POWER REQUIREMENTS FOR A REDUNDANT AUTOMATED STEERING SYSTEM FOR TRUCKS

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ABSTRACT

For automated driven vehicles with a driving automation level above two, the driver is not available immediately as fallback when the automated driving system fails. Therefore, a redundant design for each automated driving system (e.g. the automated steering system) is a central safety requirement. The grade of redundancy, i.e. if it has to be fully fail operational or just a certain level of fail degraded, depends on the definition of the safe state in case of a failure and on the way how to reach it. The safe state itself depends on the driving situation respectively the type of road, where the automated vehicle is driving. The goal of this article is to determine the amount of steering power and energy required in different use cases and road types to reach the safe state.

Therefore, a definition of the safe state for automated driving trucks is determined using the ISO 26262 and existing definitions. With the help of German national road construction guidelines for highways, rural roads and urban roads, the safe state and the necessary driving maneuvers to reach it are determined for different defined road types. A 12-t two-axle truck has been equipped with measurement equipment as test vehicle. The determined driving maneuvers to reach the safe state are driven with the test vehicle and the required steering power and steering energy are measured.

The results of this investigation are the minimum required steering torque, power and energy for each tested driving maneuver. The minimum redundancy requirements to the automated steering system for a specific use case of automated driving, such as fully automated highway driving, are determined considering all driving maneuvers to reach the safe state in the worst case. Depending on the intended use cases for the automated vehicle, different fallback requirements are determined for the redundant automated steering system. Although the achieved results of this contribution are only representative for the used test vehicle, they are still helpful to get an impression and some real data for the required fallback steering torque, power and energy. It has to be considered that the required steering power and steering energy are highly influenced by the front axle load and thus by the load of the vehicle and by the steering and axle geometry of the vehicle as well. However, based on the findings of this article, the fallback concepts of future redundant active steering systems for highly and fully automated driven trucks can be developed according to the intended use cases.

The requirements for the mentioned exemplary use case of fully automated driving on highways with hard shoulders are very low, thus it should be possible to realize the steering redundancy with low effort. However, for other use cases the redundancy requirements are much higher.

INTRODUCTION

Automated driving is a key topic of development not only in the passenger car industry, but also in the commercial vehicle industry. The increase of safety, the reduction of emissions and the cost saving are the main motivation for such development actions. Whereas there are no technical hurdles for partial automated driving of trucks, e.g. Adaptive Cruise Control (ACC) with Lane Keeping Support (LKS), there are still a lot of open questions, before highly automated driving can be introduced on public roads. Exemplary systems with higher levels of automation are “exit-to-exit highway automation”, “traffic jam assist” or “automated trailer backing” [1].

One of those challenges is to ensure a safe operation during highly automated driving in all possible situations, which also includes a malfunction of one of the systems, which are necessary for the automated driving. [2] categorizes the levels of driving automations, whereby partially automated driving is listed as level 2 (AD2) and highly automated driving is listed as level 3 or higher (AD3+). The driver is not available anymore as immediate fallback level for AD3+. Hence, the automated system has to be redundant and has to provide its own fallback level for the case of a malfunction. This redundancy can be realized inside one system or outside by an additional system. In case of an automated steering system, the steering system can be redundant by itself, but a steering function can also be realized by the brake system using differential braking to steer the vehicle. Although it is possible to steer a truck with the brake system, [3] proofs that it is not feasible for all relevant driving maneuvers of a truck. Additionally [4] argues that the dynamic and the precision of brake steering is not sufficient for the use as steering redundancy. Thus, a redundant automated steering system is mandatory for AD3+.

This article covers the question, how much steering torque, steering power and steering energy is required for the fallback level of a redundant automated steering system for trucks. Therefore, the used research methods are described first and the different results of the investigation are shown and explained afterwards. The article ends with the conclusion of the obtained test results and their discussion.

