Safe, Dynamic and Comfortable Longitudinal Control for an Autonomous Vehicle

Andreas Reschka, Jürgen Rüdiger Böhmer
Institute of Physics and Technology
Universität Hildesheim
Hildesheim, Germany
{reschkaa, boehmer}@uni-hildesheim.de

Falko Saust, Bernd Lichte, Markus Maurer
Institute of Control Engineering
Technische Universität Braunschweig
Braunschweig, Germany
{saust, lichte, maurer}@ifr.ing.tu-bs.de

***Abstract*—Driver assistance systems are commonly available in many vehicles. There are systems for security functions like the Electronic Stability Control (ESC), Automatic traction control (ATC), Anti-lock Brake System (ABS) and automatic emergency braking. There are also systems for comfort functions like adaptive cruise control with stop and go functionality. In upper class vehicles systems like lane keeping and side-wind assistance combine security and comfort functions. A control system consisting of all of theses systems would allow comfortable automatic vehicle guidance on highways.**

In an urban environment, like in the Stadtpilot [1] project, traffic situations are more complex and therefore the requirements to driver assistance systems are higher. A single failure in an autonomous vehicle guidance system could lead to a severe situation for the passengers in the vehicle and the other traffic members. As there is no driver to interfere or react on a failure in an autonomous vehicle, all humans are passengers. An essential part of our autonomous vehicle control system is a longitudinal controller for acceleration and deceleration of the vehicle. This longitudinal control system has to take care of many more conditions than an assistance system. E.g. it needs to perceive and calculate road and weather conditions with its sensors which usually is a task the driver does instinctively. In this paper we present how our autonomous vehicle "Leonie" is able to adapt its longitudinal control to changing road and weather conditions by calculating a so called *Grip Value* and we give an outlook how this parameter affects the whole vehicle guidance.

I. Introduction

A. "Stadtpilot"

The Stadtpilot is a research project at the Technische Universität Braunschweig. The project goal is to drive fully autonomous on the multi-laned ring road around Braunschweig's city. Many different traffic members, bad GPS reception, traffic lights, intersections and changing road and weather conditions make the task of autonomous urban driving very challenging. The vehicle used in the "Stadtpilot" is a Volkswagen Passat called *Leonie* equipped with RADAR and LIDAR sensors, computers and IT infrastructure as described in [1] and [3]. The current research focus is autonomous lane changing, traffic light interaction and safety. This paper presents a safe, dynamic and comfortable longitudinal control system for Leonie.

B. Problem Description

In our scenario the vehicle has to drive in traffic flow on a multi-lane road, adapt its speed to other traffic members, take care of the safety distance and perform lane changes and turning maneuvers. If the road conditions are good, which means there is no dirt on the road, the road is dry and the temperature is above 4° Celsius, the control algorithms allow a smooth and dynamic driving in traffic flow. If road friction changes due to dirt or water a human driver would normally reduce maximum speed, acceleration and deceleration and he would be more careful with steering maneuvers. The human driver knows that dangerous situations occur more often in bad road conditions. If he is driving to aggressive or faces a dangerous situation, assistance systems like ESC, ATC or ABS help him to stay in control of the vehicle.

In an automatic controlled vehicle those systems are present, but it makes no sense to calculate gas, brake and steering values for dry conditions and let the assistance systems interfere if road friction is too low and the wheels would spin while accelerating. A better approach is to collect information about the road and weather conditions and to use this information in the longitudinal controller. Another benefit is the possibility to accelerate and decelerate the vehicle close to its friction limit, which allows dynamic driving, and to combine these dynamics with comfort parameters for passengers. They should not recognize that the road friction is lower or higher and they should not be confronted with spinning wheels while accelerating or blocking wheels when decelerating the vehicle. Altogether a safe, dynamic and comfortable longitudinal control is targeted.

C. Related Work

Research projects challenging the task of autonomous driving in urban environments, Berlin's Autonomos project[1], Stanford's autonomous vehicle Junior [2] and others, made many advances in the past few years and first results have been shown to public.

In [4], [5] and [6] several different approaches to friction estimation are described. These approaches are useful especially when they are implemented in the ECUs for ESC, ATC and ABS, but not if another control system on a higher level calculates the accelerator and brake values and works in parallel to the ECUs.

