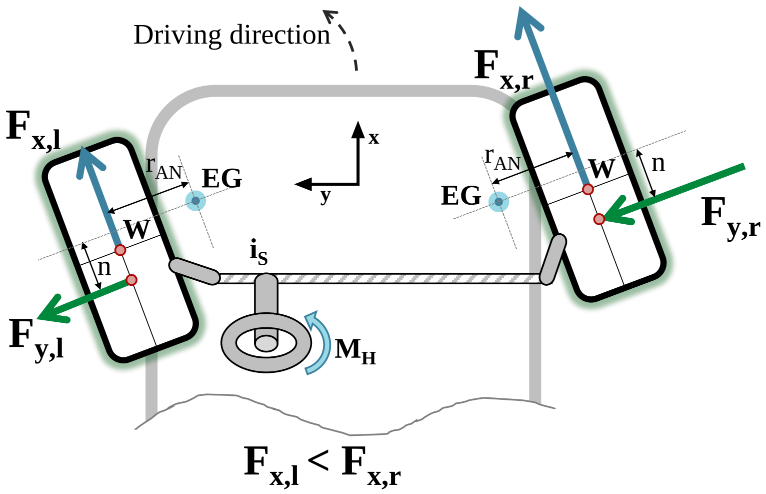
1 Introduction

As drive-trains of electric vehicles operate more efficiently compared to those of conventionally motorized vehicles, electric vehicles are a promising opportunity to reduce local carbon dioxide emissions in motion and to increase the overall energy efficiency. However, in conventional vehicles the internal combustion engine not only accelerates the car but also supplies energy to auxiliary systems, such as power-assisted steering. In electric vehicles this energy is provided by the battery, which causes the vehicle's range to be reduced. Considering new features offered by the drive-train of electric cars, this issue may be solved. Using electric drives, wheel-individual propulsion is possible. This influences the vehicle's driving dynamics and, if applied at the front axle, also the steering torque. To benefit from these features, a suitable chassis concept as well as an intelligent torque control method is necessary. The collaboration project "Intelligent Assisted Steering System with Optimum Energy Efficiency for Electric Vehicles (e²-Lenk)" between Karlsruhe Institute of Technology (KIT) and Schaeffler Technologies AG & Co. KG deals with an energy-efficient power steering system by using intelligent torque control of individual wheel drives. We launched the project in January 2015, funded by the Federal Ministry for Education and Research (BMBF).

2 Power steering system driven by wheel individual drive-torque

Power steering systems are used to reduce steering wheel torque, thus enabling a significant increase in driving comfort and facilitating vehicle guidance. Conventional power steering systems produce a supporting force using dedicated hydraulic or electromechanical actors. The objective of our research is to use wheel individual drives on the front axle to reduce the driver´s effort at the steering wheel, so that no additional actuator is necessary for power steering.

Figure 1 shows the front axle of a car driving a left curve. In order to counteract the centrifugal forces, lateral forces $F_{y,l/r}$ are generated in the tire contact patch. These lateral forces induce self-aligning torques around the steering axes EG using caster trails n as lever arms. This results in a torque M_H at the steering wheel, which the driver has to counteract. To reduce the steering wheel torque M_H, our power steering system applies a higher longitudinal force to the outer wheel (in this case on the right side) and a lower longitudinal force to the inner wheel (left side). The disturbance force lever arms r_{AN} transfer the longitudinal forces and induce a torque on the steering axis. The generated torque counteracts the self-aligning torque and hence the steering wheel torque is reduced. The effects of vertical forces are neglected in this figure.



M_H	Steering wheel torque
n	Caster trail
r_{AN}	Disturbance force lever arm
$F_{y,l/r}$	Lateral forces
$F_{x,l/r}$	Longitudinal forces
W	Tire contact patch
EG	Steering axis
i_s	Steering ratio

Figure 1: Principle of a steering system driven by wheel individual drive-torque at the front axle.