METHODOLOGY

For the determination of the demanded fallback steering requirements, it is necessary to derive the requirements for a safe state of a truck. Different safe states are defined for different Road Classes using these requirements and German guidelines for road construction. With this definitions, it is possible to determine the different relevant maneuvers, which are necessary to reach the defined safe state. With the help of a test vehicle equipped with measurement equipment for steering torque and angle, the steering power and the steering energy required for each relevant driving maneuver are recorded. The steering redundancy requirements are derived from the measured test data and the determined relevant maneuvers to reach the safe state.

Definition of a Safe State

Since an automated driven vehicle contains a lot of E/E systems (electric/electronic), the definition of its safe state bases on the ISO 26262 on functional safety of E/E systems of vehicles. According to [5] the safe state is defined as an “operating mode of (a vehicle) without an unreasonable level of risk”, whereas the risk is defined as the “combination of the probability of occurrence of harm and the severity of that harm” and the harm is the “physical injury or damage to the health of persons”. In the context of automated driving [6] describes the safe state as an operating mode, where no unreasonable risk occurs for all persons involved in road traffic. Thus, the internal system state as well as the environment of the vehicle are important for the safe state.

Based on the definitions from the ISO 26262, eight requirements of the safe state are determined here (See Table 1). The first requirement is the most important and a high-level requirement. All the other requirements serve to fulfill this superior requirement. The requirements no. 2 to no. 6 are the important requirements for this investigation. The safe state in each specific driving situation depends on those five requirements. Therefore, we separate the safe state for city roads, country roads, and highways.

Table 1.

Requirements to the Safe State of an Automated Driven Vehicle

No.	**Requirement**
1	No hazard for passengers, other road users, pedestrians or for the environment
2	Vehicle stands still
3	Visibility to other road users bigger than required stopping visibility
4	Relative velocity to other road users less than 70 km/h
5	No blocking of rescue routes
6	No blocking of bridges, tunnels, intersections or roundabouts
7	Protection of the stopping place and warning of other road users
8	Emergency call (if necessary)

To define a safe state for each different type of road, it is important to know all the specific properties of each type, especially according to the possibilities for a safe stop of the vehicle. The German guideline for the construction of city roads [7], the guideline for the construction of country roads [8] and the guideline for the construction of highways [9] describes the properties of the roads and are used to define three different Road Classes according to the possibility for a safe stop.

The different types of roads are characterized into three Road Classes (see Table 2). The number of lanes, counting both directions, the availability of a hard shoulder or an emergency stopping bay, the speed limit, the minimum curve radius and the maximum required stopping visibility are used for the classification. The first Road Class contains the roads with a permanent hard shoulder, i.e. highways except urban highways. The second Road Class describes the roads with emergency stopping bays instead of a permanent hard shoulder, i.e. urban highways and big country roads with two lanes at least in one direction. The last Road Class, which requires steering maneuvers to get to a safe state, contains the roads without a hard shoulder and without any emergency stopping bays. City roads are not part of these three classes, because according to [7] there are always speed limits below 70 km/h. A relative velocity to other road users of more than 70 km/h is not possible. Hence, the transition to the safe state is always an immediate braking maneuver and no steering is required for this classes. The claim is, that the automated vehicle knows what the safe states and the maximum distances between the single safe states are and how it gets there, depending on the Road Class.

Table 2.
Characterization of Road Classes according to [7], [8], [9]

Class	**1**	**2**	**3**
Number of lanes (both directions)	≥ 4	≥ 3	2
Hard shoulder available?	yes	partially	none
Emergency stopping bay available?	-	at least every 1000 m	none
Speed limit	none	≥ 100 km/h	≤ 100 km/h
Minimum curve radius	470 m	280 m	200 m
Maximum required stopping visibility	250 m	190 m	160 m

The safe state of the class with a hard shoulder is the stand still on the hard shoulder. Usually, no other road user drives on the hard shoulder, thus there is no relative velocity to others. In addition, the stopping visibility has no influence on this safe state and no bridge, tunnel or rescue route is blocked here. The relevant maneuvers to reach the safe state depends on the amount of lanes of the road and on which road the vehicle drives currently, when a failure occurs and the transition to the safe state is required. If the vehicle is not on the lane next to the hard shoulder, one or more lane changes and the change to the hard shoulder are the relevant maneuvers to reach the safe state. Because in areas of highway accesses or exits are no hard shoulders, a change to the hard shoulder could be temporarily not possible. In that case, the vehicle needs to drive on for a defined distance until the hard shoulder is available again.