In 2010 an autonomous Audi TTS drove up the hill to Pikes Peak with several drifting maneuvers. In [7] its control system

[1] http://autonomos.inf.fu-berlin.de/

is described and the highly dynamic longitudinal controller is presented. The difference to this approach are the safety and comfort aspect for passengers and other traffic members.

Outline

In *Control Architecture* we present an overview of our system architecture and the relevant interfaces between the control system and the vehicle, including actuators and sensors used for our longitudinal control system. The *Proposed Solution* section starts with the requirements of our longitudinal controller and an overview of the proposed approach. In more detail we describe the Longitudinal controller, the Grip Value calculation and the fusion of the Grip Value and the control algorithm. The results are presented afterward and the paper finishes with acknowledgments and an outlook on future development.

II. Control Architecture

The autonomous vehicle Leonie has an interface to the actuators and the Controller Area Networks (CANs). This interface is called *Watchdog-Gateway* and allows external communication with the vehicles electronic control units (ECUs), the sensors and actuators. Connected to the Watchdog-Gateway is the *Stadtpilot Guidance and Control System* which is the main control system for Leonie. This system collects data from several RADAR and LIDAR sensors, an inertial measurement unit, a 3G router and a wi-fi access point. An overview of the relevant hardware for longitudinal control is shown in Figure 1.

Based on data from the vehicle and the environment sensors, the PCs plan a course through the city and calculate maneuvers to avoid collisions with other traffic members. To control the actuators a software package called *VehicleControl* creates cyclic CAN messages. Those messages are sent to the Watchdog-Gateway and then to the actuators. The Watchdog-Gateway validates the calculated values for the accelerator, brake and steering wheel to avoid dangerous control actions.

To secure the system operation a surveillance system is integrated, which monitors heartbeats, cycle times and control values. This system has a software component to calculate safety decisions as well. The most common safety decision at the moment is to give the full control of the vehicle back to the safety driver if a failure in the system is detected. Another function of this *SafetyDecisionUnit* is to calculate the Grip Value in the current situation. This calculation and the fusion of the Grip Value with the longitudinal controller values are presented in section III.

A. Actuators

For longitudinal control two actuators are relevant. The electronic accelerator can be controlled via the engine control unit and accepts values in a percentage scale from 0 (no acceleration) to 100 (full acceleration).

A brake booster actuator allows control of the vehicles brake system and can be controlled with pressure demands in bar reaching from 0 (no brake pressure) to 60 bar (full brake

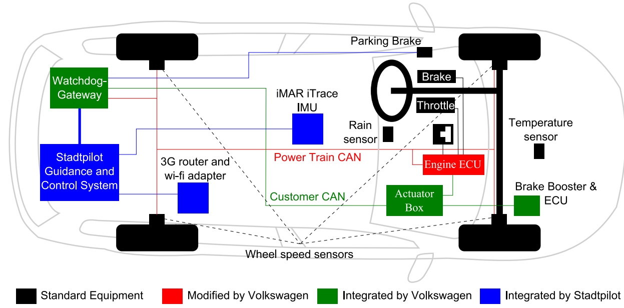

Fig. 1. Hardware architecture for longitudinal control.

pressure). Both actuators are controlled from the PCs via the Watchdog-Gateway and CAN.

The system prohibits a simultaneous use of the accelerator or the brake, which means that either accelerating or braking is allowed.

The vehicle's electronic stability program and brake assistance are activated as well to have a fallback solution if the calculated Grip Value is too high or the longitudinal controller is accelerating or decelerating too strong.

B. Sensors

There are several sensors involved in the longitudinal control system. The vehicles position is measured from the IMU as well as vehicle dynamics. The data provided by the IMU are an absolute GPS position and the vehicles longitudinal and lateral dynamics.

The only environment sensor used in this approach is a Hella IDIS® v2.0[2] LIDAR sensor, which detects the time gap to vehicles driving ahead of Leonie. The information provided is used to keep the safety distance and adapt the speed to traffic flow. This time gap is basic for the longitudinal controller in dry and clean road conditions.

Traffic light positions are stored in a digital map and traffic light states are collected via wi-fi or, if wi-fi is not available, the co-driver of Leonie. The traffic light infrastructure is provided by the German Aerospace Center (DLR)[3] and is set up in the project AIM [8]. The traffic light approach algorithms are developed in the project KOLINE [9]

The information necessary for Grip Value calculation is provided by the windscreen sensor which measures the current rain amount, a temperature sensor, the vehicle's wheel speed sensors and a surveillance system for ESC, ATC and ABS which detects activities of those systems. Especially the speed difference between the driving axle and the rear axle is necessary.

