Validation of Renault's dynamic simulator for Adaptive Cruise Control experiments

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RESUME

Le simulateur dynamique de Renault a été installé en 1999 à la Direction de la Recherche et est aujourd'hui devenu un outil complet destiné à la recherche et développement automobiles. Les études sur l'interaction véhicule-conducteur sont rendues possibles grâce à l'utilisation d'une plate-forme mobile 6 axes qui restitue, avec un niveau de réalisme satisfaisant, les stimuli de mouvement de caisse calculés par le modèle dynamique de véhicule dans le simulateur.

Une des expériences conduites avec le simulateur dynamique Renault concerne le développement d'algorithmes pour l'ACC (Adaptive Cruise Control). Le simulateur peut reproduire des scénarios paradigmes, comme l'approche, le suivi et le dépassement sur autoroute, avec un niveau élevé de réalisme, de reproductibilité et de mesurabilité. Dans le simulateur dynamique Renault, les conducteurs ressentent les accélération-décélérations du véhicules piloté par l'ACC et peuvent évaluer le confort subjectif du système plus facilement que dans un simulateur statique.

Dans cet exposé, les spécifications de la restitution du mouvement sur simulateur sont analysées en termes de validité physique (réalisme des mouvements produits) et perceptive (réalisme des mouvements perçus, réduction des conflits sensoriels). Les expériences ACC sont décrites, en présentant les modifications spécifiques réalisées qui illustrent la flexibilité d'un tel outil de recherche.

INTRODUCTION

Renault's dynamic driving simulator, installed in 1999 at the Research Department of Renault, has become today a comprehensive research and development tool dedicated to automotive research. Driver-vehicle interaction studies are made possible thanks to a 6-dof motion platform which renders physically, with a satisfactory level of fidelity, the vehicle motion stimuli computed by the vehicle dynamics model in the simulator.

One of the experiments carried out using Renault's dynamic simulator addresses the development of ACC (Adaptive Cruise Control) algorithms. The simulator can reproduce paradigm scenarios, such as approaching, following, and overtaking a lead vehicle on a highway, with a high degree of realism, reproducibility and measurability. Different parameters of the ACC functions were evaluated under these conditions by standard drivers. Such a driving simulator is an efficient tool to study the subjective comfort of ACC systems. In the Renault motion-based driving simulator, drivers can perceive the accelerations onsets caused by activation/deactivation of the ACC, and can therefore better assess the subjective driving comfort of the system than in a fixed-based simulator.

In this paper, requirements for the motion rendering are discussed in terms or physical validity (reproduction of simulated vehicle accelerations) and perceptual validity (realism of perceived car motion, minimization of sensory conflicts). Experiments on ACC systems are described, with highlights on application-specific modifications of the simulator illustrating the flexibility of such a research tool.

ARCHITECTURE OF THE SIMULATOR

Renault developed the first version of the driving simulator software, SCANeR, in 1989 in the framework of the PROMETHEUS program to study cooperative driving systems [1]. It was used for the European Eureka TRaCS project to build a truck driver training simulator using a motion platform and ground-fixed screens [2,3]. Today, several simulators are operated at Renault in various hardware configurations using SCANeR, which is also used by other companies and road traffic research centers, such as PTI (USA), TRL (UK), SINTEF (Norway) and INRETS (France).

Hardware configuration

The cockpit of Renault's dynamic driving simulator is a modified version of a full-scale instrumented Renault Clio car. Dynamic force feedback is provided on the steering wheel by an electrical motor driven by the simulation host at 500 Hz update rate. Force feedback is provided on the brake, clutch, and accelerator pedals, by passive, adjustable systems. Sound generation is performed in 3D by a PC audio card to produce engine, tire, traffic and aerodynamic noises through 4 loudspeakers placed in the simulation room.

The front view of the road environment is generated in real-time image by one SGI Infinite Reality workstation. A total field of view of 150°x40° is covered by three channels of 1024x768 pixels each with full scene antialiasing. The images are displayed on three adjacent flat ground-fixed screens by Barco 808S projectors. The rear-view mirrors images are rendered in real-time by three Pentium PCs, equipped with Quantum 3D graphics cards. They are displayed on one flat, semi-transparent, ground-fixed screen behind the cockpit, using

Barco LCD projectors. Different fully textured road databases (test track, highway, mountains, rural, urban, etc.) are available, each designed with a high level of visual realism, allowing 30 to 60 Hz image update rates depending on the complexity of traffic scenarios.

