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The Dynamics of Vehicles

Basics, Simulation and Autonomous Systems

Edited by Hüseyin Turan Arat

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Meet the editor

Dr. Hüseyin Turan Arat is an associate professor in the Department of Mechanical Engineering, University of Sinop, Türkiye. His primary research interest is in hybrid and electric vehicles, hydrogen energy, simulation, and vehicle applications. He received his Ph.D. in Mechanical Engineering from the University of Çukurova, Türkiye, in 2016. He has three book chapters, more than sixty publications, and one TR patent to his credit. He is the recipient of the 2019 Carl-Jochen Winter Award from the *International Journal of Hydrogen Energy* (IJHE). He is also a board member of the National Hydrogen Technologies Association of Türkiye.

Contents

Preface

The transportation sector is progressing rapidly. The mechanized transportation vehicles that we began using 200 years ago have made our lives easier, as have their counterparts produced for different functions and purposes.

Vehicles are transportation fixtures with complex engineering features. Vehicles have their own production methods, usage areas, types, and sizes. Their one commonality is their utility for getting drivers and users from one point to another.

One of the important aspects of vehicle engineering is movement direction. How the functions of the vehicle will correspond to the commands from the driver or user is a branch of science known as "vehicle dynamics."

The first issue in vehicle dynamics is how to calculate the forces on the vehicle while it is in motion and how to calculate the energy required for this motion to occur. Although vehicle dynamism is calculated in different ways for different transportation types (air, land, sea, and space), it serves two main purposes. First, how the driver's/user's commands/requests will be executed by the vehicle and second, how safe and comfortable driving should continue while these commands are being carried out.

Vehicles are not just about their engines (internal combustion, electric, etc.), which supply energy. Besides examining the complex mechanical processes in engines, vehicle dynamics involves studying how the motion energy from a vehicle's engine enables the movement of the vehicle.

There are several important parts in vehicle dynamics that must be identified, calculated, and manufactured accordingly. These parts play an essential role in the movement of the vehicle. Brakes, suspensions, wheels, wings, aerodynamic structure, steering, driver support systems, and many more parts form the basis of vehicle dynamics.

This book highlights the importance of vehicle dynamics, with a focus on autonomous vehicles, underscoring their importance as vehicles of the future. Chapters address such topics as vehicle dynamics and modeling, testing, and modeling in different vehicles.

I wish to express my thanks to the contributing authors for their strong efforts and participation in this project.

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Section 1

Introduction

Chapter 1

Introductory Chapter: The Dynamics of Vehicles – Basics, Simulation and Autonomous Systems

Hüseyin Turan Arat

1. Introduction

Today, developments in the transportation sector are progressing in a huge promoting way. Our mechanized transportation vehicles that we started to use 200 years ago has made our lives easier with their counterparts produced for different functions and purposes.

Vehicles are transportation fixtures with complex engineering features. All of them have their own production types, usage areas, types, and sizes. Totally, all of them are in the production area and during usage are made to reach the driver or users from one point to another.

This is undoubtedly that one of the important arguments of vehicle engineering is movement direction. How the functions will correspond to the commands that are requested from the tool should be done as classified in a teaching department. The name of this branch of science is "vehicle dynamics."

When it comes to vehicle dynamics, the first thing that comes to mind is that it is the issue of how to calculate the forces on the vehicle while it is in motion and how to calculate the energy required for this motion to occur. Although vehicle dynamism is calculated in different ways for different transportation types (air, land, sea, and space) it serves two main purposes:

1. How the driver/user's commands/requests will be executed by the vehicle.

2. It is how safe and comfortable driving should continue while these commands are being carried out.

Consequently, much of the studies that are carried out for many years relating to conceptual and mathematical equations are associated with vehicle dynamics and have been created for all kinds of vehicles and started to be used on real vehicles. All this mixture of equations of motion realized by the basic requirements of physics and the mathematics of motion mechanisms are available to the driver.

Vehicles are not just about engines (internal combustion, electric, etc.) which are energy sources. Besides working with complex mechanical processes in engines, the main purpose is about how the motion energy from the engines will provide the movement of the vehicle.

According to reachable open literature, there are important parts in vehicle dynamics that must be found, calculated, and manufactured accordingly. These parts play a very essential and key role in the movement of the vehicle. Brakes, suspensions, wheels, wings, aerodynamic structure, steering, driver support systems, and many more parts formed the basis of vehicle dynamics.

2. Discussion

For the last 20 years, production strategies and product diversity, especially in vehicles used in land transportation, are constantly developing and renewed in line with the wishes of its users. Undoubtedly, technological development, human factor, environmental factor, and necessity factor have an important place in this renewal.

The safety and driver-assisted security processes of the vehicles play an active role in the production of electromobility and semiartificial intelligence vehicles. Although the transition to the fifth phase (fully autonomous vehicles: fully automatic vehicles without any interference from the driver) is ongoing, it still has some more time to fully develop. However, fourth phase is active in most vehicles.