III. Proposed Solution

In this section we present our solution to realize a safe, dynamic and comfortable longitudinal control system. The section begins with the requirements, followed by an overview of the functionality and the approach. We present our longitudinal

[2]http://www.hella.com/
[3]http://www.dlr.de/

controller for dry conditions, the calculation of the Grip Value and finally the fusion of the longitudinal controller and the Grip Value.

A. Requirements

The main aspect of the control system is safety for all traffic members and the passengers inside Leonie. Therefore safety decision are always higher prioritized than comfort and dynamic functions. While driving on a dry and well-developed road the friction is high enough to avoid spinning or blocking wheels without an additional Grip Value calculation. If the road gets wet the friction between the road surface and the wheels decreases. If the temperature sinks below 4° Celsius the friction decreases [4] even more due to ice on the road or at least the chance of ice and snow is considered and Leonie needs to drive more carefully.

To increase safety three actions are required. The first one is to reduce the vehicle's maximum speed to stop faster in emergency situations and to approach red traffic lights more comfortable. The second one is to increase the safety distance (time gap) to vehicles ahead of Leonie. This improves the chance to react on braking maneuvers of vehicles ahead. The third action is to reduce the accelerator requests to avoid spinning wheels.

Of course it is possible to reduce the maximum speed always and increase the time gap to a higher value, but then other vehicles would more often overtake Leonie and move into Leonie's lane. This is why the longitudinal controller has to drive dynamically enough not to block traffic flow. Additionally when changing lanes a low relative speed to the vehicles on the target lane simplifies lane change maneuvers.

The third requirement are comfort issues for the passengers. It is uncomfortable when an automated vehicle accelerates with spinning wheels or brakes with ABS interference. Therefore the acceleration and deceleration values have to be reduced to a comfortable way whenever it is safe to do so. Considering emergency situations, e.g. a suddenly occurring obstacle where rapid braking is necessary, the brake pressure must not be reduced.

Altogether a combination of safe maximum speeds and distances, dynamic driving to avoid blocking traffic flow and comfortable accelerating and decelerating the vehicle promises best results.

B. Approach

To realize this trade-off a longitudinal control algorithm for dry weather and good road conditions is implemented and is the standard case for autonomous driving. To improve its performance the Grip Value, which is not a friction estimation, but an indicator for potential changes of the road conditions, is used as input to the controller. It is a basic value for reducing acceleration, changing the desired time gap to other vehicles and reducing the allowed maximum speed. The calculated value reaches from 0 (no grip) to 100 (dry weather and good road conditions). For each point the value is lower than 100 it leads to an increase of the desired time gap, a decrease of the maximum speed and a decrease of the allowed accelerator value. This reduces the risk of collisions or loss of control of the vehicle and improves comfort for passengers while still driving in traffic flow.

The approach is divided into four steps, illustrated in Figure 2 and described below. The cyclic operation has a cycle time of 10 milliseconds which results in a frequency of 100 Hertz.

1) Data acquisition from rain sensor, temperature sensor, ESC/ATC/ABS and wheel speed sensors
2) Calculation of Grip Value. For each input and the combination of input values a value for decreasing the Grip Value is calculated and applied to the Grip Value.
3) Fusion of Grip Value and longitudinal control algorithm. The Grip Value influences the output of the controller.
4) Application of the calculated value to the accelerator and brake. It is not possible to set both actuators to a value higher than zero at the same time to avoid braking and accelerating at once.

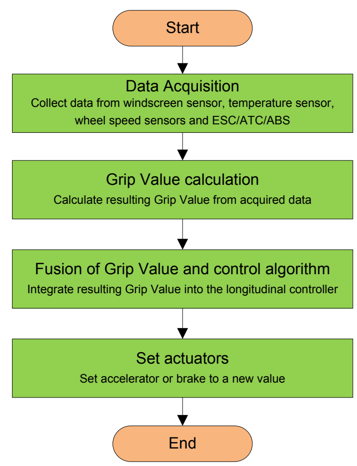

Fig. 2. Sequence of actions in the approach.

