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Safety of a torque vectoring LKAS on an in-wheel motor electric vehicle

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Abstract

Electric Vehicles with in-wheel motors offer new opportunities in term of vehicle stability control and advanced driving assistance systems. Independent braking and acceleration of each motor wheel allow creating a torque, and possibly a lateral force, that make the vehicle turn. On conventional combustion engine vehicle, several implementations of the torque vectoring exist on propulsion car, as “Vector Drive” industrialized by ZF for BMW car. For electric vehicle with in-wheel motor, the control of each wheel may allow fine tuning of the torque vectoring for stability applications with less impact on the speed of the vehicle than conventional electronic stability program, and for driving assistance as lane keeping system with a low intrusion on the driving task.
As the application aims to correct lane departure, we defined from the car accident studies the specification of the driving assistance. For instance, we limited the operating range of the application to small deviation from the lane direction, up to 4°. Next, we defined, from a simple vehicle model, the torque that need to be generated and the requirement on the braking and accelerating torque that must be generated on the wheel. Then, we applied this driving assistance system according to road specificities (highway, rural and urban road) both in term of speed limit and road geometry. Finally, we compared the results to the capacity of the motor and we analyze the impact of the driving safety according to the ASIL ISO standards.

"Keywords: Torque Vectoring, Electric Vehicle, ASIL"

1. Introduction

1.1. Context and objectives

Nowadays vehicles are more and more equipped by ADAS (Advanced Driver Assistance systems). Generally, these systems have been designed to enhance the driver comfort without knowing their impact on safety. Examples of such systems, dealing with the longitudinal mode of the vehicle, are derived from the ACC (Adaptive Cruise Control) which aims at controlling the vehicle speed according to different events in front of the vehicle.

Since a few years, ADAS working on the lateral mode have appeared on the market for conventional ICE (Internal Combustion Engine) vehicles. For example, the LKAS (Lane Keeping Assistance System) is a system aiming at keeping the vehicle inside its lane while the driver does not have to turn the steering wheel. In the case of ICE vehicles, actuators directly act on the steering angle.

Within the european eFuture project, such an ADAS is applied on an EV (electric vehicle) equipped with in-wheel motors on the front wheels. The main difference is that, due to the absence of steering actuator, the LKAS function has to be achieved using a torque vectoring strategy. In this case, the torque applied on the left and the right wheel is different, generating a yaw torque, making the vehicle turn. The main advantage of this technique is that the intrusion in the driving tasks is more transparent.

However, torques required in different situations and the safety level to be reach have to be estimated. The torques required varies mainly with the road curvature, grade and the vehicle speed and acceleration.

The aim of this study is then to assess the safety level associated to the use of a LKAS in different situations in terms of road geometry and driver commands.

1.2. State of the art

The LKAS is an ADAS aiming to assist the driver in keeping the vehicle inside its lane by adding a steering command to the one of the driver. In ICE vehicles, this is performed using a step of perception, where road markings are detected to compute the road curvature and the lateral deviation of the vehicle, and a step of control, where the vehicle trajectory is computed from the perception data. The LKAS is generally dedicated to highway situations and is effectuated by modifying the steering angle. This system is available on several passenger cars on the market :

- Lexus LS, where a stereovision algorithm provides the perception data to the control module.
- Ford Focus, with a monovision strategy measuring the lateral deviation and partially correcting the trajectory.
- Honda Accord, and Toyota Prius with a black and white camera detecting markings and correcting the trajectory.
- Fiat Lancia Delta.

Other car manufacturers propose what they call Lane keeping Assistant but, actually, it is closer to Lane Departure Warning than to real active system.

To control the vehicle trajectory, another command than the steering wheel angle is available: The torque vectoring (Raksincharoensak, 2006). Torque vectoring strategy consists in varying the torques on each side of the vehicle. Originally, this method was used to improve the vehicle traction capacities in poor weather conditions where a wheel on a side can begin to slip. In this case, the torque transferred to this wheel is reduced. This is performed using a torque vectoring differential mounted between the engine and the wheels.

Then, its basic principle has been used in ESC (Electronic Stability Control) to assist the vehicle in steering by applying the brakes differently on each side of the vehicle using a hydraulic modulator.

Nevertheless, one of the best application of torque vectoring is on electric vehicles (EV) equipped with in-wheel or dissociated central motors. Contrarily to other applications, EV do not need more mechanical components to perform a torque vectoring but only need a computation solution as all motors are already independent.

