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A complete framework for developing and testing automated driving controllers

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Abstract: Intelligent vehicles have improved their highly and fully automated driving capacities in the last years. Most of the developments are driven by the fast evolution of embedded systems for the acquisition, perception and communication modules. However, the fast growing of the automated vehicle market demands modern tools for validation, integration and testing of these new embedded functionalities, specially related to Advanced Driving Assistance Systems (ADAS). In this paper, a testing methodology for validation of path planning and control algorithms for current and future automated vehicles is presented. A high degree of modularity and adaptability have been considered in the design of the proposed method. It is based on a software tool for vehicle modeling, called Dynacar, which allows a good trajectory definition, cooperative maneuvers interaction and virtual validation. Different types of vehicles, scenarios (i.e.: urban, interurban, highways under different environmental conditions) and controllers can be tested. Moreover, Hardware-In-the-Loop configuration (i.e. electronic control units) can be also tested. Simulation results show a good performance in the implementation and configuration of urban scenarios, using different controllers in the proposed framework.

Keywords: Intelligent transportation systems, control architectures in automotive control, simulation, control validation, control testing.

1. INTRODUCTION

Nowadays, Advance Driver Assistance Systems (ADAS) and automated driving capacities are becoming a reality in mass-produced vehicles Policy (September 2016). These systems contribute to the reduction of accident rates on highway and urban scenarios, due to human driver errors. The validation of these new functionalities, and the remarkable complexity they involve, requires modern tools to integrate and test new scenarios and vehicles.

Different simulation environments are rather related to the acquisition, perception and communications stages, as in Bounini et al. (2015). Other approaches are focused in model identification (Dias et al. (2015)), based on real data from an instrumented vehicle. However, from the control point of view, almost exclusively linear longitudinal models have been considered for low speeds controllers, where the main applications include parking and adaptive cruise control.

In the automotive industry, virtual testing considerably contributes in the cost reduction of the validation and testing stages of the new intelligent functionalities, as have been presented in the DESERVE project (Kutila et al. (2014)). The goal is to develop and adjust control algorithms without the need of constantly testing them in real scenarios all the time, due to legislation limitations.

Since the development process and the validation of the embedded controller are becoming more complex, a solution for testing the modules of decision makers, path planning and control is needed. Based on the general architecture for automated vehicles used by most of the researcher groups and the automotive industry around the world González et al. (2015), in this paper, a testing framework for the validation of decision, planning and control algorithms is presented. The approach considers the 6 main stages: acquisition, perception, communication, decision, control and actuators, and the automation levels defined in SAE J3016 standard SAEJ3016 (2014) for automated driving. The solution allows a real time performance, based on software and hardware module independence. This is a valuable advantage for testing certain ADAS functions with on-board ECUs for modern vehicles, and even to emulate the setup from data acquisition sensors, as in Differential GPS. Our approach is useful to validate, first in simulation and then using HIL methods, the most common individual and cooperative maneuvers (i.e.: overtaking, intersections, merging, roundabouts, platooning, etc).

The rest of the paper is organized as follows: a review of simulation tools for automated vehicles is provided in Section II. Details of the implementation of the Dynacar simulator are also given. Section III explains the proposed testing framework. Validation and tests results are described in Section IV. Finally, conclusions and future works are listed in Section V.

2. CURRENT STATE OF MODELING AND SIMULATION ENVIRONMENTS FOR ADAS

As discussed in the introduction, vehicle simulators are very valuable for validation and testing of new functional-

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ities for automated driving. In order to increase security and safety of new algorithms, more accurate dynamic models in simulation environments are needed in the automotive research and industry.

Robust dynamic models, based on a correct environment modeling, will lead a reduction of development cost of the new ADAS. In this section, a description of the most relevant simulators available on the market is presented.

2.1 Civitec Pro-Sivic

This tool has been designed as a sensor simulator by the company CIVITEC, mainly oriented to perception and ADAS developments. It gives the opportunity to simulate a variety of complex scenarios like intersections, roundabouts, multiple vehicles and pedestrians on the road, and different weather conditions such as rain, fog, snow, brightness and others. Moreover, it has the potential of being connected with RTMaps platform to test new algorithms. Some applications use Simulink/Matlab platform to communicate it with the Pro-SIVIC simulator to test cooperative algorithms on automated vehicles Bounini et al. (2014).