In Kautzmann et al. [1] we showed that the induced steering torque correlates to the length of the disturbance force lever arm r_{AN} and that the effect of drive torque distribution on the steering system can be enhanced by using optimized suspension geometry. When designing the chassis, attention should be paid to effects on the steering torques caused by braking forces and other disturbing forces. As shown in Römer et al. [2] our power steering system has the potential to be more efficient than a conventional power steering system. The largest energy consumption reduction can be achieved in defensive driving manoeuvres (classification according to [3] and [4]). In high dynamic driving situations, high lateral forces occur which result in high self-aligning torques. To counteract these rising self-aligning torques, the longitudinal force at the outer wheel has to be further increased while the force at the inner wheel has to be reduced. In driving situations with high lateral and low longitudinal acceleration, the inner wheel drive needs to switch to recuperation mode, to avoid changes in longitudinal acceleration. This results in a higher energy consumption. In order to avoid these situations, a different suspension design is needed. In this contribution we compare two suspensions for the use with our power steering system regarding the energy consumption.

3 Energetic analysis approach

For simulation we are using the highly detailed vehicle simulation model of IPG CarMaker®. We modified the standard vehicle model (DemoCar), which represents a combustion engine driven compact car, to obtain a model of an electric car equipped with two wheel-individual drives at the front axle. The drive torque is transmitted to the wheel by driveshaft and gearbox (gear ratio $i = 9$). Figure 2 shows the schematic of the vehicle's powertrain model.

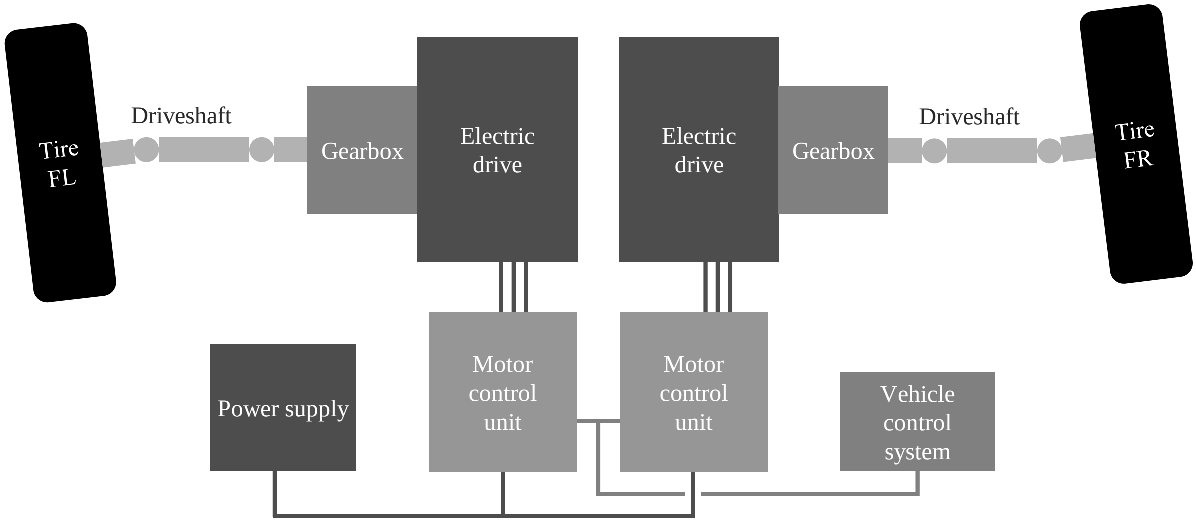


Figure 2: Schematic representation of the vehicle's powertrain model.

With this setup we can analyse the influences of wheel-individual drive torques on the steering wheel torque. Using this simulation environment, we evaluated the influences of the e²-Lenk principle by the use of ISO-standard manoeuvres and real world driving cycles to analyse the overall energy consumption. For evaluating the vehicle's energy consumption we use a realistic efficiency map for our electric drives (figure 3). The tested car represents an average passenger car. Table 1 shows the most important specifications of the tested car and suspensions.