One of the objective of the ASIL (Automotive Safety Integrated Level) standards (ISO 26262) is to propose a hazard and risk assessment combined with a software and hardware design strategies. The hazard and risk assessment are concerned with determining safety goals, called ASIL level, for the studied item such that an unreasonable risk is avoided. The rationale of the ASIL level determination considers the estimation of the impact factors, that is, severity, probability of exposure and controllability:

- Severity: Measurement of the extent of harm to an individual in a specific situation. This impact factor is estimated between S0 and S3 defining the level of severity;
- Exposure: State of being in an operational situation that can be hazardous if coincident with the failure mode under analysis. This impact factor is estimated between E0 and E4;
- Controllability: Avoidance of the specified harm or damage through the timely reactions of the persons involved. This impact factor is estimated between C0 and C3.

Then, the final ASIL level, between A and D, is determined with the tables available in the appendices. This level is used to determine conditions on the software and hardware development.

1.3. Methodology

To achieve the goals of the study, the methodology is decomposed in several steps:

After a specification step, the required torques are computed from a linearized two-wheels two-degree-of-freedom model.

These computed torques are applied in a simulated scenario that could represent highway, interurban or rural road according to specific parameters (speed, grade).

Finally, ASIL standards are applied on this driving assistance system to evaluate the hazards and risks associated with the proposed LKAS on an electric vehicle.

The reminder of this study is organized as follow: section 2 presents the torque computation, section 3 describes the scenario simulation, section 4 details the ASIL level evaluation and section 5 concludes and proposes perspectives.

Nomenclature

$\Delta\Psi$	relative yaw angle between road tangent and vehicle speed vector (rad)
V	vehicle speed ($m.s^{-1}$)
Δy	lateral deviation of the vehicle centre of gravity from the medium line (m)
R	trajectory curvature radius (m)
r	required yaw rate ($rad.s^{-1}$)
r_w	wheel radius (m)
w	vehicle track (m)
M	yaw torque (N.m)
M_{max}	maximum yaw torque (N.m)
m	vehicle mass (kg)
l_r	distance from the center of gravity to the rear axle (m)
l_f	distance from the center of gravity to the front axle (m)
C_r	cornering stiffness of the rear axle ($N.rad^{-1}$)
C_f	cornering stiffness of the front axle ($N.rad^{-1}$)
β	vehicle slip angle (rad)
T	Wheel torque (Nm)
T_{max}	Maximum wheel torque for LKAS (Nm)

2. Modeling of the required torques

Run off road results on two different scenarios:

- Lack of attention, slow departure: distraction, drowsiness…
- Loss of control, fast departure: dynamic issue, high speed

The relevant parameter is the road relative yaw angle, $\Delta\Psi$:

- Slow departure: $\Delta\Psi$ is below 4°, secondary run off road may occurs, with $\Delta\Psi$ higher than 10°
- Fast departure: $\Delta\Psi$ is around 7°

In this study, we will focus on the first case on straight lines, supposing that the assisting torque is only dependant on $\Delta\Psi$, on the vehicle speed V.
In the case of a slow departure, to compute the required torque on the wheels, the first step is to estimate the curvature radius of the trajectory needed to avoid the run off road.

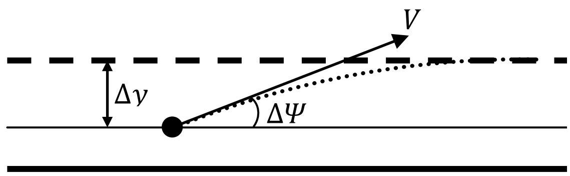

Figure 1: Vehicle trajectory

From Figure 1, the curvature radius of the trajectory can be expressed as:

$$R = \Delta y/(1 - \cos\Delta\Psi).$$

Then, the second step is to estimate the required yaw rate, r:

$$r = V(1 - \cos\Delta\Psi)/\Delta y.$$

When the vehicle is in a steady state, where variation of yaw rate and side slip angle are null ($\dot{\beta} = 0$ and $\dot{r} = 0$), the yaw torque required to generate this yaw rate can be assessed with a two-degree-of-freedom, two-wheel model. It can be proven that:

$$\begin{pmatrix}\dot{\beta}\\ \dot{r}\end{pmatrix} = \begin{pmatrix}a & b\\ c & d\end{pmatrix}\begin{pmatrix}\beta\\ r\end{pmatrix} + \begin{pmatrix}0\\ M\end{pmatrix} \Rightarrow \begin{pmatrix}0\\ -M\end{pmatrix} = \begin{pmatrix}a & b\\ c & d\end{pmatrix}\begin{pmatrix}\beta\\ r\end{pmatrix},$$

and:

$$M = \frac{bc - ad}{a} r,$$

where, M is the yaw torque, β is the vehicle slip angle and a, b, c and d are defined as follow:

$$d = \frac{2}{V}\left(l_r^2 C_r + l_f^2 C_f\right),\ c = -2\left(l_r C_r - l_f C_f\right),\ b = mV + \frac{2}{V}\left(l_r C_r - l_f C_f\right) \text{ and } a = 2\left(C_r + C_f\right),$$

where C_r and C_f are respectively the rear and front cornering stiffness, l_r and l_f the distance from the center of gravity to rear and the front axle and m the vehicle mass.

