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# Multi-Behavioural Control Allocation for Over-Actuated Vehicles

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Most of today's vehicles are over-actuated. Active researches are carried out to find satisfactory chassis systems coordination strategies. Regarding autonomous vehicles, qualitative objectives such as comfort and confidence feelings should also be ensured. This paper shows how to take into account different constraints in a multi-objective control allocation framework. A weighted least squares algorithm is used to favour an objective over another depending on the situation. Results show that different coordination solutions could be generated leading to different feelings. This can be adapted to fit driver's expectations when it comes to autonomous driving.

## 1 INTRODUCTION

Ground vehicles have always been identified as a way of providing pleasure when they are driven in contrast with other means of transport. Car manufacturers and equipment suppliers are constantly trying to propose new advanced technologies to improve the driver experience by making the vehicle more easily controllable. In the past few years, active chassis systems have realized a huge impact in this context. We recall for example the big success of the Anti-lock Braking System (ABS) in 1978 [1]. Since then, various systems have been added gradually to commercial vehicles. Some of these systems often influence the same physical variable making vehicles over-actuated. For example, the 4-Wheel Steering (4WS) system and the Electronic Stability Program (ESP) both influence the vehicle's yaw rate. This raises several questions about system's coordination especially if the ESP is activated while the rear wheels are steered.

The simpler solution consists in prioritizing one system over the other. The choice of prioritization is based on an off-line study of the most effective system in each situation. The simplicity of this method led car manufacturers to adopt it as long as two conflicted systems are concerned. However, the more numerous chassis systems are integrated, the more complex and unpredictable the car behavior becomes [2]. Optimization-based methods should be then preferred for the upcoming advanced cars and future autonomous vehicles. Moreover, control allocation methods are specially developed for over-actuated systems in general [3]. In this context, *daisy-chain* method has been put along with the *weighted pseudo-inverse* (WPI) in [4] to deal with ESP coordination with the Electric Power-Assisted Steering (EPAS) system. This gives a straightforward algebraic calculation of forces distribution using the inverse of maximum tire efforts as weights for the WPI. This can be sufficient if the only objective is allocation respecting tire maximum efforts or actuators constraints. For multi-objectives optimization problems, no general algebraic formulation exists. On-line optimization algorithms should be then preferred. Solvers based on Active Set Algorithms (ASA) showed good results to find optimal solutions in a finite number of iterations, which is essential for real-time

operations [5]. Various techniques have been derived from ASA. Sequential Least Squares (SLS) uses a two stage ASA to handle two optimization problems [5]. The Weighted Least Squares (WLS) solves the bounded least squares problem using an one stage ASA after few matrix transformations by means of different weights [5]. Other techniques not based on ASA that can be cited are Cascading Generalized Inverses (CGI) [6] and the Fixed-Point Iteration (FPI) [7].

These techniques have been tested to handle various multi-objectives problems. In [8], the Fixed-Point Iteration (FPI) has been used to handle the control allocation problem and tested in a Hardware-In-the-Loop procedure. In fact, the FPI is suitable for real-time applications [9]. Energy consumption and energy losses have been selected as performance criteria. However, these criteria were not formulated as additional cost functions to reduce the computational effort, but rather the objectives' weights have been tuned to meet the different performance requirements. The drawback is then the off-line pre-design of restriction weights, which approaches the industrial common practice. Authors of [10] have also focused on energy-efficient control allocation in the context of electric vehicles by adding a cost function. Stability has been added to energy optimization in [11]. A two-step optimal control allocation has been developed: a pre-allocation for energy efficiency optimization assuming that the vehicle is stable, then a reallocation in case of wheels skidding or locking using Model Predictive Control. Generally, the literature has been more interested in power consumption and tire energy dissipation [12]. The driving pleasure and comfort have always been ensured by the driver itself. Each driver corrects the vehicle behavior gradually until it fits its comfort and confidence requirements. But what about autonomous vehicles? To the best of our knowledge, chassis systems coordination taking into account the feelings generated has been ignored in the literature. In an autonomous driving context, coordination should be made in such a way so as to avoid generation of unexpected car behavior.

This paper raises the question of the ability of control allocation algorithms to influence car behavior. The Weighted Least Squares method based on Active Set Algorithm solver is used for its suitability by taking into account rapidly new objectives

once formulated. Results showed that with the same reference, we can induce different responses when changing the weight of comfort requirements.