C. Grip Value calculation

The grip Value calculation starts after data acquisition and consists of several steps. Figure 3 shows a flow chart of the calculation.

The most significant indicator for a low grip is the interference of ESC, ATC or ABS. If an interference is recognized it reduces the Grip Value instantly by x_i. As the calculation is done with 100 Hertz, and it is possible to reduce the Grip Value in every iteration, a longer lasting interference causes a rapid decrease of the new Grip Value g_n. This is done to react fast on spinning wheels while accelerating, but has no influence on braking maneuvers, because otherwise an emergency braking could get interrupted or the brake pressure is calculated too low. Equation 1 shows the calculation.

$$g_n = g_{n-1} - x_i \tag{1}$$

The second indicator for a low grip is the difference between the average of the wheel speeds from the front driving axle

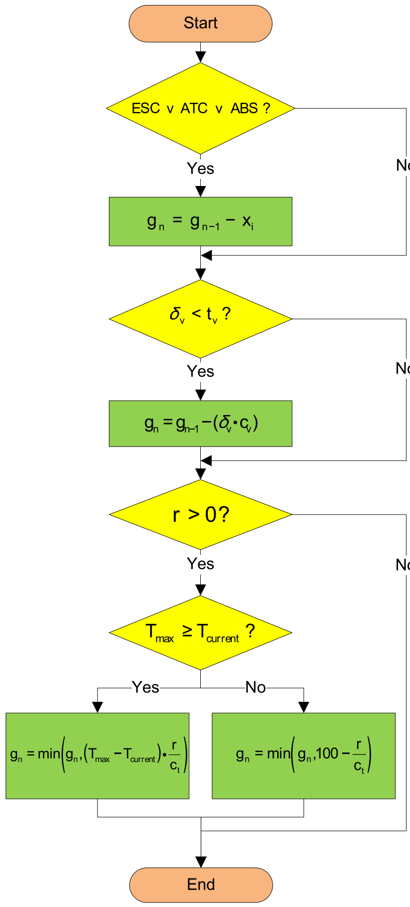

Fig. 3. Flow chart of Grip Value calculation.

and the rear axle. Usually the wheels on the driving axle spin faster than on the rear axle while accelerating. Therefore it is possible to calculate the difference δ_v which represents the current wheel slip in $[\frac{m}{s}]$ and compare it to a threshold t_v. More information about the wheel slip and methods of its estimation can be found in [4] an [5]. If the value is higher than the threshold, the Grip Value is reduced. Equation 2 shows the reduction of the Grip Value g_n. δ_v is multiplied with a coefficient parameter c_v which can be used to parametrize this equation. The resulting reduction is additional to the ESC/ATC/ABS reduction of g_n.

$$g_n = g_{n-1} - (\delta_v \cdot c_v) \tag{2}$$

The rain amount is an indicator for a wet road. If it is raining strong, the measured rain amount is high and the grip Value is reduced. The vehicles rain sensor detects 8 different values from 0 (no rain) to 7 (maximum rain). Each of these levels causes a decrease of the Grip Value only if the resulting Grip Value is smaller than the previously calculated. Therefore the minimum of the current Grip Value g_n and the reduced Grip Value due to the rain amount is used. As the rain amount r is a multiple of 14.285 in the sensor output, its values reach from 0 to 100. To avoid a too strong reduction of g_n this value is divided by a coefficient c_r and is subtracted from the basic Grip Value of 100. The coefficient c_r can be used to parametrize equation 3.

$$g_n = min\left(g_n, 100 - \frac{r}{c_r}\right) \tag{3}$$

The temperature value $T_{^\circ C}$ is not used for a direct reduction of the Grip Value, but in combination with the rain amount it is another indicator for a potential risk because of ice and snow. If the temperature decreases to T_{max} or below and the rain sensor detects rain r, the Grip Value is not reduced by equation 3, but by equation 4. Again the coefficient c_t can be used to parametrize this equation. The resulting reduction is higher compared to equation 3, because of the higher risk.

$$g_n = min\left(g_n, (T_{max} - T_{current}) \cdot \frac{r}{c_t}\right) \tag{4}$$

Due to continuously changing road conditions the calculation frequency promises a fast reaction on changes. If the grip Value is not reduced within 10 seconds it is reset to value of 100. This means that if no ESC/ATC/ABS interference is detected, the speed difference between driving and rear axle is always smaller than 0.5 and there is no rain detected, Leonie drives carefully for another 10 seconds before the Grip Value is set to 100 and the dry mode is reactivated.