Figure 2 presents the transfer function versus the relative yaw angle and Figure 3 shows the yaw torque required with respect to the relative yaw angle. This torque is rather low for the operating range of the LKAS. Parameters used for this simulation can be found in Table 1.

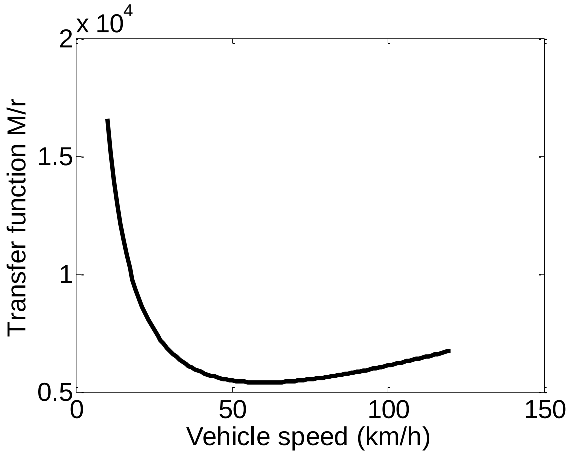

Figure 2: Transfer function according to the vehicle speed

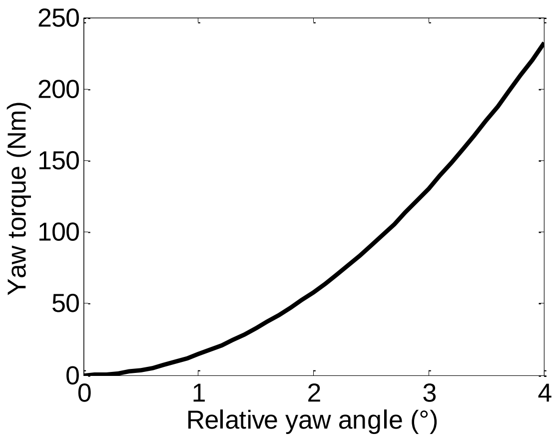

Figure 3: Yaw torque versus the relative yaw angle at $30ms^{-1}$

Considering this working conditions, the maximum torque magnitude T_{max}, applied on the wheels will be:

$$T_{max} = \frac{r_w}{w} M_{max},$$

where M_{max} is the maximum yaw torque, r_w is the wheel radius and w the vehicle track (distance between the two front wheels). We have $T_{max} = 46$ Nm that is a low value compared with torques needed to make the vehicle travel. For example, 46 Nm is the torque required to travel at a constant speed of 40 km/h on a straight line without slope.

Table 1. Simulation parameters

Parameter	Value	Unit
l_r	1.45	m
l_f	1.25	m
C_r	40000	N.rad^{-1}
C_f	40000	N.rad^{-1}
m	1618	kg

3. ADAS application

3.1. Vehicle trajectory

An ADAS application has been derived from the previous computations. Figure 4 shows in black the trajectory of a vehicle equipped with the LKAS function while the curve in red represents the trajectory of a vehicle without any reaction of the driver (distraction, drowsiness,...). The system succeeds in keeping the vehicle in its lane with the torque vectoring strategy

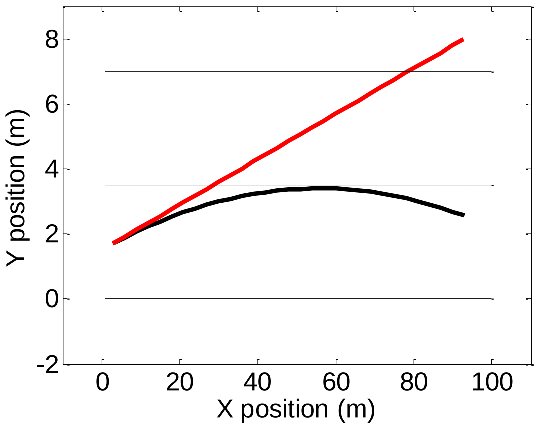

Figure 4: Vehicle trajectory controlled by LKAS in black, uncontrolled in red

However, the LKAS has to be tested according to the dynamic limits of the vehicle engines. The next section is considered

3.2. Considering torques limits

Within the eFuture project, chosen engines are two YASA 750 from YASA motors that have a maximum of 400 Nm continuous torque. To evaluate the dynamic limits in terms of road grade and vehicle acceleration Considering the maximum relative yaw angle of 4° at the maximum speed of 30 ms^{-1}, the maximum road grade and acceleration are given in Figure 5 and Figure 6. It can be noticed that, even in the worst scenarios, the vehicle is able to accelerate or to climb a rather steep slope.