2.2 CarSim and TruckSim

CarSim and TruckSim are products of the Mechanical Simulation Company. They were developed to use dynamics vehicle models, for passenger cars and light trucks, respectively.

This simulator is oriented to validation and ADAS, i.e.: obstacle avoidance algorithm using model predictive control Abbas et al. (2014), robust control for in-wheel motor vehicles Gaspar et al. (2014) and dynamic trajectory generation Hafner and Pilutti (2014).

2.3 Tass international PreScan

PreScan of Tass international is a simulator that is specialized on sensor modeling like GPS, vision, laser, radar, accelerometer and odometry. It is also based on Matlab/Simulink. They have a full spectrum camera simulation for reliable virtual development and validation of automated driving applications Molenaar et al. (2015).

2.4 SCANeR

SCANeR Studio is a software suite for HiL driving simulations. It is developed by OKTAL, and is based on works of the Vehicles Simulation and Perception research group of Renault and works of SERACD.

Several European projects have been used as background for the development of the software, for instance Prometheus, TRaCS (TRuck and Coach Simulator), CARDS (Comprehensive Automobile R&D Simulator).

2.5 SPEOS VRX OPTIS

Based on the previous experience in SPEOS driving simulator platform, OPTIS has developed the SPEOS VRX environment for ADAS and Automated Driving testing. This tool is focused on the acquisition of different sensors embedded in the vehicles. It includes camera, LIDAR, infrared sensors, among others. They also provide a 3D view of the car environment in 360 degrees.

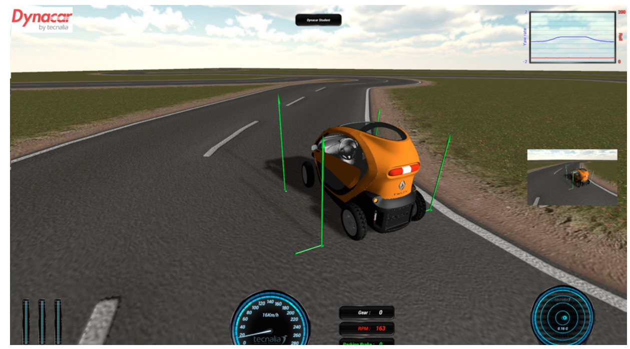

Fig. 1. Dynacar by Tecnalia

2.6 Tecnalia Dynacar

Dynacar (figure 2) is a simulation tool developed by Tecnalia Research and Innovation which provides a real-time vehicle model covering multiple domains. It focuses on vehicle dynamics, providing a high-fidelity vehicle physics simulation basing on a multibody vehicle model. This is combined with a Pacejka tire model and sub-models for elements like the engine, transmission, steering system, braking system, aerodynamics, etc Iglesias (2015).

Dynacar allows real-time and accelerated-time simulations. The real-time capability is very valuable, as, combined with its notable modularity and interfacing options.

This work is based on Dynacar's capabilities, using them to implement automated driving maneuvers. A testing methodology for the validation of control algorithms for future automated vehicles is presented. The modularity and adaptability has been exploited in the design of the proposed method based on the a general control architecture for automated driving presented in González et al. (2015). It enables a good trajectory definition, cooperative maneuvers and virtual validation with different kind of vehicles and scenarios.

3. PROPOSED TESTING ARCHITECTURE

The proposed framework is illustrated in figure 2. It includes a highly representative dynamic model of the vehicle to test automated capacities, as: real-time path generation, control, communication and other algorithms that can be embedded in an ECU.

The apporach presented in this paper has been implemented in Matlab-Simulink, as, besides being widely established in research and industry, it permits to integrate C-code functions and provides convenient interfacing capabilities (figure 3).