Driving into and stopping inside an emergency stopping bay is the safe state of the second Road Class, where such a stopping bay intended to be every 1000 m. The emergency stopping bays are at least 84 m long and 3 m wide according to [8]. Because the emergency stopping bay is no continuous lane, no other road user is able to drive on it, whereby the risk seems to be lower standing inside an emergency stopping bay as standing on a hard shoulder. The relevant maneuvers to reach the safe state inside a stopping bay contain one or more lane changes as well, the drive and stopping maneuver into the stooping bay and the required drive on to the next available stopping bay. It is also possible, that there are temporarily hard shoulders available on this Road Class, but for the design requirements of the steering system, the highest fallback requirements are used, which occur for the drive into an emergency stopping bay for this Road Class.

Because of the missing hard shoulders and the missing emergency stopping bays, the safe state of the third class is not obvious. A safe stop at the side of the road is usually not possible due to a relative velocity to the other road users above 70 km/h. However, in practice there are frequently junctions appearing on this class of roads, whereby a turn-off to a side road with a speed limit lower than 70 km/h or to a road with a hard shoulder or emergency stopping bays is possible. A safe stop on such a side road, e.g. a city road, represents the safe state in this Road Class. Hence, the relevant maneuvers are the drive on until the next turn-off to a side road and the turn-off maneuver itself. Of course, it is possible, that there is a stopping bay or a parking lot at this Road Class as well, but this is an exception and the fallback requirements of the steering system are higher for the turn-off maneuver thus these are the crucial design requirements.

Driving Maneuvers

Based on the previous defined safe states for the three different Road Classes, the different relevant driving maneuvers (see Table 3) are performed with a 12-t truck meanwhile the required steering torque, steering power and steering energy are recorded.

Besides the previous mentioned relevant driving maneuvers, the avoidance maneuver is also considered as relevant, because it is possible at any time and at any Road Class, that an avoidance maneuver becomes necessary. The different types of maneuvers are driven several times on several roads, i.e. different routes of country roads, different highways and different city routes were tested. For each type of maneuver, the biggest occurring values for torque, power and energy are used to determine the fallback requirements. With this approach, it is supposed to cover the worst case of each type of maneuver. The measured data of the several maneuvers are combined according to the definition of the safe state in the previous chapter to determine the final fallback requirements for each Road Class. Hereby, the most critical moment for the failure of the steering system is assumed. However, a complete cover of all possible situations is not guaranteed of course.

Table 3.
Relevant Driving Maneuvers driven by 12-t Truck

Maneuver type	$v_{\max}$ in $\frac{\mathrm{m}}{\mathrm{s}}$	$a_{y,\max}$ in $\frac{\mathrm{m}}{\mathrm{s}^2}$	$R_{\min}$ in m
Turn-off to side road (out of city)	-	5,00	70
Lane change (slow)	17	1,37	-
Lane change (fast)	25	2,16	-
Avoidance maneuver	17	5,00	-
(Big) Emergency stopping bay [8]	25	1,96	-
(Small) Emergency stopping bay [8]	17	1,57	-
Highway access/exit	-	3,14	150
Highway interchange	25	3,14	400
Road Class 1	25	2,45	470
Road Class 2	25	3,43	280
Road Class 3	20	3,43	140
Mountain pass	17	3,53	45
City driving	14	3,24	50

Test Equipment

For the test drives, a fully loaded 12-t truck is used with a measured front axle load of 42.6 kN (vehicle data see Table 6 in Appendix). A measurement steering wheel records the torque and the steering angle at the steering wheel. Strain gauges are applied at the pitman arm to measure the output steering torque of the steering system. In addition, the acceleration in all three directions, the velocity and the GPS position of the truck are recorded as well.

