



ISSN: 2454-132X

Impact Factor: 6.078

(Volume 12, Issue 2 - V12I2-1212)

Available online at: <https://www.ijariit.com>

A Comparative Study of Steer-by-Wire and Conventional Steering Systems in Autonomous Vehicles

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ABSTRACT

The current trends within the automotive industry hint towards a shift into Steer-by-wire (SbW) powered steering systems in automobiles. This technology is aimed at replacing the previous mechanical steering systems and promising improvements in vehicle longevity, performance bumps, improved handling, and easier integration with artificial intelligence-driven self-driving (automated) cars. However, the novelty of this technology requires an understanding of its current state of development and deeper knowledge into the extent to which it can replace mechanical steering vehicles. This paper aims to review the current state of Steer-By-Wire (SbW) and analyse it across the parameters that the technology must excel in before SbW is introduced to the mass production of self-driving cars. Moreover, this study will also analyse the current drawbacks of an SbW system and how these can be further polished to achieve desirable outcomes. The paper will provide an insight into how well SbW is really suited for taking on self-driving cars and the true capabilities of the technology driving the system.

Keywords: *Autonomous Cars, Mechanical Steering, Sensors, Steer-By-Wire System, Electric Power Steering, Vehicles.*

INTRODUCTION

Autonomous vehicles are forecasted to revolutionize transportation in the future, giving the driver a laid-back experience of driving. Using sensors, GPS and optimised control microprocessors to drive the car, there is also great consideration towards reliability. For this research, we consider an autonomous vehicle one with SAE level of autonomy at 2 or above. However, the dispute between choosing the newer steer-by-wire (SBW) versus mechanical steering arises due to the strict and effective control requirements for automated cars. Both technologies will be evaluated to conclude how well automated cars can function more effectively with one technology. Steer-by-wire (SBW) is a new development in the automotive industry, only being introduced in 2013 for mass-scale production vehicles in Infiniti Q50 (Jancer). On the other hand, mechanical steering is the classic steering method for vehicles which has withstood the test of time and has undergone multiple stages of refinement such as the addition of power steering in Chrysler's 1951 Imperial model, intended to improve manoeuvrability. In spite of the relatively newer development in Steer-by-wire, the technology holds a plethora of advantages against mechanical steering such as a lighter design, faster response times and dynamic steering control, making it a suitable competitor for future achievements (Gabriela Martínez,¹) in the vehicle industry. Mechanical steering relies on the physical contact between the steering wheel and the wheel rack, diminishing the adaptability of the mechanical steering's design, according to Gabriela Martinez. Additionally, this design also adds excess weight to the car. The SBW also allows for a parallel control of the car during autonomous driving, making a system where the autonomous driving chip's input does not pass down the same mechanical linkage as the driver's steering wheel. This permits capabilities like variable control, variable portions of control being shared by the driver and the chip, making accidental manual inputs hampering the steering less. Possibilities like reduced output delay and mechanical delay can be implemented using a SBW system. The paper reviews existing developments in SBW and Mechanical Steering to decide which technology has more potential for providing benefits to automated cars in terms of driving capabilities, passenger comfort, and safety of the systems. The aim is to provide a clear justification as to why one of the above-mentioned technologies can allow AI-powered autonomous cars to function more effectively and reduce technical flaws.

STEER-BY-WIRE

Operation

The steer-by-wire system, unlike a regular mechanical steering system, does not use mechanical linkages between the road wheels and steering wheels as shown in figure 1(b). The system can be decomposed into two subsystems as seen in figure 2 (Putra), the steering input subsystem consisting of the steering wheels, steering angle sensor and torque sensor along with a feedback motor. The steering actuator subsystem is responsible for delivering output on the road, consisting of a steering actuator motor, the rack and pinion set, wheel angle sensor and road wheels. In order to refine the input, an electronic controller system can be utilized for decision making during automated driving or cross-verifying the driver's inputs before executing them. The whole system is linked together by wires which allow communication between sensors, actuators and the controller.