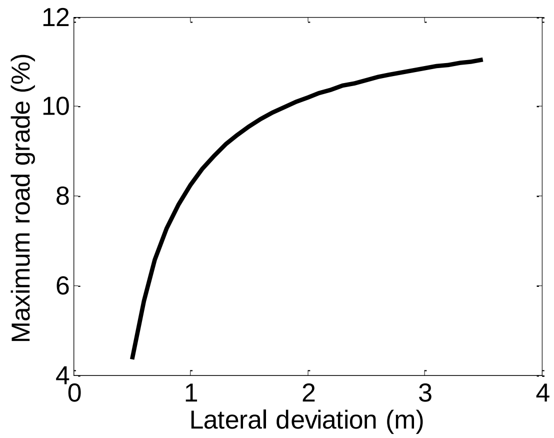

Figure 5: Maximum road grade according to lateral deviation at 30ms^{-1} without acceleration

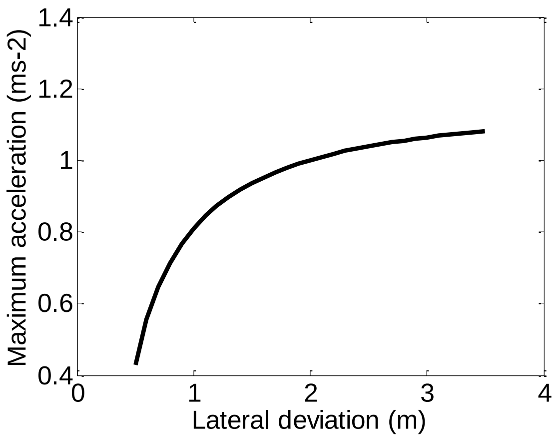

Figure 6: Maximum acceleration according to lateral deviation at 30ms^{-1} without road grade

4. Analyses and ASIL ISO standards

As presented previously, the ASIL level are evaluated using the severity, controllability and exposure impact factors. In the ASIL standards, every scenario of failure has to be investigated. The Table 2 lists the different failures that could occur in the LKAS function with the corresponding ASIL level.

Table 2. ASIL Level

Failure	Road scenario	Severity	Exposure	Controllability	ASIL Level
Right and left torque commands inverted	Highway, light traffic	S1	E2	C2	QM
Right and left torque commands inverted	Rural, light traffic	S2	E2	C3	A
Right and left torque commands inverted	Highway, heavy traffic	S2	E2	C2	QM
Right and left torque commands inverted	Rural, heavy traffic	S3	E2	C3	B

The safety level associated to the LKAS function using the torque vectoring is B meaning that the LKAS electronic components and software should designed according to this level. For example, for software design, an ASIL A means that the mechanisms for error handling have to propose a static recovery, a graceful degradation prioritizing functions but that there is no need of an independent parallel redundancy. A lot of other measures have to be taken, concerning the verification of the software, the notations used, the testing,...

5. Conclusions and perspectives

In this paper, a Lane Keeping Assistance System applied on an electric vehicle by torque vectoring has been proposed. It mainly consists of an active command (differentiated torques on front wheels) assisting the driver in order to keep the vehicle in its lane.

Torques required for this application are very low (in this specific domain of application). It permits to have a large range of dynamic limits.

While comparing required torques to available torques, it has been proven that in most situations, the LKAS will be able to keep the vehicle in its lane.

Finally, ASIL level has shown that the risk linked to the use of a such a system is rather low although an ASIL A classification means that some actions should be taken while designing software and hardware components.

In the next future works, the software and hardware architecture will be designed according to the ASIL standards and integrated on a real prototype.

Acknowledgements

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Appendices

Table 3. Classes of severity

Class	Description
S0	No injuries
S1	Light and moderate injuries
S2	Severe and life-threatening injuries (survival probable)
S3	Life-threatening injuries (survival uncertain), fatal injuries

Table 4. Classes of exposure

Class	Description
E0	Incredible
E1	Very low probability
E2	Low probability
E3	Medium probability
E4	High probability

Table 5. Classes of controllability

Class	Description
C0	Controllable in general
C1	Simply controllable
C2	Normally controllable
C3	Difficult to control or uncontrollable

Table 6. ASIL level determination

		C1	C2	C3
S1	E1	QM	QM	QM
	E2	QM	QM	QM
	E3	QM	QM	A
	E4	QM	A	B
S2	E1	QM	QM	QM
	E2	QM	QM	A
	E3	QM	A	B
	E4	A	B	C
S3	E1	QM	QM	A
	E2	QM	A	B
	E3	A	B	C
	E4	B	C	D