The steering angle velocity of the pitman arm is derived from the measured steering wheel angle and the known ratio of the steering gear. The measured output steering torque is integrated over the steering angle at the pitman arm and thus determines the overall steering energy, which itself determines the steering power by derivation over time. Exemplary for the data recording, the measured steering torque at the pitman arm, the measured angular velocity at the pitman arm, the calculated steering energy and power as well as the particular maximum values are shown in Figure 3 (see Appendix) for the maneuver highway exit.

Requirements for a Redundant Automated Steering System

The feature of a redundant automated steering system is the fail operational fallback level integrated inside the steering system. Hence, in case of a partial failure of the steering system, it is still able to steer the vehicle safely without the need of a take-over by the driver. It is required, that the fallback level of the steering system is able to transfer the vehicle into a defined safe state at any time. Therefore, the fallback steering system has not to fulfill the requirements for the failure-free steering system, but the reduced fallback requirements. This reduced performance is called fail degraded.

The maximum required steering torque and steering power determines the minimum steering torque and power the steering system has to produce at least to pass the relevant driving maneuvers in the fail degraded mode. The minimum required steering energy determines the steering system has to provide to reach the safe state even in case of a failure of the power supply.

RESULTS

The maximum occurring steering torque at the pitman arm and the maximum occurring angular velocity at the pitman arm during the different maneuvers are described first. Both parameters are used later to calculate the maximum required steering power and steering energy for each maneuver.

Steering Torque

Figure 1 shows the maximum steering torque and the maximum angular velocity occurring at the pitman arm during the different maneuver. The illustrated values of maximum pitman arm torque and maximum angular velocity of the pitman arm not always occur simultaneously during a maneuver, which is why the product of those two maximum values could be higher than the actual required maximum steering power (see Figure 2).

The maneuver types can be classified into three groups according to their required maximum steering torque. Group A considers the maneuvers requiring less than 600 Nm of torque at the pitman arm. With those maneuvers, regular driving on the Road Classes 1 and 2 is possible including lane changes, interchanges as well as the driving into a stopping bay. Group B with required steering torques between 600 Nm and 1000 Nm contains the Road Class 3 driving without turning maneuvers, the maneuvers for leaving a highway as well as an avoidance maneuver. The most advanced steering torque requirements between 1000 Nm and 1500 Nm arise for Group C during mountain pass driving, city driving and turning maneuvers.

