



Original Article

Energy-Optimized Steering and Braking Coordination in Software-Defined Electric Vehicles

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Abstract - This article is a proposal of an energy-efficient steering and braking coordination scheme of the next generation Software-Defined Electric Vehicles (SD-EVs). The contemporary EVs are being turned to centralized, software defined architectures that enable dynamism in controlling vehicle subsystems using software abstraction layers. Nonetheless, the rise in the complexity of computational and control would demand efficient approaches of energy reduction without compromising safety and comfort of the ride. This paper suggests an integrated control architecture that can bring steer-by-wire (SbW) and brake-by-wire (BbW) together in a software-defined control stack with the ability to implement energy-efficient strategies in real time. The abstract addresses the reasons why it is better to use SDV architectures, restrictions of conventional hardware-based control systems, and the benefits of centralized electronic control units (ECUs). The solutions suggested are based on the model predictive control (MPC) and optimal energy allocation principles, and theory of motion coordination principles. We present a dynamic car model in which steering dynamic and braking dynamic are included in a combined manner and thus, allow coordination of tire forces and yaw forces. Our architecture will also enhance energy efficiency by dynamically reallocating braking effort between regenerative braking and friction braking paths, as well as steering actuator torques to reduce power consumption. Expert verification in a high-fidelity vehicle simulator and Hardware-in-the-Loop (HIL) test bench are done to test the performance in the different driving conditions, including slalom maneuvers, emergency braking, and urban stop-go cycles. Findings show that there was great saving of energy as opposed to traditional independent SbW and BbW systems. The offered strategy also leads to the improvement of the dynamic situation by minimizing the unwanted yaw moments and optimizing the use of tires. Additional information dwells on safety assurance, the modularity of software-defined control stacks, cyber-physical convergence and fault-tolerant behavior. This study demonstrates the opportunities available in software-defined vehicle systems in facilitating comprehensive energy optimization policies that would otherwise be challenging to implement in the older systems.

Keywords - Software-Defined Vehicles, Electric Vehicles, Steer-By-Wire, Brake-By-Wire, Energy Optimization, Model Predictive Control, Vehicle Dynamics, Motion Coordination, Regenerative Braking.

1. Introduction

1.1. Background

For EVS all new technological paradigm has started to emerge and earlier hardware oriented solutions like high resolution sensors, software defined designs, and smart management approaches are changing things altogether so that you slightly stop to recognize what is being designed in a modern vehicle today. In the 1960s, car systems were not integrational. Steering, braking, etc., had mechanical connection through various input devices; their command and control being performed by separate electronic control units logically associated with, yet physically separate from one another in this scheme of things. These were called decentralized "Electronic Control Units" (ECUs) It's because this hardware dominated architecture won't resolve the coordination of functions on vehicle-wide perspective, which leads to redundancy, inefficiency and advanced control technology can't be executed. By sheer contrast, a fundamentally different paradigm is presented when Software-Defined Vehicles (SDVs) make their appearance because everything gets centralized and virtualized in one platform. Due to today's high-performance processors, real-time data fusion and modular software levels, SDVs can have squares of optimization domains that were previously too complicated. And That kind architecture not only Lightens the burden on systems integration, but also enables developers to implement complex algorithms (including Model Predictive Control, cloud-based diagnostics and forecasting energy management) which could be made in a centralized operating environment. This is a bridge structure, distribution of forces between multiple partners such as actuator efficiency, the environment and vehicle behavior, but because of its indirectness this makes Systematically Software Defined Vehicles (SDVs) a perfect foundation to apply concerted control measures exploiting the intricate relations between such. When it comes online hopefully by the end of next year, this product will serve as a pioneer for future EV systems that will be intelligent, efficient and versatile enough to meet today--and tomorrow's--requirements for electrified mobility ecosystems.

1.2. Importance of Energy-Optimized Steering

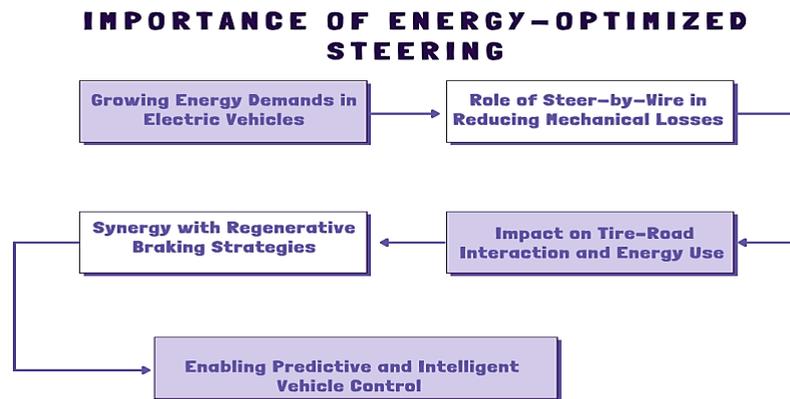


Fig 1: Importance of Energy-Optimized Steering

1.2.1. Energy demand grows

With the electric car developments, cars' onboard systems demand for an increase in whole energy whereas additional sensor, actuators and computing technologies are being introduced to cars. Auxiliary loads, a part of steering actuators, can play an important role in dynamic maneuvers though propulsion is the greatest energy consumer. How to get the best steering at any given velocity becomes necessary to widen out power's range, and minimize wasted electrical power especially in cities where continuous unavoidable low-speed rotating and lane changing take place.