The input subsystem is responsible for the driver to control the vehicle and for the vehicle to provide a form of response to the driver to alert them of physical actions of the vehicle. The input provided by the physical driver can be done by multiple modes of input, such as steering wheels, joysticks or trackpads. Steering wheels are the most common method, so will be used as an example.

The steering wheel's angle of rotation and torque can be measured by sensors responsible for it, and communicate this to the electric controller via wires. The input is then converted into the output, simultaneously, the control unit sends signals to actuators embedded within the input system to provide haptic feedback or resistance for steering to simulate the typical experience of a mechanical steering system (Martínez, 2).

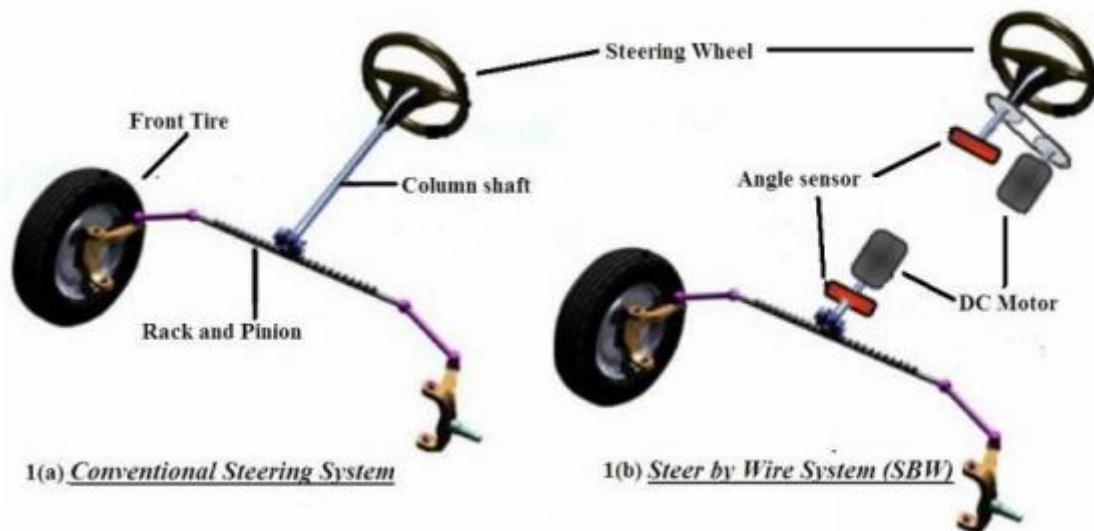


Figure-1: Differences in mechanical steering 1(a), and steer by wire 1(b) (Martínez 2)

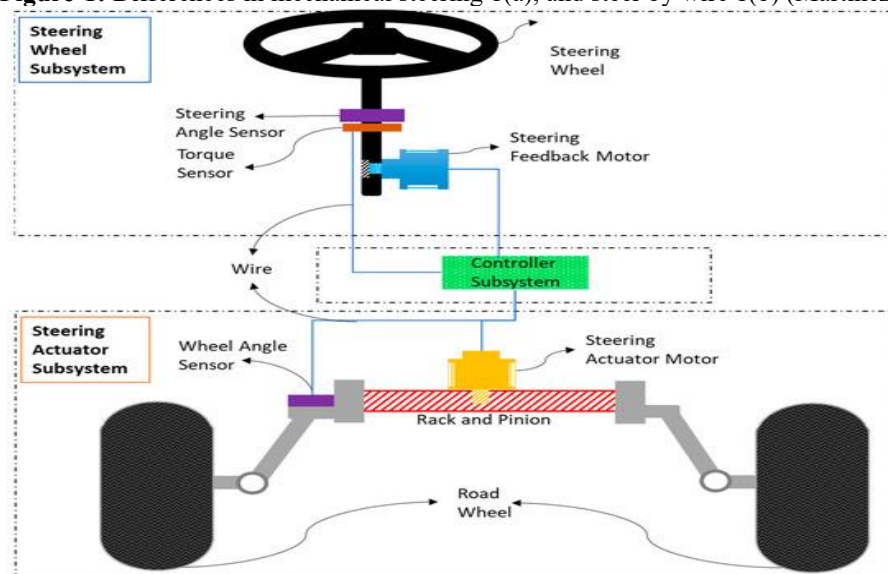


Figure-2: Subsystems of steer-by-wire system (Putra, 5)