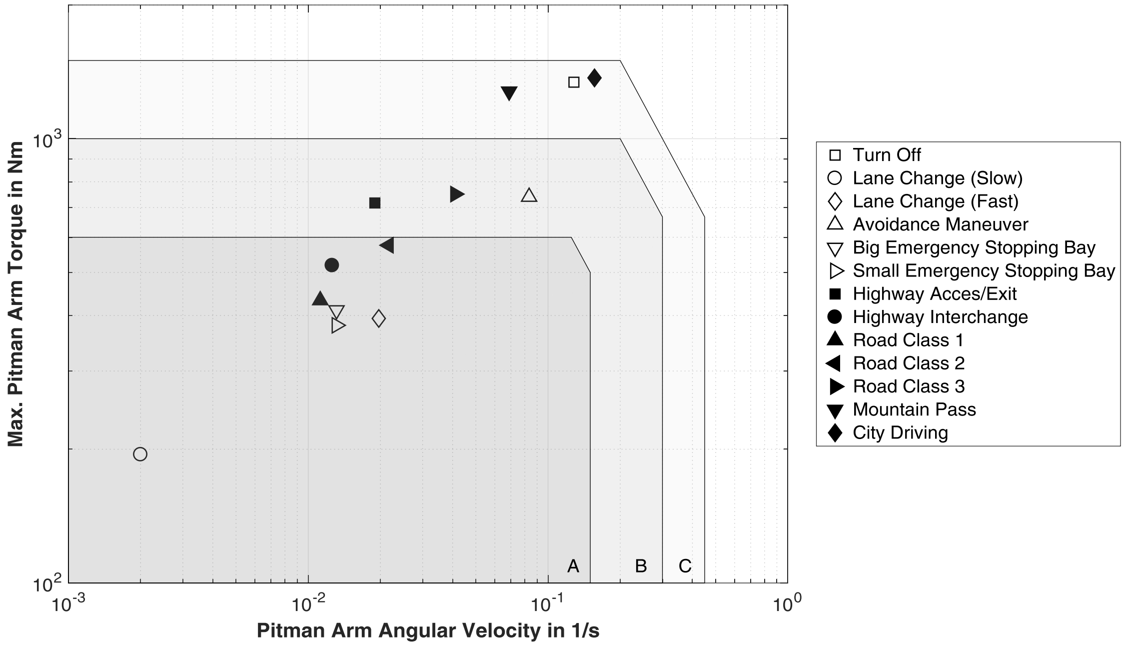

Figure 1. Maximum Occurring Steering Torque T_{Pitman} and Angular Velocity at Pitman Arm $\dot{\delta}_{\text{Pitman}}$

Steering Energy

The energy required for steering during the different driving maneuvers is the measured steering torque at the pitman arm T_{Pitman} integrated over the steering angle at the pitman arm δ_{Pitman} as described in Equation 1:

$$E_{\text{Steering}} = \int T_{\text{Pitman}} \, d\delta_{\text{Pitman}} \qquad \text{(Equation 1)}$$

The maneuvers highway driving, country road, mountain pass and city driving are special cases here, since the required energy depends on the driven distance of course. However, to get an indication for the required steering energy during these maneuvers the maximum demanded steering energy on a driving distance of 1 km is used and illustrated with the required steering energy during the other maneuvers in Figure 2.

The classification into the three Groups of driving maneuvers is also feasible for the steering energy. Group A has again the lowest requirements with a required steering energy of less maximum 100 J for the drive of a single maneuver. Between 100 J and 500 J are required by the maneuvers of Group B. Group C requires with between 500 J and 1000 J by far the most steering energy.

Steering Power

The steering power at the pitman arm of the truck occurring during the different driving maneuvers is the derivation of the steering energy E_{Steering} as described in Equation 2:

$$P_{\text{Steering}} = \frac{dE_{\text{Steering}}}{dt} \qquad \text{(Equation 2)}$$

Figure 2 shows the maximum steering power required during each maneuver type. The maneuver types are classified into three Groups according to the maximum required steering power, similar to the classification in the previous chapters. Group A with the lowest power requirement of maximum 75 W contains the Road Classes 1 and 2, highway interchanges, lane changes and the driving into emergency stopping bays. The highway exit, the avoidance maneuver and the Road Class 3 driving form Group B with a maximum required steering power between 75 W and 150 W. The maneuvers turn-off, mountain pass and city driving requires between 150 W and 300 W of steering power and thus are classified to Group C.