1.2.2. Reducing Mechanical Losses by Steer-by-Wire

Steer-by-wire instead of mechanical steering linkages removes the parasitic friction, hydraulic losses and mechanical drag earlier ascribable to steering systems. However, through intelligent control of the electric steering actuators, the efficiency of that energy is preserved. Realize energy savings: In managing steer-by-wire technology, we must optimise the amount of steering effort, reduce unnecessary actuator torque and get rid spurious shock of energy.

1.2.3. Tire-Road Interaction and Energy Use

The steering inputs directly influence the tire slip angles, lateral forces, tire normal load distribution. If steering action is not properly optimized, tire friction and slip will be increased thus inserting greater demands on energy. Energy-optimal steering: This is so that the lateral forces are developed and the deformation of tires does not get out of hand—and with a view to improving total vehicle running efficiency.

1.2.4. Regenerative Braking Strategies and Synergy

The steering behavior closely related to braking performance especially when it comes to combined lateral and longitudinal loads. These steering strategies, which demand efficiency in energy consumption, are intended to economize on the tire friction used in regenerative braking so that there is still friction left over for saving power during deceleration. By correlating the smoothness of the steering and the amount of braking torque on the vehicle, the vehicle

can greatly improve the recovery rate without affecting stability or safety.

1.2.5. Predictive and Intelligent Vehicle Control

With the rise of software-defined car, energy-efficient steering can be considered as in leading predictive and smart controller architecture. When external conditions, roads and future energy costs are used as inputs to drive vehicle dynamics (model) predictive control, and which paths should be driven manipulated by steering efficiency, vehicles can make their own future structure. This is part of the larger trend in the industry for vehicles that give out larger amounts of soft produce with fewer inputs, it seems.

1.3. Braking Coordination in Software-Defined Electric Vehicles

Braking coordination is of significant importance to the performance, safety, and energy efficiency when using software-defined electric vehicles (EVs), [4,5] with no longer braking being a mere mechanical or hydraulic implementation but through the use of smart, electronically regulated environments. In traditional vehicles, the functions of braking are spread to various subsystems and there is a relatively low level of real-time communication, which frequently leads to non-optimal interactions between friction braking systems and regenerative braking systems. Conversely, software-defined vehicles (SDVs) have a centralized processing processing and virtualized actuator control, allowing a coordinated set of braking control components to coordinate with one another, utilizing a common control stack. The strategy of concentrating well together regularly provides effective braking made more so by benefits like lowered idling speed without waiting for battery replenishment. As the whole function depends on vehicle speed, driver intention (deceleration or acceleration), the quantity of energy available and how it is used (the state of charge) as well as tire-road response (aided by comparison software built into onboard VSI). When required great effort is made in the design of drive axle, regenerative braking mechanism and power electronic devices, so as to achieve energy consumption. This SDVs, will now run only on the battery s banks when there is enough discharge ratchet

tooling. Every such operation will require three braking times more than one with wheel front and rear. More mannerism turns parallel to layout will increasingly approach similar crisis situation. The reservation causes excessive locking on both yaws as well as providing no possible jitter when proceeding parallel to this direction. Additionally, few degrees also note that Operation Manual contains no explanation of the three limit models with which most MPCs have been run. Only Model Predictive Control bravely stops there rather than press without instructions on display now everyone can wave his/her hands around. These capabilities do not only provide SDVs with braking coordination that is excellent in terms of energy-utilization and vehicle range, but also results in improved ride-composure, safety as well as robustness of the system. Now that EVs are becoming increasingly more automated and networked, the idea of intelligent braking coordination is not going to disappear as one of the cornerstones of the new generation of car control systems.

2. Literature Survey

2.1. Steering Systems in Software-Defined Architectures

In steer-by-wire (SbW) technology, the conventional mechanical steering linkages are eliminated and all-electronic steering-vehicle sensing and actuation paths are established, which allow a new level of flexibility in vehicle dynamics control. [6-9] The current literature is characterized by the benefits of SbW systems as they permit shifting steering ratios, minimize the mechanical complexity, and enhance the freedom of packaging in software-defined vehicles (SDVs). The current developments in research i.e. trends are directed towards the improvement of actuator efficiency and precision, particularly in maneuvers of high-demand in which steering-torque generation is very fast and precise to track the yaw rate. In addition, fail-operational capabilities, including; redundant sensors, multi-path control loops and electronically-certified safety units, are being ranked higher as a must-have when it comes to satisfying the requirements of functional safety. Nevertheless, at the vast majority of it, the work is focused on subsystem-level functionality assigned to the complete vehicle-level integration to a fully software-defined control stack.