The main components of the automated driving environment are:

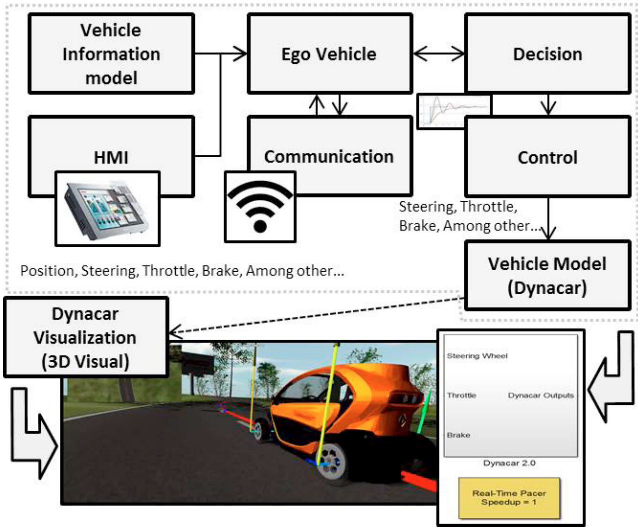

Fig. 2. Architecture framework for automated Driving

3.1 Vehicle Information Model

This module is responsible to adapt the signals of position, speed, among others, from the simulator. It provides the same magnitudes and units, as will be received on the real platform from the different sensors (GPS, odometry, lasers, among others).

One of the most relevant feature of the proposed framework is related to scalability of data from the simulator to the real platform.

The acquisition module will generated the values of X-Y coordinates, heading angle, speed and wheel angle directly scaled to used them. This module feeds the perception block (Ego-Vehicle).

3.2 HMI

The human machine interface (HMI) is responsible for communicating real-time information and configuration parameters to the modules as in the real vehicle. It represents the bridge of interaction between the automated driving platform with the user.

3.3 Communication

This module incorporates the possibility to simulating V2X (vehicle to X) communication, which is relevant in the process of testing cooperative maneuvers and more complex scenarios.

The platform is useful to test the actions that should be performed by the vehicle in loss or signal degradation scenarios due to the influence of infrastructure or other vehicles.

3.4 Ego-vehicle

The ego-vehicle module is responsible to gather data from the vehicle information model, HMI and communication modules to the decision and control modules. This module will pack the information and configuration parameters of the vehicle for the rest of the following modules.

To keep the modularity, the ego-vehicle module will generated as output a structure that contain the algorithms specifications, vehicle parametrization values, input values in raw data (information coming from the vehicle model) and the scaled values based on the HMI configuration values.

3.5 Decision

The decision module is separated in two blocks: Global and Local planners, based on the review of the path planner techniques for automated vehicles González et al. (2015). The first one provides the route to be followed, and the second generates a real-time dynamic planning.

Global planner: The global planner is in charge of reproducing the route that will be followed by the vehicle. It considers the information of the starting and the ending points, and even the possible changes of routes through the HMI.

This path should be accurate to generate a soft local planner. Special configurations of urban environments should be considered such as intersections, roundabouts and merging.

Local planner: Based on the information coming from the global planner, a soft trajectory is generated using parametric curves as in Pérez et al. (2013a). Here, the aim is to smooth the curvature change between the straight segments and curves.

The local planner considers the possibility of generating continuous trajectories in case of an unexpected scenarios such as obstacle avoidance and merging, among others. Intelligent dynamic algorithm for trajectory generation has been implemented as in Rastelli et al. (2014). To generate these trajectories are used for example bezier curves as in González et al. (2015). These curves are easy to implement, and they reproduce a soft curvature with a reduced computational cost.

Planning buffer: A communication buffer between the decision and control modules is defined to generate sudden change in the horizon view of the local planner. It will optimize and increase the response time of the control law calculation. Any unrealistic trajectory (i.e. if an obstacle is detected in front) will be deleted before being sent to the control mode.

Each point of the buffer will have the values of identification number of the point, type (roundabouts, intersections, lane changes, etc.), x-y coordinates, maximum speed of the path segment, curvature and heading angle (orientation of the segment).

3.6 Control

This module receives the buffer information from the decision stage, and it is responsible for the lateral (steering) and longitudinal (acceleration and breaking) control.