The electric controller is used for handling the inputs provided to the vehicle by the physical driver or the computer responsible for automated driving of the vehicle. The controller identifies the inputs and uses other known variables like vehicle speed to determine the strength of the movement the actuator must produce for the desired outcome to be achieved. The controller is therefore responsible for the execution of outputs and ensuring the output is smooth for passengers, staying within the safety limits of turning at a particular speed. The controller can determine a proportion of the vehicle's control under the driver and the automated driving computer's judgement (Huang et al. 411). Such implementations permit semi-automation with the computer aiding drivers (like lane keep assist) during which the controller determines a larger control proportion under the computer, hence, reducing the impact of driver's inputs during such aiding procedures. The sensors embedded within the vehicle can be used to estimate the interactions of the vehicle with the road, allowing a replication of the nuances of the road to be transmitted to the input sub-system and creating feedback. The actuator subsystem handles the output of the controller. The system utilizes the traditional rack and pinion method to turn the wheels, however, powered by the electric motor actuator under the automated. The road-wheel angle sensor allows the controller to determine the extent of steering required to achieve the desired outcome and also allows for the controller to verify that the outcome aligns with the theoretical path. This advanced steering system allows for smoother moderation of the driver's actions and permits a more un-hindered automation capability for automated cars due to the separation of the drivers actions from the final output (Martínez 3-4). Steer-by-wire systems are favoured for their high adaptability for different degrees of responsiveness required, as the torque on the wheel rack can be completely varied. This feat is achieved through the use of a controller which executes the desired outcome more precisely due to electric control of actuators responsible for steering.

MECHANICAL STEERING FUNCTIONING

Mechanical steering or a variation which aids the driver like electric power steering (EPS) is the most common system for steering used in most vehicles (Snapon). Modern mechanical steering systems incorporate power steering to aid the driver in making trickier turns with lesser physical effort. This system is an addition to the century-old design of mechanical steering.

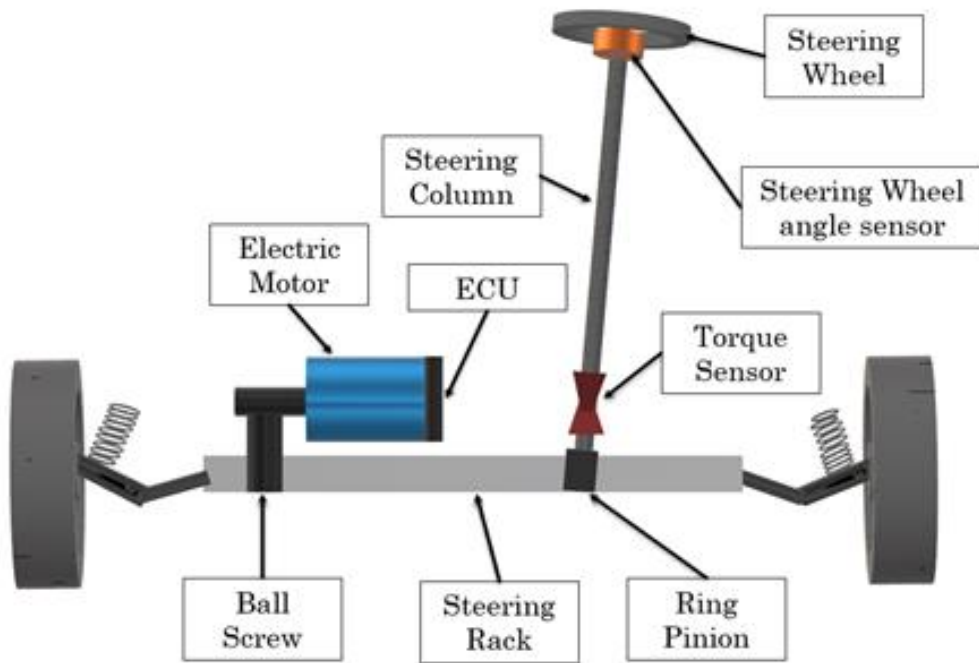


Figure-3: Mechanical power steering system (Liviu-Vasile Pop et al.)