The cockpit is mounted on a Hydraudyne Electrical 6DOF-1000kg motion platform, comprising 6 electro-mechanical linear actuators mounted in a hexapod configuration. The linear (surge, sway, heave) and angular (yaw, pitch, roll) accelerations of the simulated vehicle are computed by the software vehicle dynamics model, and transformed into position commands for the motion platform. This transformation is done by a specific motion cueing module, which principle is presented in the following. In the present configuration, the motion updates at send at 40 Hz.

Using fixed projection screens with a motion platform requires the image generator software to perform a dynamic compensation of the platform movements in order to maintain stable visual references relative to the cockpit. However, this solution was preferred to on-board projection systems to reduce the cost and constraints on inertial performances of the motion platform [3].

–View of the Renault Dynamic Simulator –

Simulation software

Architecture

The SCANeR©II driving simulator software package, developed by Renault Research Department, is a real-time distributed, multi-platform application. Its modules run under various operating systems (Windows NT, Windows 9x, IRIX and Linux) and provide a comprehensive set of functionalities for driver research and training applications.

The distribution is achieved through a specific communication protocol, presently running over an Ethernet network link. However, the architecture of the communication layer makes it easily portable over various other media if requested. To simplify the use for non-specialist experimenters, a supervision scheme has been implemented over all the platforms that allows to control all processes on several remote machines from the instructor's main station.

An Ethernet network was chosen for communication between the hosts and the application processes to ensure easy interconnection of the systems. The protocol is UDP-IP-based to avoid increased traffic when the saturation is reached at one point in the simulation. Processes in charge of rendering kinesthetic cues (vehicle motion, steering wheel force) require a tight control loop and are run on the same machine as the vehicle dynamics model, using shared memory data communication. In the case of the motion platform, the communication between the dynamics host and the motion host is done on a separate network with sufficient bandwidth to ensure a stable transfer rate. Environmental interactions, such as surrounding traffic, sound, scenario, etc., are synchronized more loosely by Ethernet, assuming a transfer rate of about 1 ms. Interpolation is performed in the occurrence of missing data.

As the simulator is used in an industrial environment, the system was CE certified for use in industrial conditions. This includes hardware and software, and a supervision program has been implemented that constantly checks the presence and coherence of the modules necessary to the safety of the users.

Traffic generator

Traffic generation in SCANeR©II is based on independent, collaborative, traffic agents. These agents can be autonomous vehicles or one or more interactive (i.e. user-driven) vehicles. Decisions are taken by the perception and knowledge systems of each vehicle, eliminating the need for a supervising entity at the tactical level [4]. This is a way to achieve a realistic simulation, as vehicles are all be considered the same, regardless of whether they are autonomous or interactive.

Initial conditions are user-specified for each entity: vehicle type (car, truck, motorbike, etc.) and a set of behavior parameters (risk levels, safety distances, maximum speeds, respect for priority rules and speed limits). These may be changed during the simulation through the scenario tool in SCANeR©II. Environmental relationship parameters define the interactions between the vehicle and the other vehicles or with the road infrastructure (e.g. crossing lights). These parameters define the decision making process when overtaking, pulling in, turning right or left, etc. This method allows for a natural-looking traffic to be generated easily, and is a good base for the experimenter to build a given scenario on. However, some specific behaviors were implemented to provoke non-natural traffic situations for the needs of future experimentations, including those related to ACC:

- “force pull out”: requests a vehicle to change lanes although its environment does not request it (no slow vehicle in front, no direction change). Pulling out is postponed when a vehicle is present in the target lane with incompatible distance and speed difference.
- “force stay in lane”: inhibits the normal behavior after overtaking (i.e. to pull back in lane when possible), in order to test the drivers’ reactions.

The architecture of the traffic generator being based on the interactions between instantaneous states of vehicles, these changes had no effect on the realism of the behavior of the other vehicles in the simulation, and allowed to implement these new functions without needing structural modifications.