The rest of the paper is structured as follows. We start in Section Section 2 by detailing the method used for the multi-objectives control allocation. Section 3 presents results obtained by co-simulation of Matlab/Simulink<sup>®</sup> and AMESim<sup>®</sup>. The control allocation algorithm is developed in Matlab/Simulink<sup>®</sup> while AMESim<sup>®</sup> is used for its high-fidelity vehicle models. A discussion about the new challenges of future cars and motion feelings requirements is provided in Section 4. Conclusions and future works are outlined in Section 5.

## 2 WEIGHTED LEAST SQUARES METHOD

Here, we remind the basics of the Weighted Least Squares method that enables taking into account multi-objectives requirements in a simple formulation. To provide a more comprehensive explanation, we apply the method to a simple case study of a car equipped with the Active Rear Steering (ARS) system and the brake-based Vehicle Dynamics Control (VDC) system at the same time. This choice is motivated by the fact that on one hand both systems act on the yaw rate making the vehicle over-actuated, and on the other hand, it concerns a real vehicle developed by our collaborators in the Group Renault<sup>1</sup>.

### 2.1 Case Study

The considered car is equipped with two conflicting chassis systems. The ARS system generates a rear steering angle to facilitate turning maneuvers. The VDC systems generates a yaw moment by means of differential braking, which functionality is similar to the ESP's. Both systems influence the yaw rate. To determine how both systems should be coordinated, other requirements should be taken into account. In fact, the two systems act differently on the vehicle's longitudinal velocity, and both longitudinal and lateral acceleration. As it would be seen in the following equations, these systems don't generate the same amount of acceleration. As comfort requirements are closely related to the overall acceleration [13], each system can induce different motion feelings. The control allocation method should give the passenger the possibility to tune the car behavior by acting on the systems' coordination.

#### 2.1.1 System modeling

To be able TO study the influence of both ARS and VDC systems on the same vehicle, a four-wheeled vehicle model should be considered. Moreover, the ARS system generates lateral tire forces, while the VDC system is based on longitudinal tire forces. Interactions between the different tire forces should be taken into account by respecting the friction ellipse concept [14].

In this case, a planar vehicle model can be considered as long as vertical forces (suspensions) are not controllable. Nevertheless, these latter influence the tire behavior and should be taken into account in the control allocation constraints. Using Newton's laws of motion, we find the following state-space representation:

$$\left\{ \begin{array}{l} \left[ \begin{array}{c} \dot{V}_x \\ \dot{\psi} \end{array} \right] = \begin{bmatrix} 0 & V_y \\ 0 & 0 \end{bmatrix} \left[ \begin{array}{c} V_x \\ \psi \end{array} \right] \\ \\ + \begin{bmatrix} \frac{1}{M} & 0 \\ 0 & \frac{1}{I_{zz}} \end{bmatrix} \left[ \begin{array}{c} F_{x_{tot}} \\ M_{z_{tot}} \end{array} \right] \\ \\ \left[ \begin{array}{c} V_x \\ \psi \end{array} \right] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \left[ \begin{array}{c} V_x \\ \psi \end{array} \right] \end{array} \right. \quad (1)$$

With:

$$\left\{ \begin{array}{l} F_{x_{tot}} = (F_{x_{fl}} + F_{x_{fr}}) \cos(\delta_f) + F_{x_{rl}} + F_{x_{rr}} \quad (3) \\ M_{z_{tot}} = (F_{x_{fl}} + F_{x_{fr}}) l_f \sin(\delta_f) \\ + (F_{x_{fr}} - F_{x_{fl}}) \frac{E}{2} \cos(\delta_f) \quad (4) \\ + (F_{x_{rr}} - F_{x_{rl}}) \frac{E}{2} - F_{y_r} l_r \end{array} \right.$$

Where:

- $V_x$  : longitudinal velocity of the vehicle,
- $V_y$  : lateral velocity of the vehicle,
- $\dot{\psi}$  : yaw rate of the vehicle,
- $M$  : vehicle's mass,
- $J_z$  : vehicle's yaw moment of inertia,
- $F_{x_{i,j}}$  :  $i - j$  braking force, where " $i$ " is front or rear, and " $j$ " is right or left,
- $F_{y_r} = F_{y_{rl}} + F_{y_{rr}}$  lateral rear force,
- $\delta_f$  : front steering angle,
- $l_i$  : distance between the front or rear axle and the vehicle's center of gravity (CoG),
- $E$  : vehicle's track.