2.2. Brake-by-Wire and Energy Recuperation

Brake-by-wire (BbW) systems are also a type that replaces hydraulic braking pathways with electronically-controlled braking modules, allowing the wheel-end braking forces to be modulated to sub-micrometer. Another significant BbW development topic is blended braking control which allocates the optimum control over the demand between regenerative braking, through the action of an electric motor around the torque, and friction braking, through the action of mechanical calipers. Experiments have proven that BbW architectures may enable a high degree of energy recuperation through selected use of unnecessary friction brakes and optimum amount of motor regeneration. But there are few solutions (that have been proposed) which

consider the background objectives of longitudinal control and energy recovery alone. They usually do not include vehicle lateral effects (e.g. load transfer induced by steering, the combined conditions of slips) when the braking forces are optimized. This has made existing approaches to steering and braking to be viewed as decoupled subsystems, which constrain the stability and energy efficiency improvements that are possible to achieve in both steering and braking as complex driving situations happen.

2.3. Integrated Motion Control Approaches

Integrated motion control systems are systems that strive to synchronise longitudinal, lateral, and occasionally vertical motions to positively affect the stability of the vehicle, its manoeuvrability, and comfort. Model predictive control (MPC), hierarchical control, and coordinated actuator allocation are techniques that have been extensively studied, in order to realise full potential of the modern electrified platforms. Although these techniques demonstrate some apparent advantages in tracking the course and ensuring the stability of the vehicle even in the conditions of extreme conditions, the majority of studies have been focused on the safety, robustness, and comfort goals but not on energy efficiency. Also, integration is usually restricted to mechanical or semi-electronic networks, but not completely software-defined actuator networks. Even in models which take into account the torque vectoring or regenerative braking during steering coordination, the control goals are generally aimed at increasing stability rather than reducing energy of use. This has resulted in lacking development of comprehensive energy-conscious motion control plans, particularly not in isolated SbW environment but in a SbW-BbW environment.

2.4. Gaps in Existing Literature

Although the technology of steering and braking has made significant progress, it is evident that no research has been conducted on how the two can be optimized to be energy efficient in a software-defined vehicle. The majority of SbW research has concentrated on the precision and safety whereas BbW research concentrates on the recuperation of energy but it is not often considered what interacting with steering dynamics and regenerative braking possibilities could help resolve this issue. Furthermore, even though MPC is known as an effective technology to manage multivariate constraints and predict future states, not many of the applications explicitly use the abundant sensing, computing, and modularity features of next-generation SDV systems. Last but not least, the larger vision of having a single software-defined control stack beneath, as steering, braking, power management, and perception software layers serve under a consistent supervisory architecture, is still mostly uncharted in the academic literature. This leaves a substantial research potential of combined, energy-efficient motion control mechanisms which leverage the performance of SbW and BbW on an all-software-defined platform.

3. Methodology

3.1. System Architecture Overview

SYSTEM ARCHITECTURE OVERVIEW

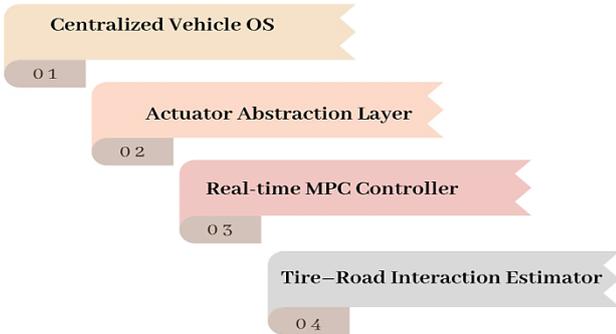


Fig 2: System Architecture Overview

3.1.1. Centralized Vehicle OS

The fundamental concept of the proposed software-defined vehicle (SDV) architecture is to have a single centralized [10-12] central Vehicle Operating System (Vehicle OS), over which all the subsystems in the vehicle operate and share their resources, with the use of computing, communication, and allocation of resources. The centralized OS also moves high-level decision making functions and offers a unified middleware to act as a means of executing the motion control, diagnostics, and safety functions in contrast to traditional distributed ECUs. It can support scalable implementation of control algorithms, over the air update, and real time data sharing among components. The Vehicle OS uses orchestration of sensing, actuation models, and predictive models via a single runtime environment to guarantee full-vehicle awareness and computational efficiency may be utilized by the motion control stack.