Vehicle dynamics model

The behavior of the simulated vehicle is computed by MADA V3.0, a vehicle dynamics model based on ARHMM (Advanced Road Handling Multi-body Model, a common development between INRETS, PSA and Renault within the SARA consortium) and further developed by Renault SA.

MADA is based on a multi-body approach improved by rule-based behavior for specific modules. This vehicle dynamics model is usually instantiated with actual vehicle data ; in the case of our experiment, the specific vehicle for which the ACC system had been designed was modeled. The dynamics model computes 250 internal variables in real-time, and a limited subset is used to control the simulator, including: vehicle position, speed, accelerations, steering wheel torque, engine RPM, speed, and tire slip angle for sound rendering. The output of the model has been validated against test track data to assess its relevance in an interactive simulation context.

The model runs in real-time at 100 Hz on a standard Pentium PC. A faster separate statico-dynamic steering wheel feedback module, running currently at 500 Hz, was developed for the needs of the simulator, since operating the steering force feedback electric motor system requires a fast control loop.

MOTION RENDERING REQUIREMENTS

The motion platform used in the Renault Dynamic Simulator can produce high instantaneous accelerations within a limited displacement. In this chapter, the validity of this system is discussed regarding general driving situations and more specifically highway driving. The perceptual validity is analyzed by taking into account basic principles of human motion perception.

Vehicle accelerations

Accelerometric measurements were carried out on Renault's test tracks with a Renault Laguna car equipped with a 6-axes inertial recording platform, in a section used for vehicle handling driving experiments.

Maximum values

Maximum linear and angular accelerations measured in the test vehicle are summarized for each degree of freedom (N.B. 1 g = 9.81 m/s²):

- surge: - 0.6 — 0.4 g
- sway: - 0.7 — 0.7 g
- heave: - 0.8 — 1.1 g
- roll: ± 320 °/s²
- pitch: ± 360 °/s²
- yaw: ± 45 °/s²

These average values may be considered as a relevant envelope for most driving situations. In highway driving though, lateral accelerations are usually limited to much lower values, typically below 0.1 g [5].

The actuators of the motion platform are limited in terms of acceleration and velocity, due to the constraints in power supply and mechanical friction. With the motion system currently used in the Renault simulator, maximum accelerations and velocities are respectively ±0.5 g and 0.4 m/s for linear motion, and 300°/s² and 30°/s for angular motion. Most of the instantaneous accelerations of a real vehicle may theoretically be rendered.

However, the analysis of the spectral distribution of these accelerations is necessary to analyze which motion cues are actually compliant with the motion platform rendering performances.

Spectral distribution

The power spectral density of the linear accelerations measured on the test vehicle shows a sharp attenuation above about 2 Hz, with a small secondary peak for vertical accelerations due to the suspension damping. On the contrary, roll and pitch angular accelerations have a predominant high-frequency content, indicating their vibratory nature. Yaw acceleration has a lower frequency part, since it is physically defined by vehicle velocity, lateral acceleration and steering angle rate.

The motion platform has a typical low-pass frequency response, with an output gain decreasing as the command frequency is above a few Hertz (about 1.6 dB loss at 3 Hz). Besides, driver commands are of low frequency by nature, typically within the 0-1 Hz range (from the steering angles values measured in the tests). The motion platform is therefore adequate to render the dynamics of a vehicle inasmuch they reflect driver actions, that is below 3.0 Hz, and not the vibrations originating from the suspensions, engine, air turbulence or car body resonance. Such vibrations may be rendered more efficiently with a dedicated system, such as an electro-magnetic seat actuator, to help drivers better estimate their vehicle speed or the road surface conditions.

Displacements

Total displacements corresponding to the measured accelerations were analyzed by frequency components for each degree of freedom. Maximum travel was computed by removing all frequency components of the displacement signal below a threshold value f_c. For f_c above a few Hertz, this travel corresponds to the car vibrations, typically below 1 cm, whereas as fc approaches zero, the full actual travel of the car appears. In our simulator, the motion platform allows maximum displacements up to about ±22 cm and ±15° in all linear and angular axes. This study showed that these limits correspond to linear motions of the car for frequencies above about 0.4 Hz, and rotational motions above 0.1 Hz. Natural roll and pitch of the vehicle may however be rendered directly by the motion platform (at least within its frequency bandwidth) since they are limited to about ±6° in a standard passenger car.