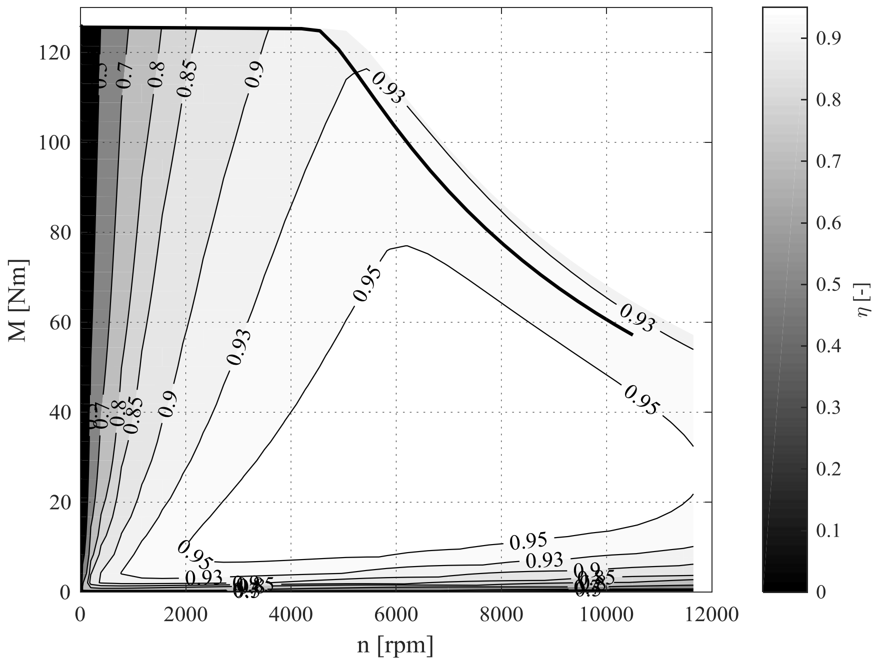
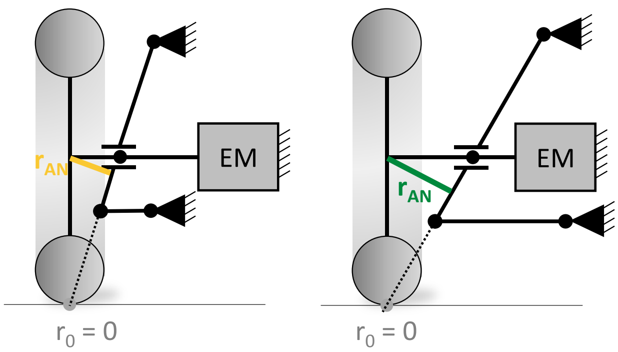


Figure 3: Efficiency map of the electric drives.

Table 1: Vehicle and suspension parameters.

Component	**Data**	
Vehicle Mass	1456 kg (without EPS), 1463 kg (with EPS)	
Wheelbase	2,53 m	
Track Width	1,51 m	
Tires	195/65 R 15	
Electric Drives	Two Inboard Drives	
Mechanical Power	65 kW (each)	
Maximum Torque	125 Nm (each)	
Maximum Rotation Speed	11650 rpm (each)	
Gear Ratio	i = 9	
Efficiency	Efficiency map shown in figure 3	
Double Wishbone Suspensions	Suspension #1	Suspension #2
Scrub radius r_0 [mm]	0	0
Disturbance force lever arm r_{AN} [mm]	68	136
Caster trail n [mm]	20	20



In this contribution we modified the double wishbone front suspension to lengthen the disturbing force lever arm (suspension #2, table 1) to reduce the vehicle's energy consumption in more driving situations. As shown in Kautzmann et al. [1], this modified suspension induces a higher steering torque compared to the conventional design (suspension #1), but is still controllable with the disturbance forces that occur while braking. To gain valid results we use realistic driving manoeuvres. Cycle #1 represents an approx. 13 km long overland trip at Herzogenaurach (figure 4 left). Cycle #2 represents a course in the region of Nürnberg/Erlangen (Germany) shown in figure 4 right. The approximately 111 km long route includes 42% urban driving, ca. 36% winding country road and approximately 22% freeway driving.

Figure 4: Realistic driving cycles.

We used an open-loop control algorithm according to Römer et al. [2] to reduce the steering torque to the same level as done by conventional power steering systems. To achieve an equivalent steering wheel torque, the effects of steering and chassis geometry as well as vehicle dynamics are considered in this control algorithm.