For instance, PID controllers for lateral and longitudinal response can be used. In the case of the lateral control, the lateral, the angular error and the curvature. Other techniques, as fuzzy logic as in Pérez et al. (2013a), model

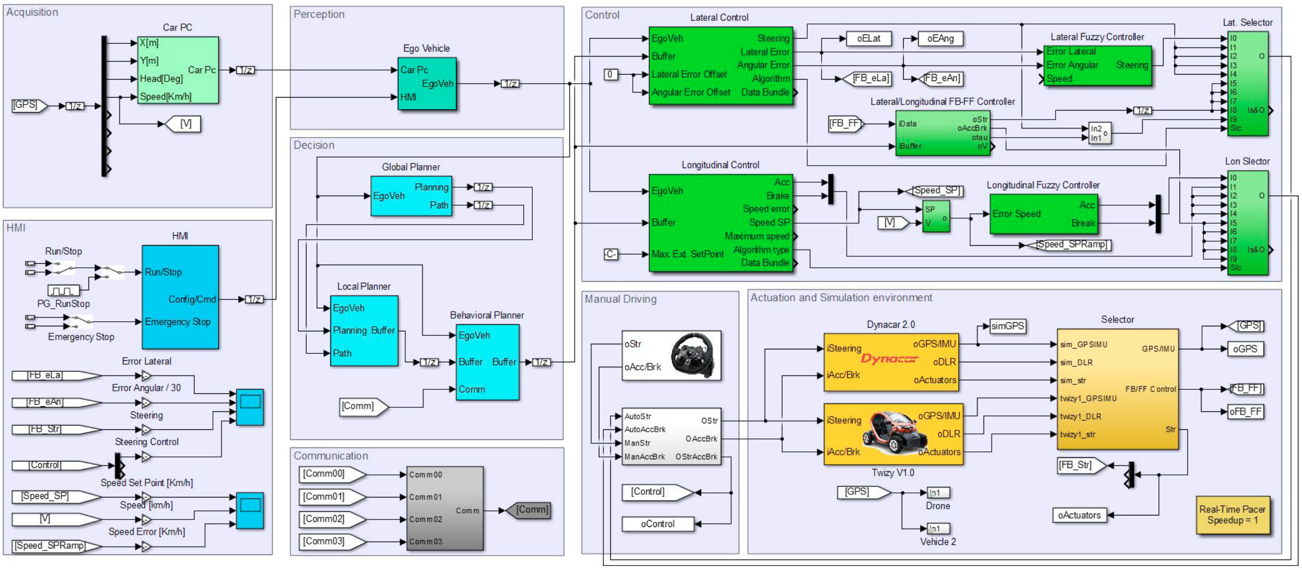

Fig. 3. Automated driving testing tool and interaction with 3D model

predictive control, among others, will be easily integrated in our framework.

The control out are signals for the actuators of the steering wheel (normalized between -1 and 1), and the acceleration and brake pedals. The last two signals are normalized between 0 and 1.

3.7 Vehicle model and visualization

The Dynacar multibody simulator has been used to model the real vehicle. Additionally, the visual system provided by this tool enables real tima monitoring of the algorithms implemented.

3.8 Hardware In the Loop configuration

The existing Dynacar platform was conceived to enable diverse HiL setups, including automated driving algorithm developments, through a physical ECU. It can be used to perform validation tests, which will be later deployed on the real vehicle by connecting the ECU to a virtual Simulink-based environment and subcomponent models, through the Dynacar framework. As this includes a multibody model, the reactions and feedback signals are very realistic. Furthermore, the ECU can interact with Simulink over a physical CAN bus, using the real vehicles DBC (CAN database file), therefore handling the messages as they will occur on the car.

4. RESULTS AND VALIDATION

This section shows the modularity of our approach, testing different lateral controllers in the same framework. Moreover, we show how parametric curves can be implemented on the local planner, to easily model urban intersections.

4.1 Tests of planning algorithm

Figure 4 shows an urban scenario, including intersection sand roundabouts. The black markers show the global