The physical validity of the motion platform is therefore in the 0.4 – 3.0 Hz range for all vehicle acceleration, which can be termed as ‘transient’ vehicle dynamics. Lower frequency or ‘sustained’ accelerations may be simulated in some situations by artificial platform tilt, as discussed below.

Perception of simulated motion

Although there is no specific study available today on the visuo-vestibular perception of self-motion when driving, whether in a car or a simulator, it is possible to use general results on sensory physiology and motion psychophysics (see [6,7] for reviews).

Transient displacements of the head are sensed by the vestibular organs (otoliths and semi-circular canals) located in the inner ear. Theoretical detection thresholds of linear and angular accelerations are about 5 cm/s² (i.e. 0.005 g) and 0.3 °/s² respectively. Rendering transient vehicle dynamics is therefore a primary requirement in a motion-based simulator to achieve a satisfying level of perceptual validity.

Simulating the effect of low-frequency accelerations within a limited displacement is possible taking advantage of the perceptual ambiguity between sustained linear accelerations and rotations by the vestibular system. This simulation technique was initially developed for flight simulators and is often referred to as ‘tilt coordination’ [8]. When a visual scene representing an accelerated translation is presented to the driver while the simulation cockpit is tilted at an undetectable rate, the relative variation of the gravity vector will be partly interpreted as an actual linear acceleration. To achieve this, the visually simulated horizontal acceleration G and the platform tilt angle α are coupled by:

$$\alpha_{pitch} = asin(G_{forward} / g) \text{ and } \alpha_{roll} = asin(G_{lateral} / g)$$

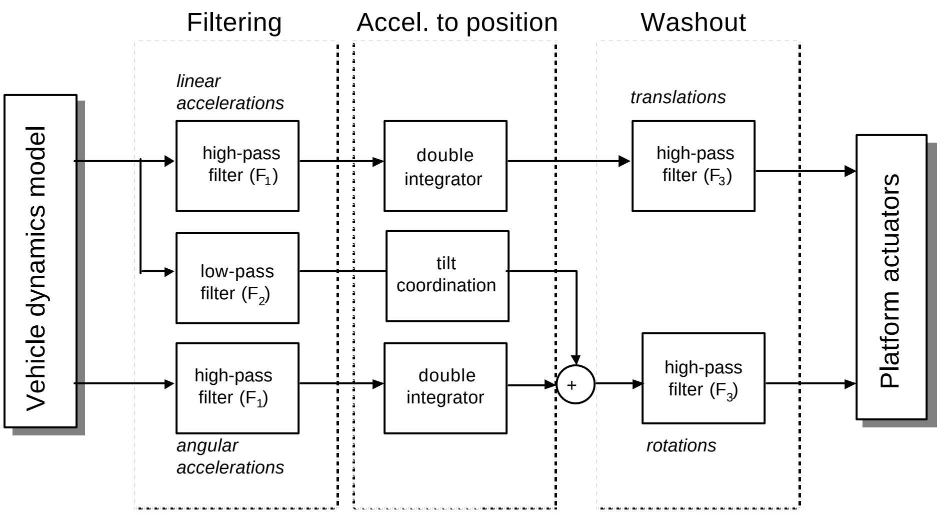
Artificial tilt accelerations $d^2\alpha/dt^2$ should be limited to vestibular tilt detection thresholds. During highway lane change maneuvers, lateral acceleration varies too rapidly to use this technique. However, longitudinal accelerations and decelerations commanded by the ACC system were sufficiently smooth to be rendered efficiently by tilt coordination.

Generation of motion cues

A classical motion cueing algorithm [8] commonly used in most motion-based simulators is a combination of frequency filters which :

- remove the low frequency of accelerations by high-pass filtering, then integrate the signal twice to output a position command,
- extract the low frequency horizontal accelerations by low-pass filtering, then compute a 'tilt coordination' angle which is added to the output command,
- bring the platform back to its neutral position by high-pass filtering of the resulting position commands.

The last processing stage is often referred to as 'motion washout' and is necessary to avoid saturating the actuators. The corresponding platform motion is performed at undetectable rates.