After each iteration the Grip Value is sent to the longitudinal controller which calculates the next accelerator or brake value with the same frequency.

D. Longitudinal Control algorithms

The realization of the driving behavior is based on the low level control divided in lateral and longitudinal controller.

The vehicle's longitudinal control strategy is based on the "Intelligent Driver Model" [10] to adapt a realistic and stable car-following behavior. The current desired acceleration of the vehicle $\dot{v}$ is calculated by

$$\dot{v} = a \cdot \left(1 - \left(\frac{v}{v_0}\right)^d - \left(\frac{s^*}{s_a}\right)^2\right) \tag{5}$$

$$s^* = s_0 + T \cdot v + \frac{v \cdot \Delta v}{2\sqrt{a \cdot b}} \tag{6}$$

with the gap s_a, the velocity difference Δv to the vehicle ahead, the desired velocity v_0, the safe time headway T, the maximum acceleration a, desired deceleration b, the acceleration exponent d, and the jam distance s_0 [10]. Autonomous driving in urban environments requires also the correct reaction to traffic lights at signalized intersections. If a braking maneuver is required, red traffic lights are handled as virtual targets by the model. The vehicle adjusts its speed to both real targets in front of "Leonie" and virtual targets according to the higher necessary deceleration.

The longitudinal control consists of two different control loops for acceleration and deceleration in a cascade controller structure [11]. Generally, the reference input can be either a desired acceleration or a given speed. An additional feedforward based on an inverted engine and drive train model generates both a necessary engine torque and a necessary deceleration. Using an engine map the gas pedal position and the braking pressure, respectively, is calculated. A defined state machine assures the transitions between acceleration and deceleration to prevent the simultaneous use of throttle and brake.

TODO: Die Umrechnung der Sollbeschleunigung in die Gaspedalstellung wird nicht sichtbar

TODO: Hier könnte noch ein Bild der Reglerstruktur eingefügt werden

E. Control and Grip Value fusion

The calculated Grip Value can be used in three parts of the longitudinal controller.

1) The desired velocity v_0 can be reduced to drive slower.
2) The safe time Headway T can be extended if the Grip Value is lower than 100. This allows safer driving behind other vehicles and a safer approach to obstacles and traffic lights.
3) The maximum allowed accelerator value can be reduced to accelerate smoother with less wheel spin in bad road conditions.

The following fusion procedure is for the accelerator value only. The other two possibilities are not considered in this paper and will be described in a future publication together with the influence on lateral control.

In each iteration new accelerator and brake values are calculated by the control algorithm with respect to desired speed and distance to objects, vehicles and traffic lights. After this calculation the Grip Value g_n is applied to the resulting accelerator value acc_n if the brake value is zero and the accelerator value is higher than a threshold acc_{min}. Equation 7 shows the influence of the Grip Value. The fusion coefficient c_f is used to parametrize this equation. Its value is both, a minimum border and a factor which is applied to the Grip Value to guarantee values between 0 and 100 for the accelerator.

$$acc_n = min\left(acc_n, c_f + acc_n \cdot g_n \cdot \frac{\left(1 - \frac{c_f}{100}\right)}{100}\right) \quad (7)$$

With this reduction the acceleration of the vehicle is supposed to be more comfortable and with less ESC/ATC interference on roads with reduced friction and with comparable vehicle dynamics.

IV. Results

To measure the performance of the control system several test drives were done. The following data relies on automated driving in snowy road conditions. The road was covered with three to five centimeters of wet snow. The vehicles task was an automated acceleration from 0 to $14\frac{m}{s}$. Figure 5 shows the velocity profile, the acceleration profile and the accelerator and Grip Value profile for an acceleration without Grip Value consideration. Additionally the ESC interference is shown in each of the figures because our target is to reduce this interference as a human driver would try to do. A value of 100 shows a ESC interference, a value from 0 shows no interference.

The ESC/ATC interference in this test drive was about 6.75 seconds long starting at 0.5 seconds which means that most of the acceleration was done with ESC interference. This leads to an uncomfortable acceleration process as the acceleration profile shows. The acceleration values of the vehicle reaches from -0.5 to $4.0\frac{m}{s^2}$.