Now, Figure 3 shows the rack-and-pinion mechanical system with an EPS utilized in cars due to a straight-forward design approach and years of reliability. Without the EPS, the system works on the basis of using a mechanical linkage between the wheel rack and the steering wheel, which are connected using the steering column similar to that in figure 3, only without the ECU and electric motor to provide extra power to the steering system. The column connects to a pinion gear which sits and moves the steering rack. When the rack moves sideways, tie-rods attached at each end move the wheels in compliance with the rack. Therefore, turning them. Over time, due to issues such as poor steering designs, steering friction and parameters of the vehicles systems (Upadhyay et al. 1), the designs had to be revamped to create a design with lower efforts. Therefore, the addition of a hydraulic or electric motor to augment the drivers input torque has been done on the steering rack. Such a design has allowed for lower driver fatigue and lower effort required to manoeuvre the car, however, the opportunity to automate steering through this motor can also be done.

Existing automated cars of notable manufacturers like Tesla and Mercedes-Benz utilize existing mechanical steering designs, refined for comfort, to make automated cars as seen when Tesla had to recall model X vehicles due to issues in its EPS system (“Model X Steering Assist Motor Bolt Recall”). The designs adopted by their cars have similar set-ups to non-automated cars, but instead of the motor restricted to the function of electric power steering, the motor has capabilities of controlling the whole steering of the car. Despite the existence of mechanical steering systems allowing for evolutions in the technology, such as the introduction of electric power steering, which attempt to make it safer and cover up the previous flaws of mechanical steering, there still are some flaws in the system which have to be deeply compared to decode its suitability in an automated car.

COMPARATIVE ANALYSIS BETWEEN STEER BY WIRE AND MECHANICAL STEERING FOR AUTOMATED DRIVING

The steer-by-wire system was explained in terms of its mechanical workings above. The software behind steer-by-wire is majorly responsible for its control and modification at different speeds. Controllers the software which is loaded onto the processor responsible for processing sensor data and giving output to the actuators. Different controllers are analyzed below which are independently designed, the result of each controller’s performance alongside the mechanics of steer-by-wire will give us a basic overview of the extent to which steer-by-wire is capable of powering a self-driving car for the comparison.

Table-1: Shows SBW control performance with latest controller techniques used (Putra 15-16)

SBW Performance parameters	Control technique used	Note
Accuracy	<ol style="list-style-type: none"> 1. Synergistic Predictive Fusion Control (SPF) 2. Nested Adaptive Super Twisting Sliding Mode (NASTSM) 3. Variable horizon robust model predictive control (VHRMPC) 	<ol style="list-style-type: none"> 1. Improve response speed and accuracy while reducing errors 2. High tracking precision and robustness 3. Minimize side-slip and yaw rate error
Fault Detection	<ol style="list-style-type: none"> 1. Delta operator MPC 2. Composite degradation model 3. Fault tolerant 	<ol style="list-style-type: none"> 1. Able to deal with high sampling rates 2. Intermittent fault diagnosis 3. Works well for multi-motor SBW

In order to assess the suitability of SBW for handling the control of an automated car, accuracy and fault-detection are the most important parameters to determine how capable certain steer-by-wire controllers are when it comes to managing driving performance and delivering the steering output as desired by the automated computer of the car. To understand the table, a shallow-level understanding of each control method is provided below -

- i. Synergistic Predictive Fusion Control (SPF) (Yang et al. 1) - Fixes issues related to previous sampling methods for getting road-wheel interaction data, allowing for more accurate results from the controller and faster responses from the controller when navigating the road.
- ii. Nested Adaptive Super Twisting Sliding Mode (NASTSM) (Sun et al. 2-3) - Removes disturbances from readings of the road-wheel interactions to get data for the controller to make decisions in turning the wheels. Therefore, reducing the time taken to process the data and increasing accuracy as the controller is only handling clean data.
- iii. Variable horizon robust model predictive control (VHRMPC) (Shao et al. 1) - Adjusts the horizon based on a predictive model, allowing for higher degrees of control and more accuracy because of its ability to cope with the road-wheel interactions at various angles.