4 Results

Figure 5 shows the steering wheel torque M_H over time for both suspensions while driving a slowly accelerated circle. The circle's radius is $R = 100\ m$ and the vehicle's maximum speed is $v = 100\ km/h$, which results in a maximum lateral acceleration of $a_y \approx 7.7\ m/s^2$. The conventional suspension design (suspension #1) and the modified suspension #2 generate nearly the same assistance torque as the conventional power steering system EPS. Hence, the steering wheel torque is comparable in both cases.

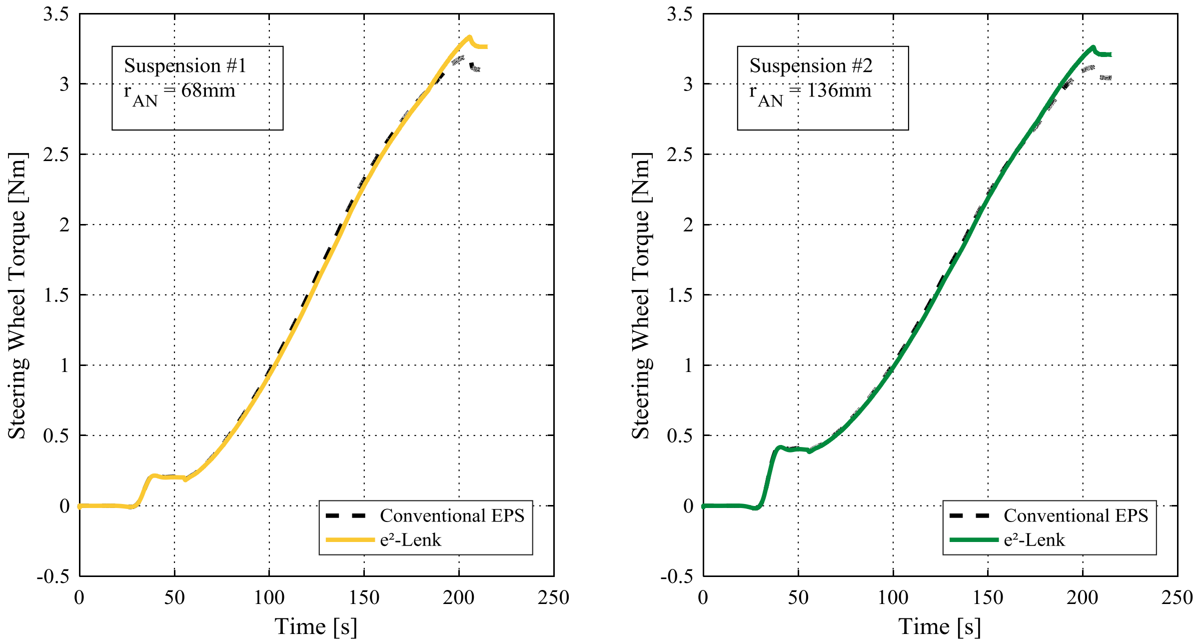


Figure 5: Steering wheel torque at slowly accelerated circle using two different suspensions.

The slowly accelerated circle is according to Römer et al. [2] one of the critical driving manoeuvres evaluating the novel steering system regarding energy consumption. High lateral accelerations cause high self-aligning torques. Low longitudinal acceleration afford only low longitudinal tire forces. Figure 6 (left) shows the motor torque of the inner wheel drive vs lateral acceleration for the vehicle with both suspensions. By the use of the conventional suspension #1 (orange coloured) a high torque distribution is needed to support the driver. Hence, the inner wheel switches to recuperation mode above $3.5\ m/s^2$ and the novel power steering system increases the energy consumption of the car. This effect no longer occurs by the use of the modified suspension #2 (green coloured). Using suspension #2 the inner wheel drive does not have to switch to recuperation mode, also at high lateral acceleration and just low longitudinal acceleration. Figure 6 (right) shows the energy consumption of the vehicle in this manoeuvre depending on the two suspensions. The use of the new suspension #2 reduces energy consumption in our test configuration around 1.9 % compared to suspension #1 and around 0.3 % compared to the same vehicle configuration with conventional EPS. The holding force of the EPS motor is neglected in this simulation model. The consideration of this force would further increase the energy consumption of the vehicle with conventional power steering system.