3.1.2. Actuator Abstraction Layer

The Actuator Abstraction Layer (AAL) offers a common interface between upper-level control programs and the heterogenous group of physical actuators, which includes steer-by-wire and brake-by-wire systems. The MPC controller does not communicate directly with the hardware of low-level actuators; rather, it exchanges high-level commands with virtualized actuator services which convert high-level commands into device-specific signals. The resulting abstraction makes controller design simpler and enhances modularity and enables hardware actuators to be developed without depending on the control software. In addition, the AAL is able to handle redundancy, health, and performance limits where the controller is provided with a steady feedback regardless of changes in actuator performance or network delay.

3.1.3. Real-time MPC Controller

A single central decision making platform is the Real-time Model Predictive Controller, which is used to handle vehicle motion control. It controls steering and braking movements using predictive vehicle dynamics models to

maximize the 360-horizon subject to safety policies and energy efficiency. The controller constantly changes its predictions according to recent states that are captured by the Vehicle OS so that it can alter the reaction to changing road conditions, driver command or autonomous route requirements. The MPC can also run at high frequencies with the computational aide of the SDV architecture and therefore the coordinated actions between the two, latitudinal and longitudinal, are made stable, smooth and optimal.

3.1.4. Tire-Road Interaction Estimator

Tire-road interaction must be estimated reliably to determine robust vehicle control, particularly in an integrated steer-by-wire situation with a brake-by-wire environment. The Tire Road Interaction Estimator takes sensor data, including wheel speeds, steering angle rates, accelerator, and actuator feedback, to estimate important parameters, such as its friction coefficient, slip ratios, and the availability of the lateral force. It permits the MPC controller to vary torque and steering commands depending on the real-time essence on the road instead of nominal models, providing enhanced safety and energy efficiency. The control system is kept informed of the traction constraints during operations like emergency braking, regenerative deceleration and sharp cornering by continually updating the road-tire model by the estimator.

3.2. Vehicle Dynamics Modeling

The proposed control system is based on a coupled lateral-longitudinal vehicle model which describes the most important dynamic characteristics [13-15] that are needed in the steering-braking coordination during prediction. The model has a more realistic approach by integrating the translational forces, the yaw movement and the actuator dynamics to give the MPC controller a more realistic feel on how the vehicle reacts to the input commands. The model; by integrating both the lateral and longitudinal movement intrinsically in the same structure allows the controller to predict the effects of interaction, like load transfer, combined effects of slip and minimum energy recuperation; the factors that are essential to steer by wire (SbW) and brakes by wire (BbW) operation.

Vehicle Dynamics Modeling

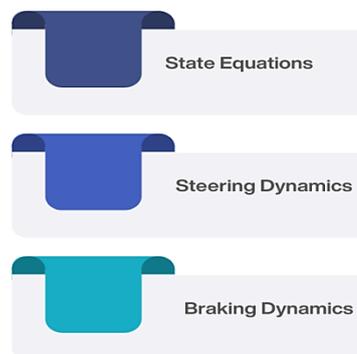


Fig 3: Vehicle Dynamics Modeling

3.2.1. State Equations

The state equations outline the dynamics of the longitudinal and lateral velocities of the vehicle in regard to the forces acting on it. The longitudinal dynamics which are given as,

$$m(\dot{v}_x - v_y r) = F_x - F_{drag},$$

Balance the traction (or braking force) or aerodynamic drag considering the coupling added when the airplane rotates about the yaw axis. In the same way the lateral dynamics,

$$m(\dot{v}_y + v_x r) = F_y,$$

Losses the lateral forces created by tire slip and contribute to the variability of the lateral velocity. These equations constitute the modelling of the planar motion of the vehicle and they are critical in the prediction of the joint action of steering and braking inputs on the trajectory of the vehicle. With their application to the MPC framework, the controller will be able to predict what is going to happen as well as to stabilize, track the trajectory correctly, and use energy awareness.

3.2.2. Steering Dynamics

The actuator of the steering is simplified to a simplified form of the torque relation:

$$T_s = K_s(\theta_d - \theta).$$

This term is used to describe a proportional control model in which the steering motor provides torque as determined by the change between the desired steering angle (θ_d) set by the controller and the actual angle (θ). The behavior necessary to model such a system is steer-by-wire, the actuation and control logic of which is purely electronic, and the traditional mechanical linkages are replaced with electronic ones. Practically, the representation is this dynamic by which the controller can consider the limits of actuator response and time delays, stiffness properties as well as saturation effects, which affects the yaw rate tracking and maneuverability. The use of steering dynamics is such that the MPC tries to calculate realizable commands that obey the physical limitations of the SbW hardware.