Similarly, to aid the control methods, fault-tolerant methods are also explained at surface level below -

- i. Delta operator MPC (Huang et al., 1811) - Uses the delta operator approach to create a linear matrix of inequalities to determine the fault tolerance of systems. Such a model predictive control (MPC) can also increase robustness against loss of tracking due to actuator failures, thus increasing safety of the SbW system.
- ii. Composite degradation model (Yu et al. 557) - Establishes a degradation model of specific components related to SbW, allowing for fault diagnosis on the go. Therefore, warnings of any intermittent faults can be provided and the controller can adjust its handling to compensate for the natural degradation.
- iii. Fault tolerant, active and passive systems. (Huang et al. 98-100) - Fault tolerant control systems (FTCS) are used widely in SbW in its FTCS active form. This uses classifications of the different faults developed in an SbW system into classes like duration of fault and seriousness of fault. Then, the system actively works to isolate the faulty component and attempt to perform up to specifications using the remaining components until the fault is resolved.

An accurate and fault tolerant system for SbW therefore can be developed using the existing technologies which yield successful results (Notes column on table 1 above.) An autonomous SbW system can heavily benefit from these individual control systems as they patch the weak points which many previous SbW systems have failed to address, thus, allowing for an overall enhancement in the various aspects of keeping SbW secure and accurate. For instance, the SPF control produces a substantial improvement in the data which controllers use in determining the next decisions and fostering a greater fidelity between the actual conditions of the road and the information which the controller can get. Similarly, findings from the composite degradation model improves the predictive nature of degradation of various components (Putra, 15-16), allowing for SbW controllers to recalibrate power distribution in accordance with components' reduction in performance. However, challenges in making an SbW system which incorporates the benefits of each controller mentioned above will require collaboration between the independent systems both mechanically and electrically. Such developments will require more research and development as automobile manufacturers aim to push the SbW system into mass production vehicles. Such developments will also require rigorous testing to meet the global standards of safety and accuracy of autonomous vehicles which exist today. In order to achieve this, massive amounts of funds must be put into the development process which may pose as unfavourable to many companies which already use automated driving achieved with mechanical steering like Tesla, therefore, until and unless the integration of the various individual systems with each other does not become smoother, convincing companies into using SbW will take much longer to achieve despite the immediate benefits which SbW systems can bring forth. Likewise, research into a fail-safe SbW system which can completely compensate for the system's lack of redundancy in the form of a mechanical linkage must be done in order to build a safer car capable of steering minimally without any external intervention in the event of an SbW failure, some alternatives can include a steer-by-brake system (Nexteer) where the wheels of different sides are braked non-uniformly which causes the vehicle to turn due to a difference in speed. Additionally, once the SbW system is made up to standards of an autonomous car using the above mentioned controllers and more, an autonomous car controller software can be added to the system which can automatically control the steer-by-wire car in a similar way that it can be added to a mechanical steering module of a car.