In order to optimally distribute the efforts into tires, we need also a tire model. This tire model should be simple enough for controllability requirements, depicts the combined slip as longitudinal and lateral forces are concerned, and depends on varying parameters that could be estimated on-line. We use then the Linear Varying-Parameter (LPV) model described in [15].

#### 2.1.2 High-level control

Before getting into the control allocation method, we should establish a high-level control that transforms target motion quantities into the generalized force and moment to distribute:  $F_{x_{tot}}$  and  $M_{z_{tot}}$ . According to equations (1) and (2), the problem is Multi-Inputs Multi-Outputs with a varying parameter  $V_y$  with several parametric<sup>2</sup> and dynamic<sup>3</sup> uncertainties. Moreover, according to the structure of the matrix  $B$ , transfer function for each diagonal term can be approximated by an integrator. For all these reasons, a diagonal PI-structured gain scheduled  $\mathcal{H}_\infty$  controller has been developed. Due to space limits and the scope of this paper, details of the high-level controller are not provided.

## 2.2 Control Allocation Method

The control allocation problem can be defined as follows [16]: find the control vector,  $\vec{u} \in \mathbb{R}^n$  such that

$$\mathbf{B}_{\text{eff}} \vec{u} = \vec{v}_{des} \quad (5)$$

subject to

$$\left\{ \begin{array}{l} \vec{u}_{min} \leq \vec{u} \leq \vec{u}_{max} \quad (6) \\ \dot{\vec{u}} \leq \dot{\vec{u}}_{max} \quad (7) \end{array} \right.$$

where  $\mathbf{B}_{\text{eff}} \in \mathbb{R}^{m \times n}$  is a control effectiveness matrix,  $\vec{u}_{min} \in \mathbb{R}^n$  and  $\vec{u}_{max} \in \mathbb{R}^n$  are the lower and upper position limits, respectively,  $\dot{\vec{u}} \in \mathbb{R}^n$  is the control rate,  $\dot{\vec{u}}_{max} \in \mathbb{R}^n$  is the maximum

<sup>1</sup>More specifically, the Renault Talisman equipped with the two systems.

<sup>2</sup>Basically the mass and moment of inertia.

<sup>3</sup>Due to the negligence of vertical motions.

control rate,  $\vec{v}_{des} \in \mathbb{R}^m$  are the desired accelerations,  $n$  is the number of control effectors, and  $m$  is the number of axes to control.

As  $n > m$ , several solutions can be found. The control allocation algorithm should be able to pick the best solution by defining optimization objectives or cost functions. The algorithm can try to fulfill these objectives separately in a sequential way [5]. The objectives order in the algorithm determines the priority of each objective. However, we want this priority to be tunable. Another way to express a multi-objectives problem is to merge optimization criteria into one by summation[5]. This is called the *Weighted Least Squares* problem:

$$\vec{u}_{opt} = \arg \min_{\vec{u}_{min} \leq \vec{u} \leq \vec{u}_{max}} \sum_l \gamma_i \|\mathbf{W}_i (\mathbf{B}_i \vec{u} - \vec{v}_i)\|^2 \quad (8)$$

- $\vec{u}_{opt}$  : optimal control vector,
- $l$  : number of objectives,
- $\gamma_i$  : weight of the  $i^{th}$  objective,
- $\mathbf{W}_i$  : non-singular weighting matrices,
- $\vec{v}_i$  : desired vector of the  $i^{th}$  objective,
- $\mathbf{B}_i$  : effectiveness matrix of the desired  $i^{th}$  objective.