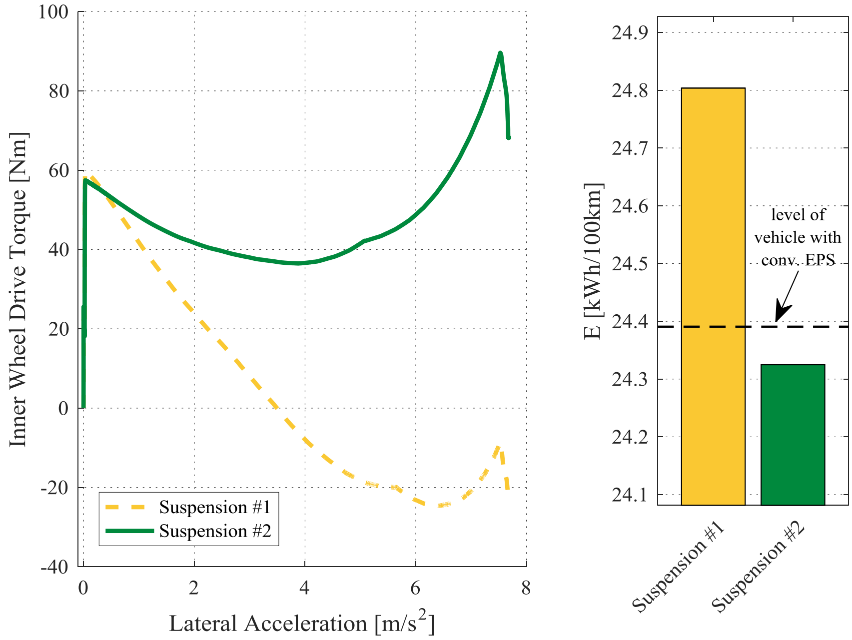


Figure 6: Inner wheel drive torque (left) and energy consumption of the novel power steering system (right) using conventional suspension #1 and modified suspension #2 at slowly accelerated circle.

Figures 7 and 8 show the comparison of the energy consumption between both tested suspensions while driving the realistic driving cycles. In this case, we use a bar plot to show the vehicle's overall energy consumption using the e²-Lenk principle relative to the vehicle's energy consumption using a conventional power steering system. Compared to suspension #1, suspension #2 can further reduce the vehicle's power consumption mainly in normal and dynamic driving situations in both cycles (driver types are set according to Schulz & Fröming [3] and Mayser et al. [4]). In cycle #1 the new suspension #2 enables the e²-Lenk principle to reduce the vehicle's overall power consumption at high lateral accelerations while suspension #1 results in a higher power consumption. However, in defensive driving situations the power consumption of the vehicle using suspension #2 is slightly increased in both cycles compared to the suspension #1 vehicle.