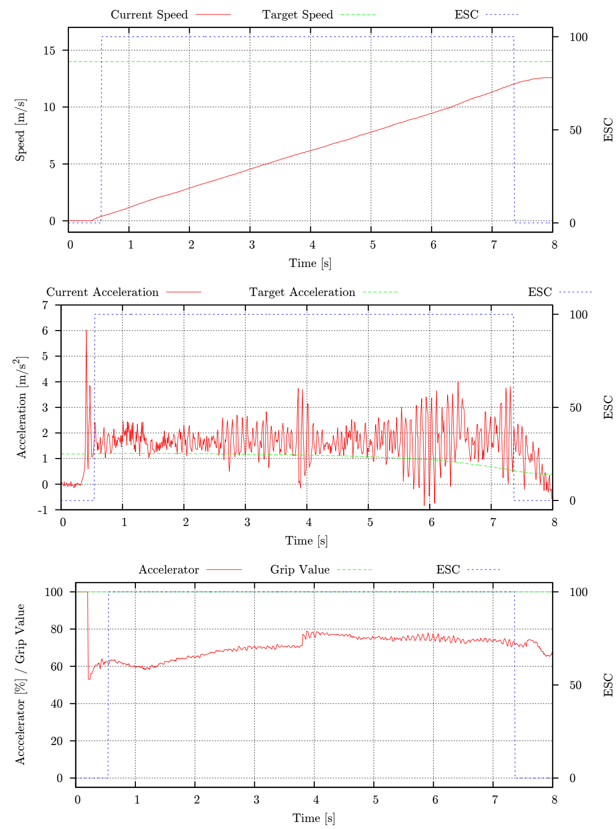

Fig. 4. Speed, Acceleration and Grip Level without Grip Value

Figure 4 shows data of a representative acceleration with Grip Value consideration. The graphs show that the acceleration did not last much longer but had lesser ESC interference and the acceleration profile is smoother and therefore more comfortable for passengers. There is also lesser wheel spin.

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V. Conclusion

In this paper we introduced the calculation of a so called Grip Value as an indicator for bad road conditions. This Grip Value influences the magnitude of accelerator demands for our longitudinal controller. The test drives showed good results with reduced ESC/ATC interference and a smoother acceleration profile.

In future development the Grip Value will be used to adapt the safety distance to other traffic members and to approach obstacles and traffic lights smoother to avoid ABS interference. Additionally the lateral controller can be influenced by the

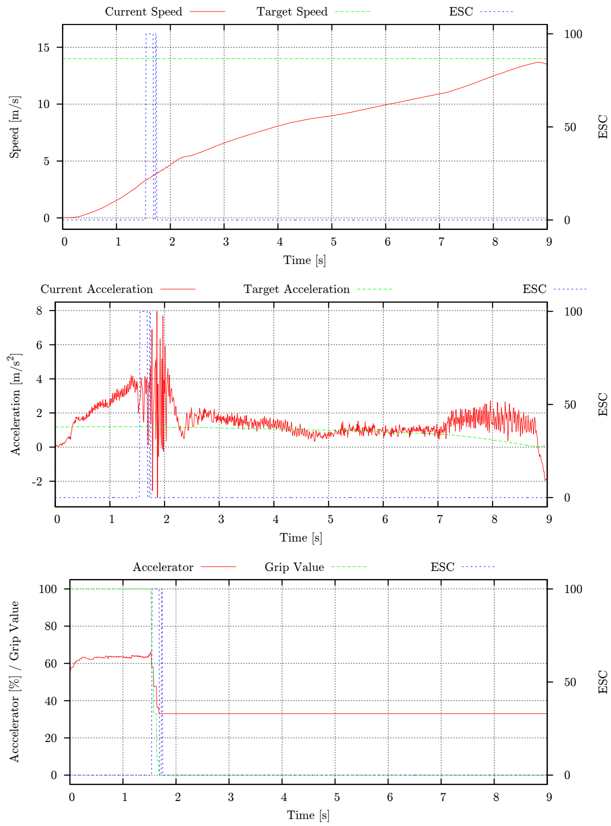

Fig. 5. Speed, Acceleration and Grip Level with Grip Value

Grip Value calculation and it can be used as an input to our path planning system to reduce speeds for planned trajectories when the weather conditions are not perfect as well.

ACKNOWLEDGEMENT

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