### 2.2.1 Problem definition

For the ARS-VDC coordination case, the control vector contains controllable tire forces:

$$\vec{u} = \begin{bmatrix} F_{xfl} \\ F_{xfr} \\ F_{xrl} \\ F_{xrr} \\ F_{yr} \end{bmatrix} \quad (9)$$

$\vec{u}_{min}$  and  $\vec{u}_{max}$  reflect tire limits with respect to the friction ellipse concept [15]. The desired acceleration  $\vec{v}_{des}$  contains:

$$\vec{v}_{des} = \begin{bmatrix} F_{x_{tot}} \\ M_{z_{tot}} \end{bmatrix} \quad (10)$$

To complete the problem definition described in (5),  $\mathbf{B}_{eff}$  is filled by geometric relations between the vehicle and its tires using equations (3) and (4):

$$\mathbf{B}_{eff} = \begin{bmatrix} \cos(\delta_f) & \cos(\delta_f) & 1 & 1 & 0 \\ b_{2,1} & b_{2,2} & -\frac{E}{2} & \frac{E}{2} & -l_r \end{bmatrix} \quad (11)$$

where:

- $b_{2,1} = l_f \sin(\delta_f) - \frac{E}{2} \cos(\delta_f)$ ,
- $b_{2,2} = l_f \sin(\delta_f) + \frac{E}{2} \cos(\delta_f)$ .

### 2.2.2 Objectives formalization

Stability and robustness of the global control have been moved to the high-level control. If the combination of tire forces achieve the generalized forces required to stabilize the vehicle, then the stability is ensured. One can speculate that the prior objective of the weighted least squares algorithm should be then the control allocation precision. This prioritization is ensured by setting the control allocation precision corresponding weight to the highest value. However, when following this procedure, no effect could be obtained in terms of accelerations to change the vehicle's behavior as the algorithm prioritizes forces tracking generated by the high level control. Here, a penalization of precision is permitted in order to fulfill a secondary objective. The control effectiveness matrix and the desired acceleration vector have been

defined in the previous paragraph. Regarding the corresponding weighting matrix; it enables us to favor one control axis instead of another. We remind that our first objective is to control the yaw rate by means of two chassis systems, but we also want to minimize the effect on the longitudinal speed. The weighting matrix, that we note  $\mathbf{W}_{ca}$ , is then chosen to be diagonal with higher value of the weight corresponding to the yaw moment.

The originality of this work lies rather in the motion feelings objective. Motion sickness and discomfort are tightly related to the vehicle's accelerations [13]. The major problem is how to fit the desired accelerations to each driver perception. The goal of this paper however is to show the ability of the control allocation algorithm proposed to change the vehicle's behavior. No standardizations are intended to be given for now as more experimental tests are needed. We chose then in this work to let the user set its preferences manually. In other words, as drivers have the option to select their preferred driving modes in recent cars, those modes are linked here to the second objective criteria. Let us first determine the relations between the control vector and accelerations. Equation (1) can be used for the longitudinal acceleration. In the same way, we can use Newton's laws of motion to express the lateral acceleration. The effectiveness matrix is therefore expressed as:

$$\mathbf{B}_{mf} = \begin{bmatrix} \frac{\cos(\delta_f)}{M} & \frac{\cos(\delta_f)}{M} & \frac{1}{M} & \frac{1}{M} & 0 \\ \frac{\sin(\delta_f)}{M} & \frac{\sin(\delta_f)}{M} & 0 & 0 & \frac{1}{M} \end{bmatrix} \quad (12)$$

The weighting matrix here, noted  $\mathbf{W}_{mf}$ , will favor the longitudinal acceleration to the lateral one or the opposite. As we are more interested in the overall acceleration, this matrix is set to the identity matrix.

Desired tunable accelerations are contained in the desired vector noted  $\vec{v}_{mf}$ . This vector should not contains predefined values as this could lead to accelerations demand while the driver does not ask for them. This vector should rather be expressed according to the control vector. The objective is then:

$$\|\mathbf{W}_{mf} (\mathbf{B}_{mf} \vec{u} - [\mathbf{B}_{mf} \vec{u} + \vec{\varepsilon}])\| \quad (13)$$

where  $\vec{\varepsilon}$  is the tunable weight that varies with the driver's preferences. One could think of the risk of divergence of the commands as the difference  $(\mathbf{B}_{mf} \vec{u} - [\mathbf{B}_{mf} \vec{u} + \vec{\varepsilon}])$  is never null for  $\vec{\varepsilon} \neq \vec{0}$ . However, the first objective prevent the control vector from increasing too much to keep minimal the control allocation error. A null  $\vec{\varepsilon}$  corresponds then to a neutral behavior, a non-null  $\vec{\varepsilon}$  with the same sign of the current acceleration would give a higher acceleration than expected and corresponds then to a more sportive mode, and a non-null  $\vec{\varepsilon}$  with an opposite sign would give a lower acceleration than expected and corresponds then to a more comfortable mode.