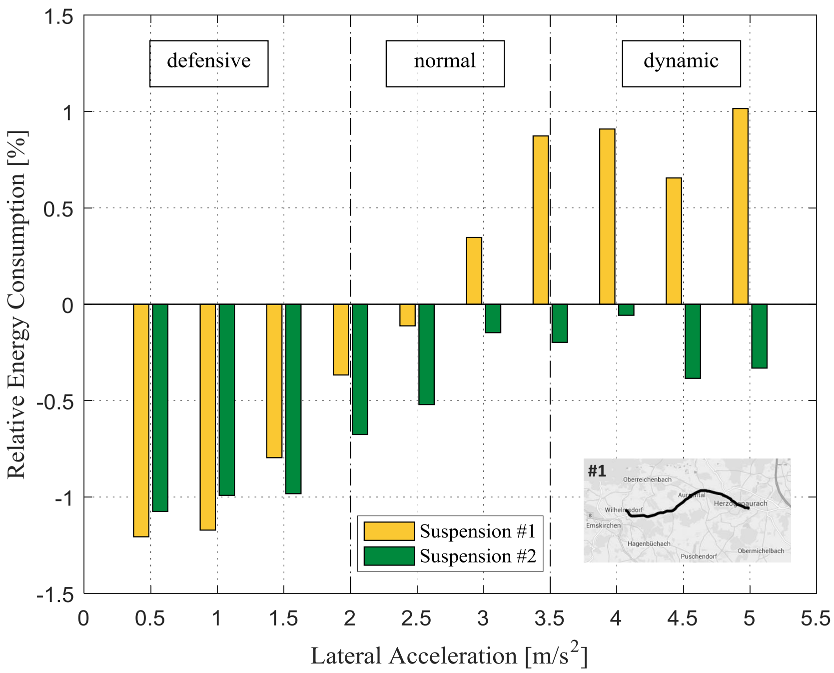


Figure 7: Vehicle energy consumption using conventional suspension #1 and modified suspension #2 while driving cycle #1 relative to the vehicle's energy consumption using a conventional power steering system.

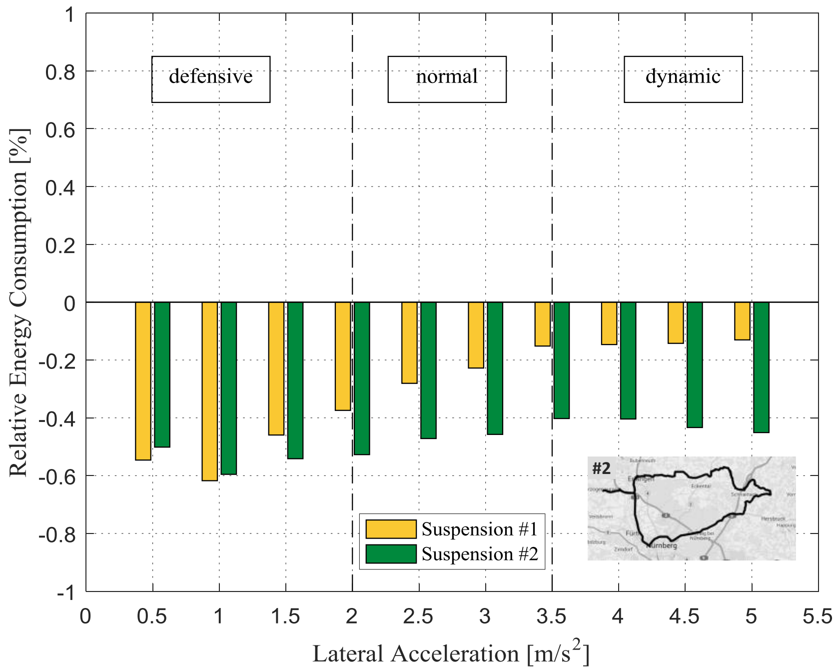


Figure 8: Vehicle energy consumption using conventional suspension #1 and modified suspension #2 while driving cycle #2 relative to the vehicle's energy consumption using a conventional power steering system.

5 Conclusion

Using a power steering system driven by wheel individual drives reduces the vehicle's energy consumption compared to a vehicle with conventional power steering systems in many driving situations. By the use of an optimized chassis and suspension with an enlarged disturbing force lever arm the reduction effect can be further increased also in high dynamic driving situations. An enlarged disturbing force lever arm reduces the need of large driving torque differences between the inner and outer wheel drive. Hence, the inner wheel drive can still remain in propulsion mode and doesn't have to switch to the (energetic poorer) recuperation mode.

Nevertheless, there are some driving situations that reveal negative effects of such a large disturbing force lever arm. Suspension #2 induces a high self-aligning torque at low lateral accelerations due to the bigger wheel load lever arm. We assume this effect as reason for the increasing energy consumption for defensive drivers, because more steering torque assistance is needed. We also see that a smaller disturbing force lever arm would also be sufficient, since the inner wheel drive torque is still far from recuperation mode also at its minimum. Therefore a suspension geometry has to be found that reduces the inner wheel drive torque only to the extent of avoiding recuperation mode. Consequently, further chassis design optimizations and optimizations of control method are in progress, which will further improve the novel power steering system.

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