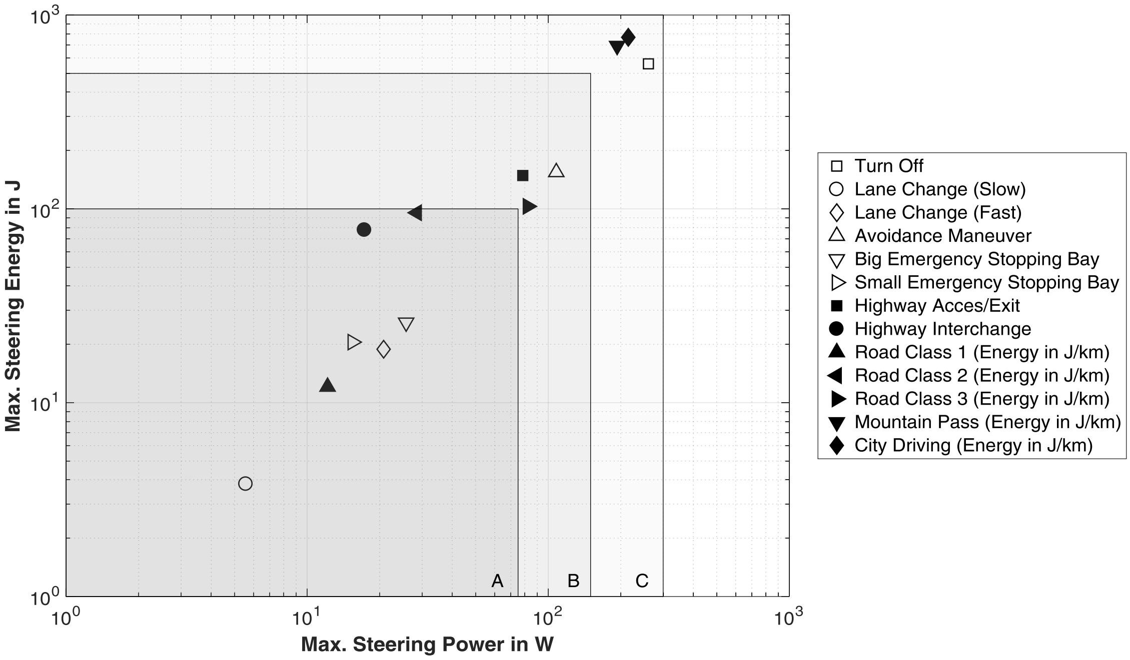

Figure 2. Maximum Steering Power and Maximum Steering Energy

The results from the performed test runs considering the required steering torque, power and energy during the defined relevant maneuvers as well as the classification of these maneuvers into three Groups according their requirements are listed in Table 4. The maneuvers are separated into the three Groups without any overlapping.

Table 4.
Steering Requirement Groups

Group	**Maneuver type**	$T_{\text{Pitman,max}}$	$P_{\text{Steering,max}}$	$E_{\text{Steering,max}}$
A	Lane change (slow)	< 600 Nm	< 75 W	< 100 J
	Lane change (fast)			
	(Big) Emergency stopping bay			
	(Small) Emergency stopping bay			
	Highway interchange			
	Road Class 1			
	Road Class 2			
B	Avoidance maneuver	600 – 1000 Nm	75 – 150 W	100 J – 500 J
	Highway access/exit			
	Road Class 3			
C	Turn-off to side road (rural roads)	1000 - 1500 Nm	150 - 300 W	500 - 1000 J
	Mountain pass			
	City driving			

Redundancy Requirements

The determined requirements for the different Groups (see Table 3) are used to develop exemplary redundancy requirements for the three different Road Classes and the available 12-t truck. For each Road Class an exemplary combination of maneuvers out of the three different requirement Groups is set up, which are necessary to reach the defined safe state (see Table 4). The exemplary cases are set up according to the worst-case situations for the occurrence of a malfunction, which were found by analysis the roads in the surrounding area of Darmstadt. The torque and power requirements are independent of the amount of necessary maneuvers to reach the safe state. Of course, the required steering energy increase with an increasing amount of necessary maneuvers and with an increasing necessary driving distance.

For the Road Class 1 with a permanent hard shoulder, a worst-case scenario of a failure is, if the malfunction occurs when the truck is on the third lane from the hard shoulder, thus to reach the safe state, three lane changes are required to stop on the hard shoulder. Because lane changes are not always possible immediately, 1000 m of Road Class 1 driving are considered as well for determining the redundancy requirements. If an avoidance maneuver is necessary as well, the requirements are much higher for this Road Class (see Table 4). The Road Class 2 with emergency stopping bays is quite similar to the Road Class 1, but the difference is, that a safe stop is not possible at any time. A safe stop is only possible at an emergency stopping bay instead, which are only available at a distance of 1000 m. Therefore, to reach a safe state of this Road Class in the worst-case, 2000 m of Road Class 2 driving, two lane changes and the drive into an emergency stopping bay are necessary. The requirements for this class are also much higher, if an avoidance maneuver or another maneuver from Group B is necessary (see Table 4). The Road Class 3 differs from the other two, because there is no safe stop possible at the side of the road. In contrast, a turn-off maneuver is necessary to get to a road where a stop at the side of the road is possible or where the speed limit is below 70 km/h and thus a safe stop in the road is possible. Since a turn to such a road is not possible within a short distance in any case, a 5000 m Road Class 3 drive and a subsequent turn to a side road are considered as relevant to reach a safe state of this class. These maneuvers causes the highest steering redundancy requirements (see Table 5).