The optimal control vector is then:

$$\vec{u}_{opt} = \arg \min_{\vec{u}_{min} \leq \vec{u} \leq \vec{u}_{max}} \gamma_{ca} \|\mathbf{W}_{ca} (\mathbf{B}_{eff} \vec{u} - \vec{v}_{des})\|^2 + \gamma_{mf} \|\mathbf{W}_{mf} (\mathbf{B}_{mf} \vec{u} - [\mathbf{B}_{mf} \vec{u} + \vec{\varepsilon}])\|^2 \quad (14)$$

### 2.2.3 Solver algorithm

The solver is based on Active Set Algorithm (ASA). For details regarding this algorithm, refer to [5]. In this paper, we are more interested in how we can make use of the ASA to solve online the control allocation problem. To do so, we simply have to rewrite the cost function following the ASA formulation:

$$\vec{u}_{opt} = \arg \min_{\vec{u}_{min} \leq \vec{u} \leq \vec{u}_{max}} \|\mathbf{A} \vec{u} - \vec{b}\| \quad (15)$$

Which means rewrite the cost function in (14) as:

$$\left\| \begin{pmatrix} \sqrt{\gamma_{ca}} \mathbf{W}_{ca} \mathbf{B}_{eff} \\ \sqrt{\gamma_{mf}} \mathbf{W}_{mf} \mathbf{B}_{mf} \end{pmatrix} \vec{u} - \begin{pmatrix} \sqrt{\gamma_{ca}} \mathbf{W}_{ca} \vec{v}_{des} \\ \sqrt{\gamma_{mf}} \mathbf{W}_{mf} [\mathbf{B}_{mf} \vec{u} + \vec{e}] \end{pmatrix} \right\|^2 \quad (16)$$

The algorithm tries to satisfy both objectives at the same time when possible. If it is not possible, then the cost function is at least minimized by favoring the objective with the highest weight. For real-time maneuvers, number of iterations are limited to a finite value. A sub-optimal solution could then be generated rather than an optimal one.

#### 2.2.4 Low-level commands

The control allocation algorithm generates tire forces commands. These commands cannot be fed directly to the different actuators. As the relations between efforts and actuators inputs are dynamic, a proper way to interpret the tire forces commands would be to add additional low-level controllers. However, this will add additional time lags to the global control logic, and for good precision and robustness, a closed-loop will be needed while tire forces are not measurable in commercial vehicles. Therefore, here only an algebraic transformation is added to transform forces into torques or angles. Due to space limits, no further details are provided.

### 3 CO-SIMULATION RESULTS

To validate our control logic, a high-fidelity vehicle model equipped with a differential braking and a rear steering actuator has been validated in AMESim<sup>®</sup>. However, AMESim<sup>®</sup> does not contain enough features to test directly sophisticated control algorithms as the one presented in Section 2. AMESim<sup>®</sup> is rather used for vehicle dynamics validation for its high fidelity components. The algorithm is then written in Matlab<sup>®</sup>, called in Simulink<sup>®</sup>, and a co-simulation is carried out between AMESim<sup>®</sup> and Simulink<sup>®</sup>.

Regarding the scenario tested, a real experiment in a french road has been conducted by the Group Renault to test only vehicle dynamics. We use the steering wheel angle, the acceleration pedal, and the brake pedal inputs registered to generate longitudinal speed and yaw rate targets and then evaluate the influence that would have the proposed control logic on the vehicle motion. Driving modes are changed manually in Simulink<sup>®</sup> by means of a rotary switch.

Fig. 1 and 2 show the variation of the longitudinal acceleration and the lateral one respectively when changing the driving modes. We can see that the control allocation algorithm allows different behaviors, and therefore different motion feelings using the same inputs.

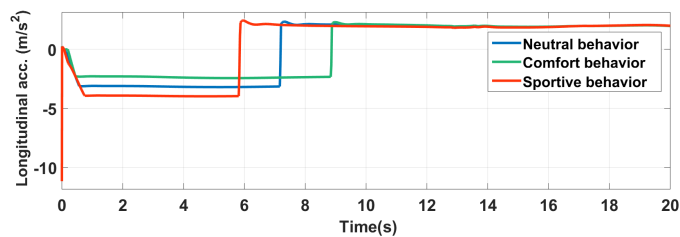


Figure 1: Longitudinal acceleration depending on driving behavior.