In order to further unlock more capabilities of using a steer-by-wire system, Artificial Intelligence (AI) can be used in order to enhance the discussed controllers and improve the passenger experience in automated cars which use SbW; Some controllers which can benefit with AI integration are listed. Firstly, when it comes to predictive control models (MPC) such as Variable horizon robust model predictive control (VHRMPC) for controlling the wheel angle based on speed and other factors, AI neural network systems can provide benefits for such static models which do not change as the conditions of the roads and tires change. To achieve this, (Emergent Mind) a proposed residual dynamics system can work which uses neural networks to create additions to existing models by analysing the error, or residuals as stated by emergent minds, occurring between the predicted outcome and the actual/observed outcomes. In vehicles, this means that corrections to the VHRMPC model can be done on the spot and permit more accuracy and greater precision using the neural networks. Secondly, controllers which aim at reducing accuracy errors due to incorrect data like Nested Adaptive Super Twisting Sliding Mode (NASTSM) is a controller method which cleans off the disturbances caused by chattering of vehicles in sensor readings before giving it to the controller to handle SbW can also benefit from Fuzzy Neural Network. The benefit is that an AI system of such can eliminate the need to train NASTSM on data from various conditions (such as different speeds and terrain), instead the neural network system can assess the conditions and modify the level of NASTSM's interference in the SbW system along with providing direct places which the NASTSM should focus on under different conditions. For instance, in rougher terrain the cause of SbW sensors giving wrong data may have more to do with the rotation of wheels and the weight on wheels rather than the angle of wheels, thus, AI can allow NASTSM to focus only on the important sensors. Lastly, SbW systems can improve their Human-Machine-Interface (HMI) not only by replicating the road environment on the steering wheel, but by also offering customizability in terms of the level of realism which the driver may want to feel from the road and the steering to wheel turning ratio.

By incorporating Machine Learning systems which can analyse the amount of effort a does to rotate a steering wheel to the degree of the turning of the wheels, AI can analyse if the driver preferred having more effort to turn the wheels or lower effort to turn the wheels, based on this data, the AI will modify the software responsible for handling the steering to wheel ratio of the car to come close to the driver's preferred steering style at all speeds as done in (Yang et al.) research stated in (Putra,8) where a proposed hierarchical control of the SbW system is used and a learning-based strategy is used to control the steering ratio. Overall, Seyed Abolfazl Mortazavizadeh et al says that "The SBW system is a key to the development of the intelligent automobiles and autonomous vehicles" (Mortazavizadeh et al. 1236), showing the potential of SbW in entering the sector of intelligent vehicles and its potential for integrating AI in making newer and more efficient SbW systems.

Whereas steer-by-wire has its own advantages in its application for the future of self-driven cars, many existing cars listed in (CarADAS) such as Tesla model S (2024), Mercedes-Benz EQS (2024, and more use a form of mechanical steering aided with power actuators (power-steering). Therefore, in order to completely understand whether or not a shift should be made to the upcoming SbW technology, we must analyse the physical limits of using mechanical steering in automated steering and how can SbW patch them.

Cars which utilize mechanical steering cannot incorporate a lot of the software sophistication of Steer by wire due to the restriction of a fixed linkage between the steering wheel and wheel rack, thus, models mentioned in table 1 cannot be used to enhance such a rigid system, therefore, power steering is the furthest a mechanical steering car can be modified till. Existing mechanical steering systems such as the one in Tesla Model S use an Electric Power steering system (EPS) which reduces the effort which drivers have to exert on the wheels at various speeds.

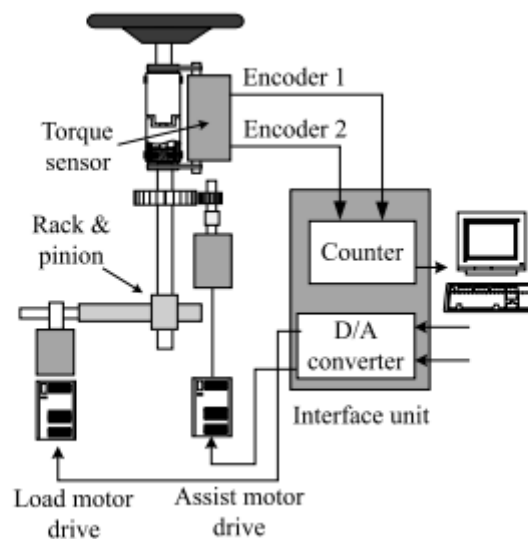


Figure-4: Working of an EPS mechanical steering system (Kim and Song 449)