– Structure of the classical filter for motion cueing –

Usually, the high- and low-pass filters are chosen as linear. Parameter definition (gains, order and time constants) is a compromise between the motion platform characteristics and the vehicle dynamics, depending on the application or driving task considered. Considering the allowed frequency bandwidth in acceleration discussed above, a main high-pass time constant of T=0.1 s was chosen with first-order filters.

However, using linear filters to remove the low-frequency part of the acceleration signal can produce disturbing artifacts. Let us consider a driver acting on the brakes for a time significantly longer than T: after releasing the brakes, the high-passed surge acceleration signal will show a 'sag' (as mentioned in [9]) or 'backlash effect'. This effect is a characteristic of the linear high-pass filters, which output a zero-mean signal for any limited-energy input. This backlash motion will be perceived by the driver as a push forward after his braking action, which is particularly disturbing and somewhat nauseogenous. For lateral accelerations, as occurring during lane change maneuvers, it can cause the driver to perform unnecessary steering corrections, a situation usually interpreted as a steering instability of the simulated vehicle. To limit this effect, a non-linear adaptive post-filtering module was designed to anticipate these situations and control the motion output accordingly: in the present configuration, a variable gain G is applied to the high-pass filter output $f(g)$ of the classical filter stage, depending on the predicted cueing error $|f(g)-g|$.

DESCRIPTION OF THE ACC EXPERIMENT

Principle of an ACC system

Most of the front-rear collisions are due to a lack of attention or to a disrespect towards safety distances by drivers. In such circumstances, passive safety systems (e.g. safety belt, air bags) may minimize the seriousness of the passengers' wounds but do not allow to avoid the accidents. An electronic system such as the Adaptive Cruise Control (ACC) is in a position to control the distance to the vehicle ahead and therefore to warn the driver from a possible danger of collision. However, the ACC system at present is not an avoidance system since it cannot detect stationary and slow moving objects, such as stopped vehicles, pedestrians or obstacles. It is hence an aid to driving, not a substitute, simply allows a more relaxed driving in motorways, thus improving driver comfort (see [10] for a general presentation of such systems).

The ACC system is designed to maintain a pre-set constant cruising speed whenever the road ahead is clear. When the radar detects another vehicle preceding the ACC vehicle in its lane or entering its lane, the system maintains a pre-set time gap with it, by determining the inter-distance and relative speed and automatically adjusting the throttle and brake commands. A dedicated man-machine visual interface communicates efficiently and rapidly with the driver, and specific commands are set out on the steering wheel so that the driver can handle easily the ACC system.

After accelerating to the desired speed, the driver presses a button to store the current speed in the system. The driver may then release the accelerator pedal and the vehicle will maintain the set speed, which may be adjusted by pressing the 'set +'or 'set –' buttons. The driver can always override the set speed by using the accelerator pedal, and releasing it will bring back ACC into operation. The ACC can be disengaged at any time by using the brake pedal. Should a fault occur in the system while driving, the ACC switches off automatically and the driver is informed to intervene. During "follow" mode, if the system has to apply a maximum braking level to maintain a safety distance with the vehicle ahead, the driver is alerted to take hard braking or evasive action.

Objectives of the ACC simulator experiments

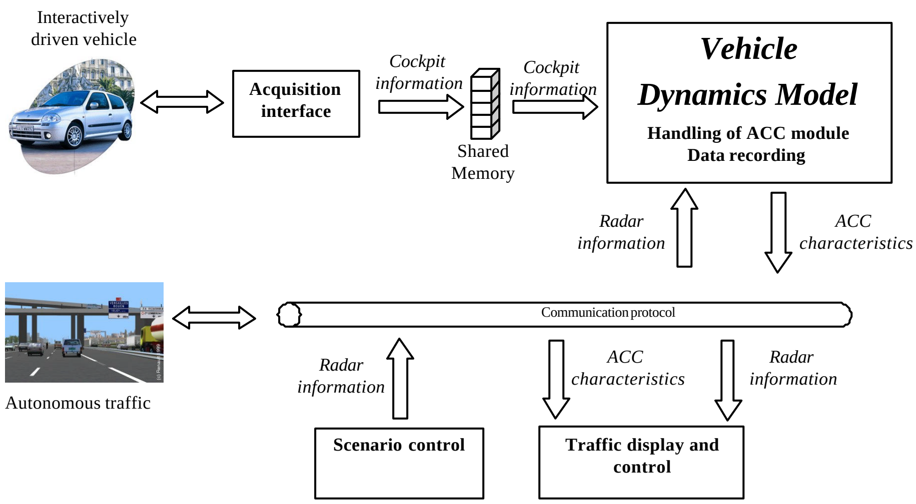
Tuning and assessment of an ACC system on a vehicle prototype requires many hours of driving. Moreover, some specific road and traffic configurations are difficult to reproduce on test tracks. Test driving protocols may present too many risks for the driver but also for the other motorists in real highway traffic. The driving simulator is therefore a valuable tool to reproduce various road situations in total safety.