This comes without significance variation of the yaw rate to stay in the stability envelope as Fig. 3 shows. This is mainly due to the prioritization of the yaw rate control with respect to the longitudinal speed control.

This influence how chassis systems are solicited. Fig. 4 shows the braking torque variation of the front-left tire for example

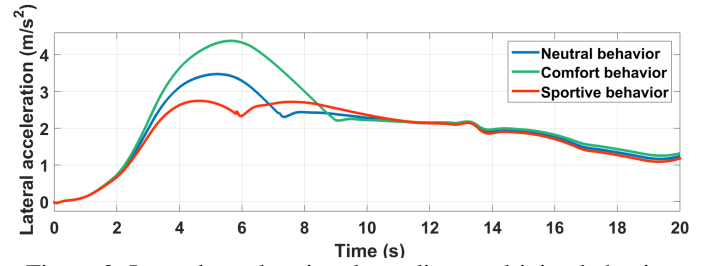


Figure 2: Lateral acceleration depending on driving behavior.

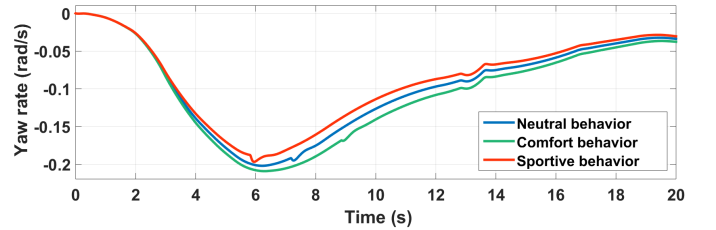


Figure 3: Vehicle's yaw rate depending on driving behavior.

from a driving mode to another. As expected, to give a more comfortable feeling, the use of brakes is minimized, while it is maximized in a more sportive behavior. The same remark holds for the rear steering angle as Fig. 5 illustrates. In a sportive behavior, the rear axle is more agile, while it is slowed to give a more comfortable feeling. It should be noted also that this vari-

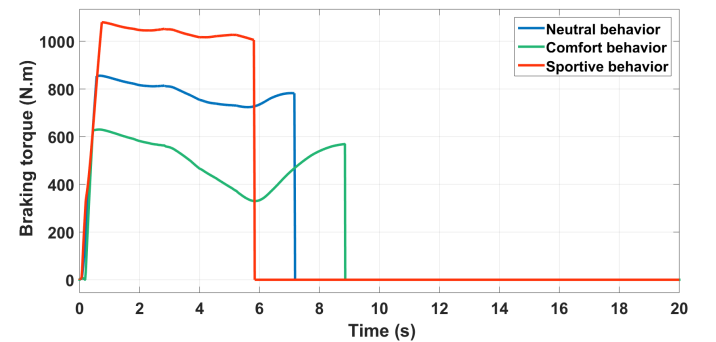


Figure 4: Front-left tire braking torque depending on driving behavior.

ation respects the physical behavior of tires. Thanks to the linear tire model integrated with varying parameters, variation of the rear lateral tire stiffness variation due to brake activation has been estimated to adapt generation of the rear angle to the real potential of the tire (see Fig. 6).

The rear steering angle sign could be even changed to steer in the same direction than the front angle, which would give a sort of a lateral transitional motion of the car as experienced drivers do when drifting. Weights of each objective could also be variable depending on the driving mode (including autonomous or not). This is not shown here to keep the idea simple. A further investigation could be needed in the future.

### 4 OPEN CHALLENGES FOR FUTURE CARS

Autonomous vehicles seems to be the next big revolution in automotive industries. All car manufacturers are concentrating their efforts to their development. Several challenges still need to be overcome.