The above diagram (figure 4) shows the basic EPS system widely used. The key components are the torque sensor, interface unit, and assist motor which help in converting the basic mechanical steering model into an EPS system. The torque sensor measures the steering force exerted on the steering by the driver which is given to the interface unit of the logic unit. The assist motor is responsible for adding some extra force beyond that of the force exerted by the driver to ease steering. This force directly results in a turning of the wheel rack at a different ratio compared to the steering wheel. The load motor drive in diagram 4 must be ignored for the purpose of this paper as it is not an actual part of a vehicle using EPS. The result of the EPS system however depends on the logic used to determine the amount of additional force which must be provided to the wheel rack by the assist motor. JH Kim's (Kim and Song 453) research suggests that this must be dependent on a PI controller which determines the force given to the assist motor based on the vehicle's speed, the force opposing the turning of the wheels, and the torque sensor reading of the steering wheels. Based on this, the EPS logic can be tuned to provide some variability in the ratio of the steering wheel and road wheel, allowing for the driver to either experience added support at lower speeds where turning tighter corners may have traditionally required more force, conversely at higher speeds the driver may experience some resistance by the assist motor which can offer more stability by preventing immediate sharp turns which may be disruptive to the motion of the vehicle at very high speeds.

Additionally, AI can be further integrated to use machine learning in order to determine how much force would the driver prefer to put with the help of the torque sensor and the wheel sensor, allowing for a more customizable approach to this rigid design. Secondly, AI can also be integrated into modelling the wear of gears, thus, modifying the PI controller's model to compensate for the wear build up over time using fuzzy logic controllers or neural networks as these can figure out patterns in the wear much better than human mechanics and save cost in the long run due to fewer requirements of modifying the model externally or servicing the gears which experience wear and tear. This can prove beneficial for many of the cars which use EPS in order to aid mechanical steering. However, EPS as a system to integrate newer AI controllers and automated system controllers can be more challenging than the SBW system. Firstly, the larger amount of gears can result in a greater inertia which any motor will have to combat to produce a movement. This is from the simple fact that EPS is an entire system ranging from the wheel rack to the steering shaft, connected by multiple gears, thus, a movement in any part will result in a movement in the entire system, and will require much more force. Such a downside will result in autonomous cars unable to make quick and evasive decisions without requiring a lot of valuable energy unlike steer-by-wire systems, therefore, SBW can be made more modifiable without the requirements of making manoeuvres compliant with the restrictions imposed due to mechanical stress on the mechanical steering components. Secondly, there would always be a requirement to have a fully linked drive shaft to the wheel rack in an EPS system, which restricts the positioning and layout of cabins of vehicles which are self-driving or partially self-driven as in a mechanical system, if the driver were to make any intervention to the system, a mechanical link would be required.

Lastly, whenever a driver wishes to immediately jolt control of the wheel, to keep the transition between manual-driven and self-driven smooth, the EPS system will have to provide a resistance to the steering wheel which may feel uncanny for the driver and also result in greater mechanical wear and tear compared to the SbW system which has a mechanically decoupled steering wheel, thus, reducing possibility of any issues related to smoothness of such a transition. The final results of whether or not steer-by-wire must be used in self-driving requires a general comparison between steer-by-wire and mechanical steering along with the level of control a self-driving car will get independent of the human driver. The longevity of a SbW system is much greater as a result of fewer moving parts which means a lower chance of breakage and less frequent services due to lower wear and tear, and lower margins of error; Unlike mechanical steering, where immense forces must be given out through the assisting motor to a larger contraption of gears which ranges from the steering wheel to the road wheels, thus, more parts which can potentially fail. Secondly, the power which a self-driving car with SbW will require is much lesser in contrast to a mechanical steering system as the motor will have a lower gear inertia to overcome due to fewer gears in the system. Therefore, such a SbW system could potentially save more power and require smaller motors. Moreover, a mechanical steering car will also underperform in contrast to steer-by-wire, due to added weight and extra space required to house the larger system. This will lower the potential performance of a car due to extra load and result in less agility during turns which may be important escape manoeuvres in self-driving cars during fatal incidents, additionally, the extra space saved in SbW can be used to place a larger engine or a higher capacity battery pack for a vehicle, increasing power and range. Next, SbW can offer unparalleled levels of customizability amongst control of the vehicle between the driver and the self-driving system, which can allow drivers to modify their level of automation due to the connection between the steering wheel and wheel rack being electronic and not physical. Drivers can also customize other possible distractions like road haptics or steering wheel movement during self-driving modes in higher SAE rated vehicles. However, a steer-by-wire system lacks the redundancy which a mechanical linkage can provide. In the event of a complete SbW failure, alternative solutions like a back-up system with a back-up power source or non-uniform wheel speeds, such as steer-by-brake (Nexteer) (Nexteer), will be required for turning the vehicle, which are expensive add-ons, thus, increasing the cost. Furthermore, these extra features could, in some cases only, diminish the advantage of SbW being lighter than mechanical steering. On the other hand, mechanical steering always has a mechanical linkage between the steering wheel and wheel rack which is much safer and always reliable