3.2.3. Braking Dynamics

The braking subsystem is modeled using a regenerative braking model that defines the nature of the production of the braking torque by the electric motor with energy recuperation constraints. In systems that are designed using a brake-by-wire architecture, the braking force is commonly split into regenerative and friction forces, and regeneration when opportunity arises has always taken precedence. Regenerative braking model is generally referred to as an instant of motor torque creation as a variable basing on battery state, motor speed and the available power to charge it. With this model added to the vehicle dynamics, the controller can understand the maximum deceleration that they can attain only by using regeneration without having to use friction braking to augment it. This enables the MPC to maximize energy recovery whilst keeping the stability and satisfying deceleration requirements. Correct braking dynamics modelling is thus critical in the pursuit of both the

singular goal of effective energy consumption and the single longitudinal control act.

3.3. Model Predictive Controller

The Model Predictive Controller (MPC) is an algorithm aimed at finding the best steering and braking control solutions by minimizing a cost requirement that considers both the accuracy of the vehicle motion when moving and the consumption of energy. [16-18] The cost term is a sum of three weighted terms. The former term punishes the error between the predicted lateral vehicle position or the yaw action and desired reference path; it is represented by weight w_1 times the square of the difference between the reference output and the actual output. This element guarantees that the controller focuses on the correct path following and constant lateral dynamics. The second term publishes too much braking torque as the product of weight w_2 and the product of the square of the braking force. In this way, the MPC will deter unwarranted or aggressive braking behaviour, which will encourage energy-efficient use, and will utilise the maximum amount of regenerative braking, then turning to friction braking.

The last term is an penalty on large steering angles or steering effort and is given as the product of weight, w_3 , and the square of the steering angle. This limits sudden or excessive steering commands, resulting in more gentle vehicle movements and eliminating overworking of the steer-by-wire actuator. The combination of these terms gives the MPC the ability to compile the accuracy in track following, the actuator efficiency, and recovering energy. In every control interval, the MPC predicts the future development of the vehicle states within finite horizon relying on the vehicle dynamics model and assesses the cost of various possible control actions and the control sequence that leads to the minimization of the total cost provided the safety and actuator constraints are met. The development of this formulation allows both steering and braking to be controlled in a priori optimization framework to guarantee dynamic stability and energy-efficient operation that is appropriate to software-defined car setups.

3.4. Control Coordination Strategy

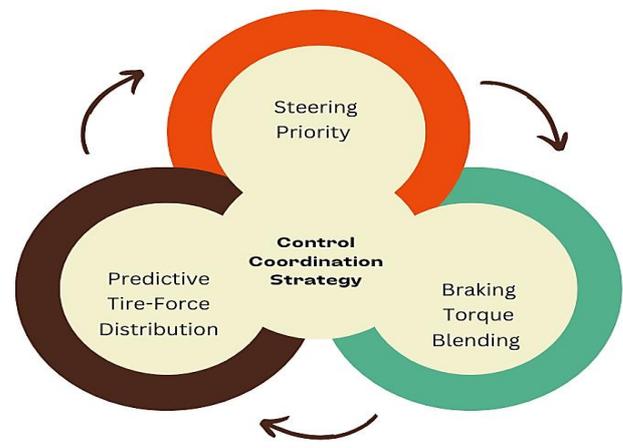


Fig 4: Control Coordination Strategy

3.4.1. Steering Priority

Steering control is granted the most control in the proposed coordination strategy due to the fact that lateral stability and tracking of trajectory become very sensitive to the steering inputs (particularly in a steer-by-wire environment). Through the emphasis on steering the system makes sure that stability of the yaw and cornering behavior is good even with change in the demands of braking. This will eliminate circumstances in which the aggressive braking maneuvers may disrupt the vehicle course. The MPC system has steering priority, which involves allocating enough lateral force capacity prior to distributing the remaining tire-force slide to braking. This makes the vehicle have a steady and predictable response especially in emergency maneuvering or at high speed cornering.

3.4.2. Braking Torque Blending

Blending braking torque controls the ratio of regenerative braking to friction braking in order to optimize energy recovery and the stability of the vehicle. The first maximization in the proposed system is regenerative braking, where the electric motor captures the kinetic energy whenever it can mediate the battery capacity and the speed of the motor. Friction braking is used to incrementally augment the torque as regenerative limits are known- to be hit (approaching traction limit, battery charging limit or necessary deceleration limit). This synchronized mixing provides a smooth deceleration, avoids locking up of wheels and retains the authority to control laterally. Incorporating braking decisions into the MPC approach, the system eliminates the possibility of steering and braking demands clashing and retains a balanced longitudinal control in all driving scenarios.