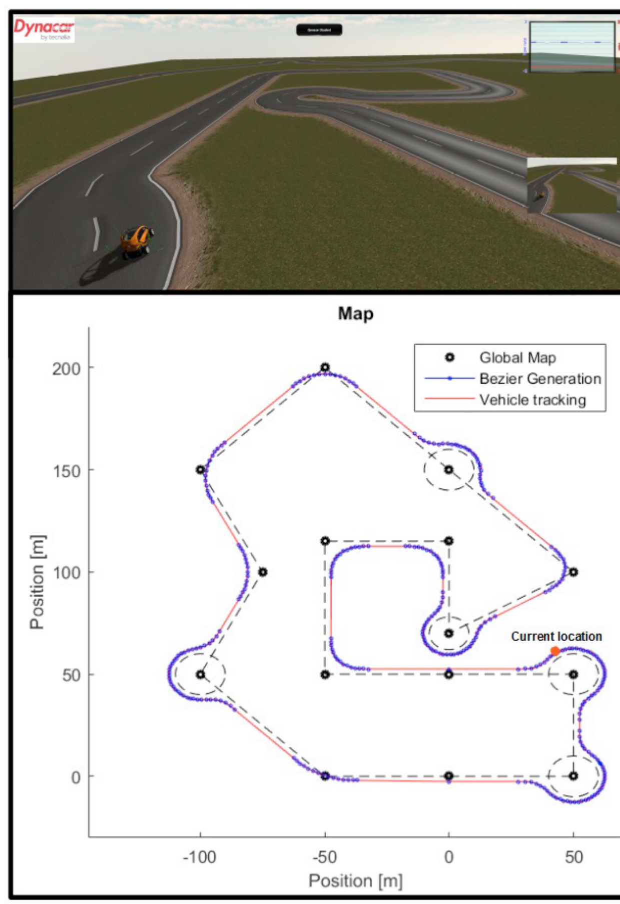

Fig. 4. Urban scenario route.

map, modeling five roundabouts and ten intersections. The local planning points are plotted on blue color and the red line represents the tracking of the vehicle.

4.2 Tests of lateral control algorithm

To validate the model, diverse tests have been made on the lateral control. Five different controllers were used,

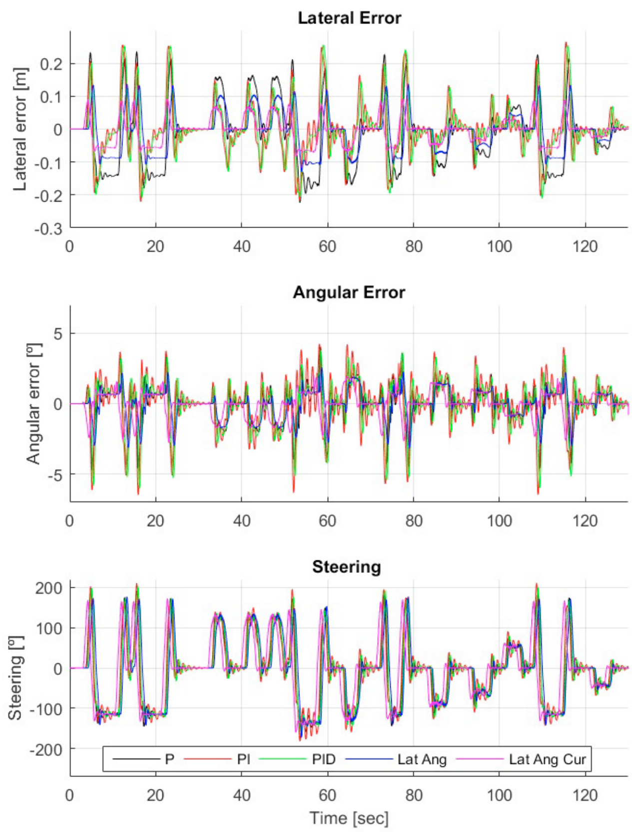

Fig. 5. Data recorded at 25 km/h.

considering lateral error, angular error and the curvature as parameters.

Figure 5 shows the controllers tested at 25 kilometers per hour. The upper part of both figures shows the evolutions of the lateral error, i.e.: the higher speed reference value, the higher lateral error. The other graphics show the angular error and steering output in each experiment.

Proportional (C1) The proportional controller -represented in black on figure 5- delivers the worst behaviour regarding error.

Proportional-Integrate (C2) The PI controller -represented in red on figure 5- delivers a better result, reducing the lateral error in comparison with the proportional controller but increases the presence of stronger overshoots and the time to stabilize is longer.

Proportional-Integrate-Derivative (C3) The PID controller improves the results of the first two controllers, with the reduction of the lateral error and the overshoots produced by the integrate part. This is represented with a green color line.