CONCLUSION

In this paper, a comparative analysis of steer-by-wire (SbW) systems and mechanical steering systems was done to assess its suitability for the upcoming automated “self driving” vehicle technology. The SbW has become a highly sought-after steering system as vehicles pursue advancements towards the drive-by-wire systems. Companies like Mercedes-Benz (Mercedes-Benz) are proceeding towards making steer-by-wire an integral part of their lineup in the second half of this decade. The effective development of SbW will however encounter multiple cross-functional challenges such as securing its acceptance amongst drivers, enhancing feedback mechanisms, integrating various controller types, and fixing the technology till a level suitable for non-human control of the vehicle. On the other hand, mechanical steering slowly transforms into a relic technology which does not promise more aid for our future vehicles. The system’s main strength was its sturdy mechanical link allowing drivers to confidently steer, which becomes its drawback as vehicles transform into a new era where human intervention in their utilization reaches a minimal amount. Although existing car manufacturers like Mercedes and Tesla have built automated steering around this system, these examples are only from the initial days of self-driving technology as new models like the Tesla Cybertruck becoming completely steer-by-wire (Kay 1), begging the requirement for exploring the fundamental benefits of SbW over mechanical steering and harvesting them in a new type of automobile. The comparison in the above section highlights the capabilities of steer-by-wire as a more versatile design and modifiable system due to its impeccable mechanical freedom from the steering wheel. Such a system, paired with the softwares integrated with Artificial Intelligence can prove to be revolutionary in the era of self-driving vehicles for enhanced control of more power-efficient vehicles. Steer by wire can also allow for more unique vehicle designs without the worry of wheel-cabin mechanical linkages to be made, which is a restriction for mechanical steering vehicles, and the implementation of larger power modules like engines or battery packs can be used in the space saved by removing the mechanical steering housing in steer-by-wire systems. Mechanical steering on the other hand was built around the need for a rigid connection between the steering-wheel and the wheel rack, which is of minimal requirement for a self-driving system in modern cars, moreover, even when the requirement for self-driving arises, steer-by-wire as a system on its own can perform it equally as well. However, the only real drawbacks of SbW lie in the backup system it must use in order for steering the vehicle in the event of an SbW failure, proposed methods like steer-by-brake may increase production cost due to more connections, for instance between the steering wheel and brake, to be made which may increase the production cost and slight increase in the weight. Overall, the advantages of an SbW system can prove it to be worthy investing in and making it into a base for self-driving car operations in the coming future. However, due to the technologies recency, controllers for SbW systems will have to be rigorously tested and made more reliable in order to make SbW reach levels of reliability of the mechanical steering.

SCOPE FOR FUTURE

Out of the topics discussed in this paper, further research should examine the various fault-tolerant mechanisms which SbW can use and benefit from, artificial intelligence (AI) in making controllers for SbW, and the integration of automated systems of self-driving cars with the controllers of SbW.

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