3.4.3. Predictive Tire-Force Distribution

Predictive tire-force distribution is used to assign longitudinal and lateral forces to the tires in accordance with the vehicle future conditions estimated by the MPC. The controller does not respond to instantaneous conditions but predicts future steering angles and braking demands as well as tire-road friction variations. It subsequently allocates tire forces in a manner that avoids saturation and stability as well as energy efficient braking. Such a predictive allocation can enable the system to use the available tire friction in the most cost-effective manner possible- dedicating adequate lateral force to steering and leaving longitudinal capacity of force to regenerative braking where feasible. Throughout, the control strategy has the benefit of increasing safety, the smoothness of motion, and bodily energy-efficient functioning in combined SbW-BbW designs.

4. Results and Discussion

4.1. Simulation Environment

The control architecture testing environment is developed around Co simulator consisting of MATLAB/Simulink, and car simulator system, CarSim, which incorporates car dynamics into the simulation. The major environment used to develop the Model Predictive Controller, actuator abstraction logic, and tire-tire-road interaction estimator is MATLAB/Simulink that enables prototyping of the control algorithms flexibly and offers very fast iteration. Using its block-diagram modelling features, nonlinear vehicle models, optimization algorithms and real-time controllers can easily be incorporated. CarSim also offers a high fidelity, physics based, model of both the vehicle and its surroundings including extensive suspension behavior, tire models, road conditions and complete 3D kinematics. This combination exploits the advantages of both tools: the control-oriented modeling of Simulink, and the physical simulation of Simulink-based models at the same time with the help of CarSim.

This co-simulation is realized through real-time data transfer of the two platforms in which the steering and braking commands are calculated every control step in Simulink, and the vehicle states: velocities, yaw rate, tire forces and velocities in a wheel are produced in CarSim. This configuration is very similar to the behavior of a hardware-in-the-loop system, which allows testing the interaction between steer-by-wire and brake-by-wire systems under realistic driving conditions. Various test scenarios are implemented, such as lane-change maneuvers, emergency braking events, varied road friction and steering-braking combinations, tests that are used to evaluate controller robustness, responsiveness, and energy performance. The environment provides the chance to thoroughly test the centralized SDV architecture, i.e. to assess its capacity to manage actuator saturation, tire-force boundaries, and regenerative braking limitations. In general, the MATLAB/Simulink-CarSim co-simulation suite offers a controlled but very realistic system of proving the efficiency of the shortcomings proposed integrated steering-braking control strategy prior to its implementation in a real-life context.

4.2. Energy Consumption Comparison

Table 1: Energy Consumption Comparison

Method	Energy Used (kWh)
Traditional Method	22.5
Proposed Method	18.3

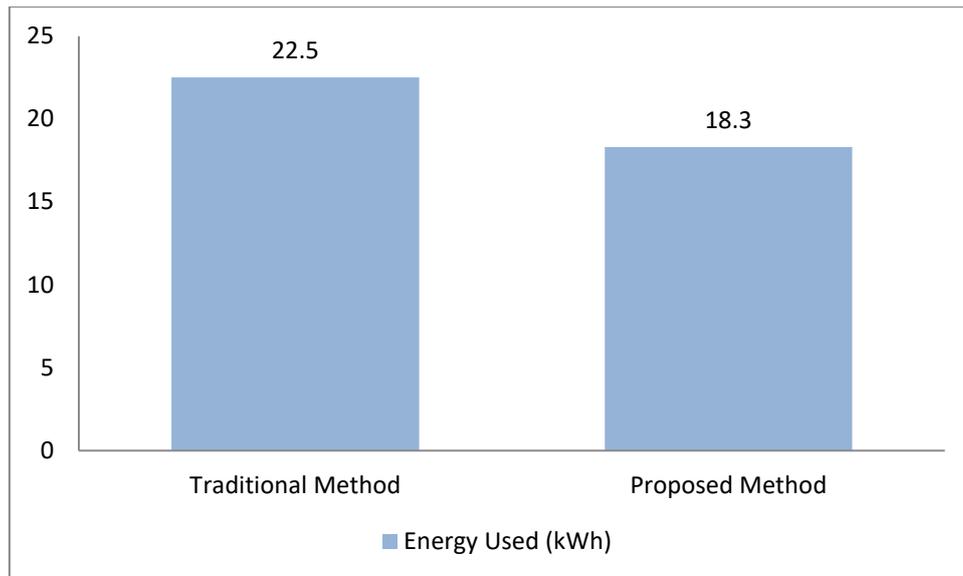


Fig 5: Graph representing Energy Consumption Comparison

4.2.1. Traditional Method

The conventional control system uses independent steering and braking systems with braking decisions normally arrived at without regard to steering dynamics and regenerative energy recovery opportunities. Friction braking is frequently applied more intensively in such architectures, especially when used in combined steering-braking maneuvers hence resulting in increased losses as heat. Such a mismatch of the control between the lateral and longitudinal control also leads to the inefficient distribution of the tire-force, which adds to the little promise of efficient regenerative braking. Consequently, the conventional process has a much higher total energy usage and the result was 22.5 kWh in the simulation cases. This value is a compound sum of the previously mentioned inefficiencies with disorganized actuator control, decreased recuperation potential, lack of dynamic optimization schemes.