Table 5.
Redundancy Requirements

Road Class	**Exemplary Maneuvers to reach Safe State**	$T_{\text{Pitman,max}}$	$P_{\text{Steering,max}}$	$E_{\text{Steering,max}}$
1	4x Group 1 (add. avoidance maneuver: 1x Group 2)	600 Nm (1000 Nm)	75 W (150 W)	400 J (900 J)
2	5x Group 1 (add. avoidance maneuver: 1x Group 2)	600 Nm (1000 Nm)	75 W (150 W)	500 J (1.00 kJ)
3	5x Group 2 1x Group 3	1500 Nm	300 W	3.50 kJ

CONCLUSION

This paper investigates the redundancy requirements exemplary for a 12-t truck. Therefore, the requirements for a safe state of an automated vehicle are developed with the help of the definitions from the ISO 262626 [5] and [6] (see Table 1). According to German road construction guidelines three different Road Classes are defined according to their different safe states. Several driving maneuvers are determined, which are necessary to reach the different defined safe states (see Table 3).

With the help of driving tests with an available 12-t truck equipped with appropriate measurement equipment, the steering requirements for each of these defined relevant driving maneuvers are recorded and the maneuvers are classified into three groups according their requirements (see Table 4). By combining some of these maneuvers to reach a safe state in an exemplary scenario, the redundancy requirements are calculated for each Road Class (see Table 5).

Although the determined requirements are only exemplary for the used test vehicle and the combinations of maneuvers to reach the safe state are only exemplary as well, it is significant, that the requirements for the Road Class without a hard shoulder or stopping bays are much higher compared to the requirements of the other two Road Classes. Hence, it is concluded that the redundancy requirements for steering systems are much lower, if the automated driven truck only drives on roads with hard shoulders or emergency stopping bays. The fully automated highway driving is such a use case. According to the definition of the safe state in this paper, there are no steering redundancy requirements for inner city automated driving, since an immediate safe stop is possible here at any time. If the truck should be able to drive automated on all types of roads, including on roads with an operation speed above 70 km/h and without hard shoulder or stopping bays, such as country roads, the highest steering fallback steering torque, steering power and steering energy are required.

To determine feasible values for the steering redundancy requirements, an exact definition of the intended use case is necessary to be able to determine the relevant maneuvers to reach the safe state at any time. With this information, the steering requirements necessary for these maneuvers can be used to determine the final steering requirements for this defined use case.

With the help of a simulation model of a truck steering system, including the geometry of the truck’s front axle and its tire properties and the trajectory of the described driving tests as an input, it is possible to simulate the required steering torque, power and energy. Such a model is adaptable to calculate the redundancy requirements for other trucks, for example with higher steering axle loads. Of course, not only the axle load, but also the axle geometry and the tire properties has to be adapted to other trucks.

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APPENDIX

Table 6.
Vehicle Data

Parameter	Value
Total mass	11900 kg
Front axle mass	4340 kg
Wheel base	3.25 m
Track width front axle	1.94 m
Track width rear axle	1.79 m
Tire dimension	245/75 R17.5 134/132 L
Tire pressure	8 bar
$\dot{\delta}_{\mathbf{SteeringWheel}}/\dot{\delta}_{\mathbf{Pitman}}$	16.4 – 18.9
$\dot{\delta}_{\mathbf{SteeringWheel}}/\dot{\delta}_{\mathbf{FrontWheel}}$	12.0 – 20.0