#### 4.1 Industrial Constraints

One of the challenges is the fact that different stakeholders are concerned. These actors should have a common framework in which each one can operate at ease. However, the know-how of several stakeholders manifests in their control algorithms. The overall control architecture should be elaborated in such a way

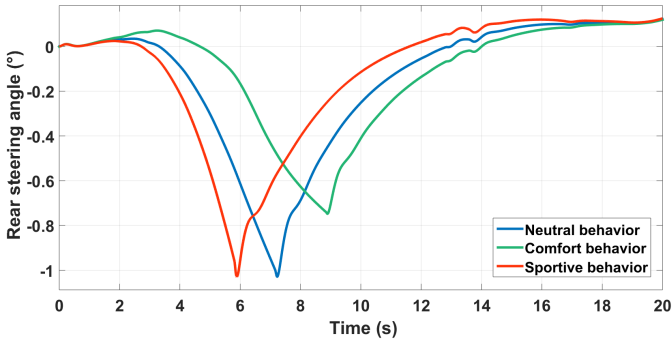


Figure 5: Rear steering angle depending on driving behavior.

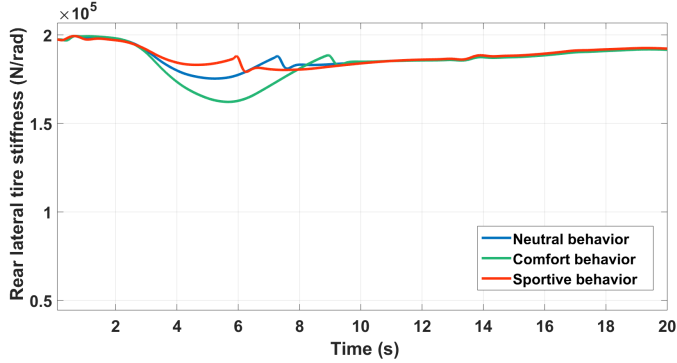


Figure 6: Rear lateral tire stiffness depending on driving behavior.

to allow a plug-and-play way of operating where each actor can protect its intellectual properties. For this reason, in [2], several characteristics that the overall control architecture should respect have been determined:

- *Adaptability* to face environment changes and drivers behaviors [17]. A high-level control based on gain scheduled  $H_\infty$  controller satisfies an adaptive and robust control.
- *Fault-tolerance* to propose some degraded modes and keep ensuring safety even if a chassis system break down. In the control allocation framework, this is easily taken into account by adding in the matrix effectiveness the different systems' flags to update this matrix when a failure is detected. This has been tested by simulation and will be published in a future work.
- *Dynamic reconfiguration* to ensure soft switching and prevent loss of stability [18]. A way to add this feature is to tune the weighting functions used in control allocation [16].
- *Extensibility* to rapidly insert additional technologies without redesigning the whole architecture [17]. This is one of the major industrial concerns as autonomous vehicles needs are not frozen yet. Control allocation methods are designed to handle over-actuated systems with a dimension of  $\mathbb{R}^{m \times n}$ . The same algorithm presented in this paper could be applied to a bigger set, which makes it extensible.
- *Modularity* to ensure flexibility, which is already the case in most of vehicle dynamics control architectures.
- *Openness* to support various systems from different sources without jeopardizing the intellectual property rights of the different stakeholders [17]. This supposes interfacing modification, which needs a tight collaboration between car manufacturers and equipment suppliers.

It seems clear then that the different stakeholders should start thinking about joining forces to implement this control allocation layer for future cars by enabling a certain degree of openness of their algorithms.

## 4.2 Human Acceptance

Another autonomous vehicles challenge is their acceptance by humans. Here, the feeling that generates the vehicle behavior plays a major role. Not only the trajectory tracking is important but also how this trajectory is followed. The motion of the car should be done in a way to make drivers trust their vehicle. A discussion about human trust and autonomous systems is provided in [19]. The difficulty is the fact that the definition of comfort or excitement differs from a driver to another due to inter-individual variability. Current commercial vehicles enable you choose manually the driving mode. We could expect that future vehicles would learn and remember your preferences. However, the most suitable behavior may differ from the three main drive modes. A continuous space defining car behavior tuning would be preferred to make driving experience more personalized. This is one of the main innovations of the Group Renault<sup>4</sup>. This tuning is done at the reference calculation level. Again, the vehicle should be able to respond correctly and generate the expected feeling. A smart coordination between chassis systems should be ensured. This could be done by formalizing a multi-objective problem. As it is depicted in Section 3, formalizing an objective related to the vehicle's acceleration allows allocating the commands differently to increase or reduce the acceleration with respect to a neutral behavior. This comes without jeopardizing the vehicle's stability by means of higher weight for the stability objective. The additional acceleration term vary with the driving mode. As a consequence, commands fed to different subsystems vary from a behavior to another. This can be generalized to a bigger set of subsystems. To do so, the effectiveness matrices should be simply updated. However, precautions should be taken. The more complex the problem gets, the more time and calculation effort the solver require. Depending on the financial decisions the car manufacturer would take regarding its calculators, the set of subsystems to integrate with a feasible real-time coordination will be limited.