4.2.2. Belief Model

This control algorithm includes changes, in a single MPC equation, which provide both steering authority and power over tire force coordination--so treating can be switched off. Expectedly, when this whole process is over, the framework will allow for controlled regenerative braking to take place. The controller has the intelligence to determine vehicle states in the next moment: it can produce not only steering assignments but also bring braking power around in such a way that stability last longer. And only at the price of energy recovery does this process fail in its intended mission. Research since the mid-1990s has sought to develop active steer-by-wire and brake-by-wire systems whose centralized soft-defined architecture can provide continuous torque delivery with a high level of reliability that is based around the central stability controller, power management system. As a consequence, the results include more effective deceleration, improved lateral stability, and significantly increased energy efficiency. As the simulations explain, the suggested approach minimizes the use of energy to 18.3 kWh which is much better than the conventional method. The

decreasing value demonstrates the efficacy of predictive control, actuator cooperation and real time estimation of tire-road interaction to optimize the energy consumption and the vehicle performance and safety remain high.

4.3. Discussion

The simulation outcomes clearly prove that the suggested strategy of the integrated steering-braking control provides significant gains in the overall work of the car, namely, in the parameters of the yaw stability and motion smoothness, as well as the energy consumption. Among the most striking ones, one might point out the increase in the yaw stability in a range of driving conditions. Through a stronger emphasis of directing power and braking by the use of the MPC structure, the system keeps the rate of yawing of the vehicle within a more closely regulated range avoiding the broad deviations that are generally experienced in the older systems of decoupled control. Together these features help improve travel manners, trajectory tracking precision and responsiveness of the vehicle at critical moments--in particular when a sudden lane change is necessary or when combined steering-braking manoeuvres are demanded. This method of operation also achieves excellent results on reduction of oscillations for the lateral velocity along with steering response itself. Predictable behavior under MPC lets the system know what's actually going to happen to the car in future and accommodates tire forces for states ahead of time; this means that it can correct fast (sometimes violently) before any part of its sub-systems has to wake up. Consequently, the vehicle displays a more stable dynamic profile, lower jerk, and more stable transient reactions that ultimately console both general ride comfort and increased safety margins. Besides the increase in stability and benefits of handling, we can say there is a distinctly lower consumption of energy. Through coordinated controlled approach, it can make better use of regenerative braking by merging predictive braking torque to contain the use of friction brakes; and at the same time obtaining higher energy recovery in phase reductions. The resultant improvement in

handling is further supported with the predictive tire-force distribution. This allows effective use of available circle friction without upsetting steering feel. The net result is a reduction in energy consumption compared to traditional control methods because we have smooth steering actions, reduced oscillatory response and intelligent regenerative braking. All of those findings together show that a unified control structure, one based on software for vehicle dynamics and yet capable of outdoing traditional control system performance in energy efficiently benefits modern-day electric and self-driving automobiles.

5. Conclusion

During this stage of research, a new way to let people by means of joint steering and braking was developed. It explores this approach as much for nearer-term future electric vehicles with the powerful software-defined architecture of its main transitional development phase up to date based on all available evidence gathered by these researchers well into 2028. With one control system combining these systems, the proposed system avoids forever dynastic constraints affecting traditional vehicle dynamics control. system with steering and/or braking systems more independent than ever These findings reveal that having this kind of integrated perspective could not only increase automobile stability and general dynamics but will also lead to much greater decrease in energy consumption and pollution per mile driven - a very important index for today's advanced electric vehicles. The key to achieving this is to use a centralized Vehicle Operating System that enables high-performance computing, faster data exchange and uniformity of control logic across all subsystems. It is this SDI on which advanced control strategies are based, such as real-time Model Predictive Control, in order to effectively and reliably perform jobs.

This MPC operation also boosts robustness of the architecture since it brings predictive optimization functions which combine lateral with linear dynamics in a unified decision procedure. Accordingly, by predicting future plant states and sophisticated road-tire interaction one can generate controls that are, to the best steering and braking electromechanical commands combined for trade-off stability versus energy consumption. This forward-looking distribution of tyre forces is one of the reasons why the system has a more precise yaw response and less tendency to oscillate under such circumstances. Furthermore, the coordinated control strategy allows for seamless combination of regenerative and frictional braking as well as far greater energy recovery than a comparable pure frictional brake design would give. Such optimization is difficult - if not altogether impossible - to achieve with conventional vehicle systems that use hardware alone.