Lateral error and angular error equation (C4) This controller is based on Pérez et al. (2013b), established on the lateral and angular errors, with a proportional and derivative action, respectively. K_1 and K_2 are the gains fixed manually on the vehicle. In this sense, the equation used in the fourth control law is:

$$C_v = K_1 * e_{lat} + K_2 * e_{ang} \tag{1}$$

This presents results similar to the PID controller, but reducing even more the lateral error. The tuning process was simpler than in the PID case, because only two variables were used. It was plotted with a blue color line.

Lateral error, angular error and curvature equation (C5) A double proportional (using lateral error and angular error) controller was used to tune real vehicles in Rastelli et al. (2014). An improvement of this method before, it is showed as follow:

$$C_v = K_1 * e_{lat} + K_2 * e_{ang} + K_3 * Curvature \tag{2}$$

This equation includes a third parameter. The curvature improves further improvements over the lateral error in comparison with the PID. This last controller is represented with a pink color line on figure 5.

Table 1. Mean lateral error for different controllers.

	Lat. error 15km/h $[m]$			**Lat. error 25km/h** $[m]$		
	Mean	**Median**	**Max.**	**Mean**	**Median**	**Max.**
P	0, 063	0,049	0,19	0, 067	0,044	0,24
PI	0, 036	0,016	0,17	0, 052	0,027	0,27
PID	0, 036	0,015	0,18	0, 051	0,024	0,26
C4:	0, 023	0,018	0,07	0, 040	0,028	0,14
C5:	0, 024	0,019	0,07	0, 026	0,018	0,09

Human intervention in the control loop: Sharing control and arbitration are of increasing interest in future researching activities. In this sense, the current architecture gives the opportunity of switching between both automatic and manual control to test these new approaches.

4.3 Longitudinal control

The test presented in figure 5 were performed on constant speed, using a PID controller, for both speeds.

Our approach is capable of dealing with profile speeds adapted to the curvature of the path. Figure 6 shows the behavior with consecutive curves and roundabouts, using a *fairy uncomfortable* lateral acceleration (based on Labakhua et al. (2008)).

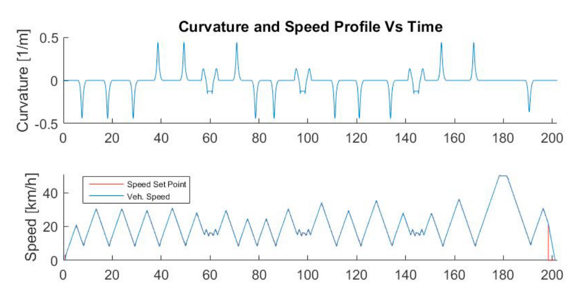

Fig. 6. Speed profile for urban scenarios, based on the curvature

5. DISCUSSIONS AND CONCLUSIONS

Figure 4 shows how an urban scenario was modeled for testing a planning algorithm considering urban scenarios (with multiple roundabouts and intersections) and, the dynamical characteristics and conditions of a Renault twizy (Vehicle model used). However, this platform is fully capable to change to other vehicle dynamics.

Different lateral control algorithms were tested. On table 1 presents a comparison of mean, median and maximum values for the lateral error with respect to the reference line.

These results demonstrate how lateral control algorithms are tested on the virtual platform using low (15 km/h) and average (25 km/h) speeds in urban areas, and how each controller is compared among them (see table 1). Moreover, a speed profile generator based on the path curvature was presented. The current framework is able to test high speed scenarios. In this paper are presented different control techniques to validate the automated capabilities of an electric vehicle at different speeds in urban scenarios.

6. FUTURE WORK

On the last two years, the developments on automated driving functions have been increased significantly. On the current approach, a complete framework for automated driving testing has been presented with different controllers and path planning algorithm in urban scenarios.

The current approach allows testing different blocks for the validations of automated driving vehicles. Safety and security will be considered in future implementations over the methodology to have a higher level of integrity, as addressed by the ISO-26262 standard.

Lateral acceleration and comfort will be considered in the current platform to validate them for embedded longitudinal and lateral controllers. Fault injection for safety and controllability evaluation in different scenarios can be also tested. Finally, communication among vehicles and infrastructure will be tested considering dangerous situations like package data lost or corrupted information.

This work is developed in the context of EU and national projects. Next steps are related to the implementation and validation of different scenarios for real automated vehicles (i.e.: two lines intersection, overtaking, cooperative roundabouts, etc).

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