## 4.3 Motion Feelings Formalization

Knowing that the vehicle behavior influence the passengers feelings, these motion feelings should be formalized in a way to make an autonomous vehicle behavior predictable and reliable. Research on motion sickness related discomfort to high acceleration values. ISO 2631-1 defines standards of the r.m.s. (road motion sickness) overall acceleration related to passengers comfort (Table 1) [13]: However, these researches concerned ground

Table 1: ISO 2631-1 standard

r.m.s. overall acceleration ( $m/s^2$ )	Passenger comfort level
$a_{rms} < 0.315$	Not uncomfortable
$0.315 < a_{rms} < 0.63$	A little uncomfortable
$0.5 < a_{rms} < 1$	Fairly uncomfortable
$0.8 < a_{rms} < 1.6$	Uncomfortable
$1.25 < a_{rms} < 2.5$	Very uncomfortable
$a_{rms} > 2.5$	Extremely uncomfortable

vehicles in general, without differentiating cars from buses for example. In a bus, passengers could be standing. One cannot generalize the comfort notion to any type of ground vehicles without taking into account the passengers' postures.

Other researches have related ride quality to jerk, which is the time derivative of acceleration [20]. Unfortunately, it is hard to obtain good results by deriving the acceleration signal in real time, as this latter is already noisy and corrupted by the gravitational acceleration.

However, in hazardous situations, high acceleration values are often required to stabilize the vehicle. This does not go into contradiction with ISO 2631-1, as this latter concerns only the r.m.s.

<sup>4</sup>The Multi-Sense project.



of the overall acceleration. In other words, high accelerations must not be maintained for a long period of time. Nevertheless, high values of acceleration or jerk can cause discomfort even during a short period of time [21]. Maximum allowable values of acceleration should be identified separately. According to [22], discomfort threshold lies around  $1m/s^2$  to  $1.47m/s^2$ . These values were set for different means of transport including buses and trains. Again, this has generalized the problem to both seated and standing passengers. Since we are interested in cars where passengers are always seated, it might be reasonable to set the maximum acceleration values up to  $2m/s^2$  [21]. This shows the gap in the literature regarding motion feelings formalization. This field still should be investigated to facilitate autonomous vehicles introduction to the society.

The major problem is the fact that motion feelings are perceived differently from a driver to another due to the inter-individual variability. In this work, we supposed that the driver itself can select the behavior desired as in driving modes proposed by recent cars. These modes should be extended to personalized behaviors. Experimental studies are needed to associate a certain vehicle behavior to motion feelings and drivers' profiles. The reverse could be then imagined then when the driver profile can be estimated, control allocation weights would be automatically updated in order to generate the expected motion feeling in an autonomous mode.

## 5 CONCLUSIONS

In this paper, a new problematic regarding motion feelings and vehicle dynamics control has been introduced. A solution using multi-objectives control allocation algorithm has been proposed in order to tune vehicle's motion. This method is based on amplifying or reducing the acceleration generated by tire forces to generate different feelings. A co-simulation between Matlab/Simulink<sup>®</sup> and AMESim<sup>®</sup> has been realized in order to validate complex algorithms in high-fidelity models. Results showed different use of subsystem when it comes to motion feelings. This comes without jeopardizing the vehicle's stability ensured by the high-level control layer.

This demonstrates the need of implementing such algorithms in future cars, especially for autonomous cars so their behavior stays predictable and fit best drivers' preferences.

The goal of this paper is to sensitize and start a debate about the objectives that future cars should satisfy. The authors recognize that more evidence should be provided by means of real experiments before proposing any standards. A closer collaboration with car manufacturers is expected for this reason.

Finally, the control allocation framework offers richer possibilities as fault-tolerance. Conflicted chassis systems can be used to complete each other maneuvers. In this way, if a system fails, the other one will easily take over. This will be detailed in a future work to prove that with this approach, both safety and comfort can be ensured.

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