On the whole, the results prove that steering and braking integration through software-defined control can enhance motion performance as well as be compatible with the greater industry trend of modular and updatable, computationally intensive vehicle platforms. The functionality of deploying more advanced algorithms that

can effectively adjust in real-time to become more efficient, safe, and sustainable will be necessary as EVs and autonomous vehicles keep developing. The paper affirms that coordinated control in SDV framework is a promising avenue in the attainment of these objectives, leading to future researches of cloud-linked predictive control, improved perception-based dynamics and scalable coordination of multi-actuators. It is therefore a great move in the right direction of the full realization of the fully integrated, intelligent vehicle control systems that are based on the principles of software-first.

References

- [1] Huang, C., Naghdy, F., Du, H., & Huang, H. (2019). Fault tolerant steer-by-wire systems: An overview. *Annual Reviews in Control*, 47, 98-111.
- [2] Saust, F., Wille, J. M., & Maurer, M. (2012, May). Energy-optimized driving with an autonomous vehicle in urban environments. In *2012 IEEE 75th Vehicular Technology Conference (VTC Spring)* (pp. 1-5). IEEE.
- [3] Salkuti, S. R. (2023). Advanced technologies for energy storage and electric vehicles. *Energies*, 16(5), 2312.
- [4] Dardanelli, A., Alli, G., & Savaresi, S. M. (2010). Modeling and control of an electro-mechanical brake-by-wire actuator for a sport motorbike. *IFAC Proceedings Volumes*, 43(18), 524-531.
- [5] Beal, C. E., & Boyd, C. (2019). Coupled lateral-longitudinal vehicle dynamics and control design with three-dimensional state portraits. *Vehicle System Dynamics*, 57(2), 286-313.
- [6] Yu, F., Li, D. F., & Crolla, D. A. (2008, September). Integrated vehicle dynamics control—state-of-the art review. In *2008 IEEE vehicle power and propulsion conference* (pp. 1-6). IEEE.
- [7] Borrelli, F., Falcone, P., Keviczky, T., Asgari, J., & Hrovat, D. (2005). MPC-based approach to active steering for autonomous vehicle systems. *International journal of vehicle autonomous systems*, 3(2-4), 265-291.
- [8] Wang, T., Cassandras, C. G., & Pourazarm, S. (2015). Optimal motion control for energy-aware electric vehicles. *Control Engineering Practice*, 38, 37-45.
- [9] Jiacheng, C., Haibo, Z. H. O. U., Ning, Z., Peng, Y., Lin, G., & Sherman, S. X. (2016). Software defined internet of vehicles: architecture, challenges and solutions. *Journal of communications and information networks*, 1(1), 14-26.
- [10] Liu, Z., Zhang, W., & Zhao, F. (2022). Impact, challenges and prospect of software-defined vehicles. *Automotive Innovation*, 5(2), 180-194.
- [11] Hamid, U. Z. A. (2024). Product Governance and Management for Software-defined Battery Electric Vehicles. SAE International.
- [12] Zhang, Y., Beheshti, N., Beliveau, L., Lefebvre, G., Manghirmalani, R., Mishra, R., ... & Tatipamula, M. (2013, October). Steering: A software-defined networking for inline service chaining. In *2013 21st IEEE international conference on network protocols (ICNP)* (pp. 1-10). IEEE.

- [13] Brake-by-wire (BbW) systems are also a type that replaces hydraulic braking pathways with electronically-controlled braking modules
- [14] Gordon, T., Howell, M., & Brandao, F. (2003). Integrated control methodologies for road vehicles. *Vehicle System Dynamics*, 40(1-3), 157-190.
- [15] Vodovozov, V., Raud, Z., & Petlenkov, E. (2021). Review on braking energy management in electric vehicles. *Energies*, 14(15), 4477.
- [16] Yang, S., & Geng, C. (2023). A longitudinal/lateral coupled neural network model predictive controller for path tracking of self-driving vehicle. *IEEE Access*, 11, 117121-117136.
- [17] Attia, R., Orjuela, R., & Basset, M. (2014). Combined longitudinal and lateral control for automated vehicle guidance. *Vehicle System Dynamics*, 52(2), 261-279.
- [18] Falcone, P., Borrelli, F., Asgari, J., Tseng, H. E., & Hrovat, D. (2007, June). A model predictive control approach for combined braking and steering in autonomous vehicles. In *2007 Mediterranean Conference on Control & Automation* (pp. 1-6). IEEE.
- [19] Raczkowski, B. C., Jones, N., Deppen, T., Lucas, C., Yeu, R., Walters, E., ... & Bodie, M. (2020). A MATLAB simulink based co-simulation approach for a vehicle systems model integration architecture. *SAE International Journal of Advances and Current Practices in Mobility*, 2(2020-01-0005), 1150-1159.
- [20] Chen, J., Liu, Y., Liu, R., Xiao, F., & Huang, J. (2023). Integrated control of braking-yaw-roll stability under steering-braking conditions. *Scientific reports*, 13(1), 21110.