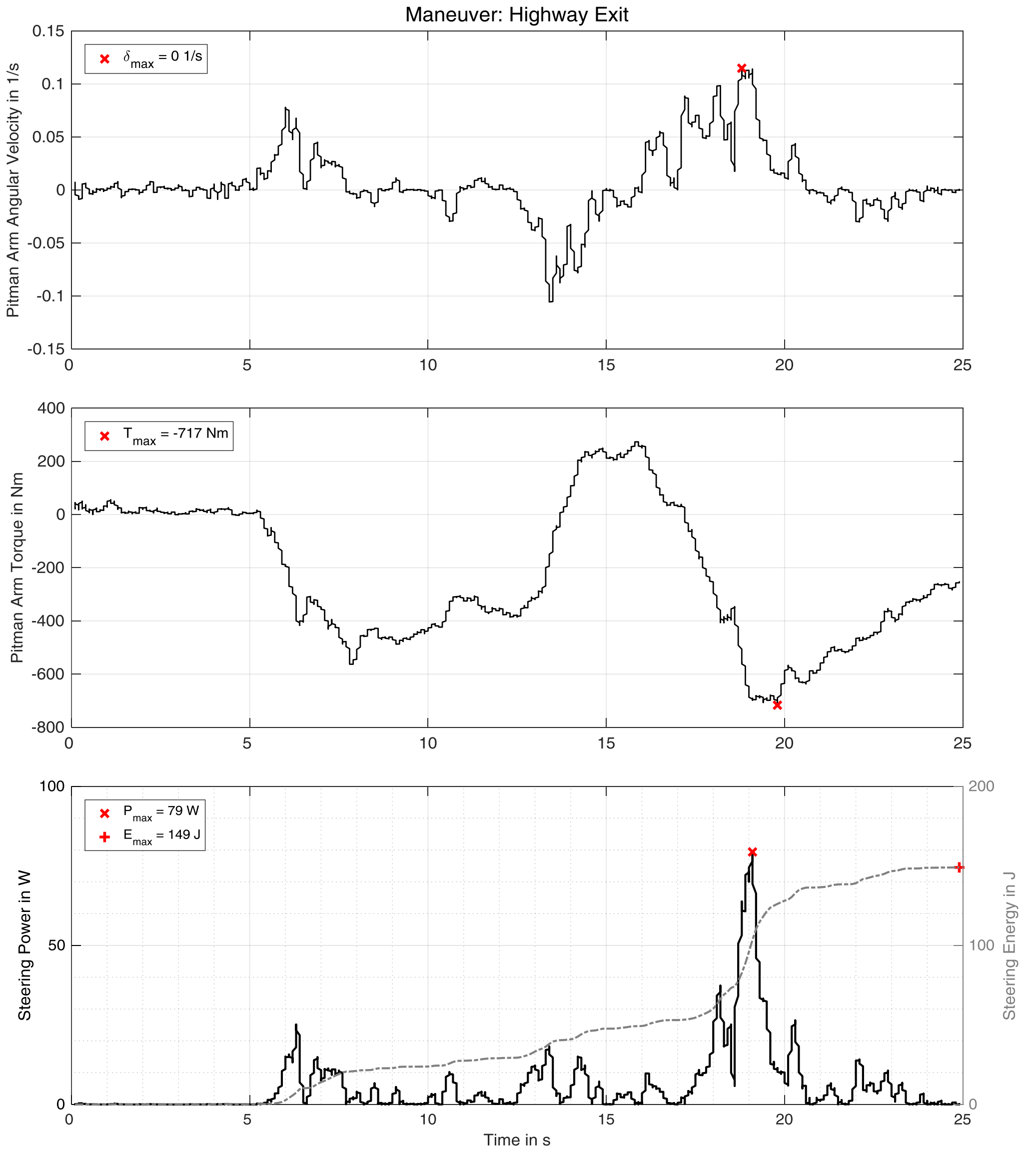

Figure 3. Pitman Arm Angular Velocity, Pitman Arm Torque, Steering Power and Steering Energy exemplary for the Maneuver Highway Exit