The ACC system is characterized by specific acceleration-deceleration parameters and time gaps depending on the driving conditions. The purpose of the simulator experiment was to assess different ACC strategies to insure that the resulting vehicle behavior would not induce any feeling of danger to the driver.

The tests carried out on the driving simulator enable not only to tune and make the ACC system reliable, but also to assess the ergonomics of the instrumentation panel. This allowed to study the design and position of the corresponding ACC switches as well as of the global man-machine interface.

Modifications to the simulator

A first step in the integration of the ACC module in the driving simulator consisted in modifying the driver's environment to be able to re-create the ACC context in the vehicle prototype, by replacing the original Clio2 dashboard and steering wheel.



– Integration of ACC functions into the simulator –

The ACC radar function was simulated in the SCANeR©II scenario interface.

The ACC software unit was integrated into the process in charge of the vehicle dynamics model to achieve:

- the frequency performances required by the ACC specifications,

- rapid information retrieval from the vehicle model itself (e.g. vehicle speed, position, accelerations, etc.) and the scenario interface dealing with the ACC radar,
- rapid transmission of ACC commands (throttle and brake values) to the dynamics model,
- high frequency data recording as required by the ACC development team.

Experimental protocol

Specific ACC traffic scenarios were developed for the experiment. Those were primarily based on critical or even dangerous road situations the driver might have to face while driving on motorways.

For the first experiment now completed, a simpler scenario composed of a line of vehicles driving at the same speed and separated by the same distance was also created. It allowed to evaluate the feelings of the drivers while following a vehicle at a given distance or while pulling out after having followed a vehicle, in reproducible conditions. This experiment was carried out with a dozen of subjects.

A first driving session was used for the subjects to get familiar with the Dynamic Simulator. Then, while experimenting the different ACC scenarios, the subjects were interviewed to get their direct impressions concerning the ACC dynamic behavior. The subjects were systematically video recorded so that their reactions could be viewed afterwards. Several numerical parameters from the dynamics model and the driver actions on the vehicle commands were also recorded. These different data have already permitted to modify and adjust some of the ACC strategies. Further analysis will allow to continue improving the services provided by the Adaptive Cruise Control system.

CONCLUSION AND PERSPECTIVES

Before the ACC experiment took place, a pool of professional expert drivers experimented the behavior of the simulated vehicle during highway driving tasks, such as lane following and overtaking. The non-linear motion cueing filter, after integration in our simulator, produced a driving sensation which was deemed superior by test drivers to the initial configuration based on a classical filter. It also improved significantly their steering performance, compared to a situation where a lane change produced inevitably a post-motion sag sideways which the drivers tried to counter-steer unnecessarily. These test drivers also confirmed the realism of the driving sensations and vehicle behavior produced by the ACC system in the simulator.

The ACC experiment setup process also demonstrated the value of the Renault simulator as a prototyping tool, since the actual behavior and stability of the ACC system could be studied in driving conditions before being integrated in an actual vehicle prototype. The modularity of the simulator cockpit allowed however the integration of the prototype ACC-driver interface, which could be used as a testbed for ergonomics and functionality assessments.

Using fixed screens for a motion-based driving simulator has shown to be a cost-effective yet very acceptable solution from the drivers' point of view. The wide field of view covered by the 3-channels front display reduces the interference of static visual cues from the simulation room. Compared to traditional on-board display systems, this approach is today the best compromise for automotive simulators; however, the on-going Eureka CARDS project, led by Renault with 7 European partners, is currently building a simulator prototype combining a motion platform and a head-mounted display, which eliminated the weight of the projection systems while removing external visual references from the drivers' vision.

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