The vehicle dynamics concerned details and the development process is roughly illustrated in **Figure 1**.

Nearly 90% of traffic accidents in the world are due to driver's fault [1]. Therefore, to support/assist the drivers vehicles are integrated with driver-assistance devices and systems. These systems are developed in such a way that they can perform instant analysis and react with a control unit. The phenomenon of "assistant" that started with ABS and ESC has taken a highly developed form with new

Figure 1.
An illustrated figure on vehicle dynamics (photos taken from Google Images).

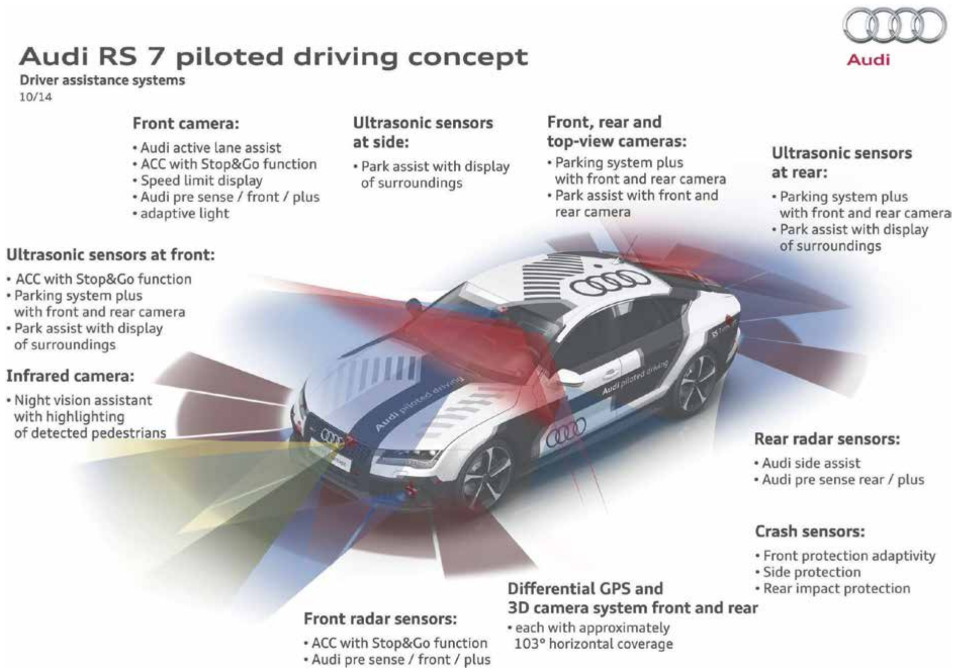

Figure 2.
Audi RS7 driver assistance system (Audi, faithfully to original, by [2]).

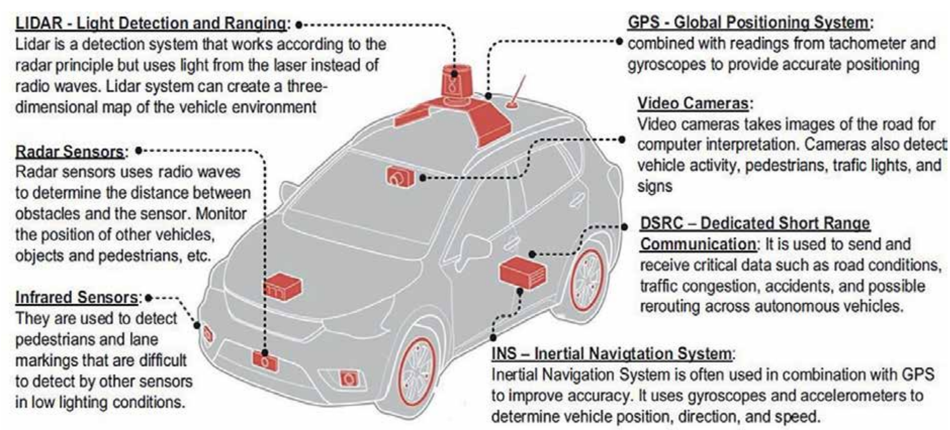

Figure 3.
The system components and sensor design of an autonomous vehicle [5].

technologies. In an example as is illustrated in **Figure 2** shows the driving assistance systems of the Audi A7 concept.

Most of these support systems are produced to increase the interaction of the driver with the vehicle and to achieve a safe and comfortable riding more easily. Hundreds of hours of simulation and practical experiments are carried out under these productions. After these trials, the optimized systems become systems that are manufactured and coupled to the vehicle. In engineering applications, before creating a product, it is inevitable to create an analysis with simulation and programming. The math behind this procedure is done with basic vehicle dynamics math. Mathematical calculations of different organs and major case studies can be found in Refs. [3, 4].

More autonomous driving and driverless operations of such vehicles starting to run in the coming years. Certain companies (Google, Tesla, etc.) continue to work and try on autonomous vehicles.

The system components and sensor design of an autonomous vehicle is shown in **Figure 3** [5].

3. Conclusion

As a general result, this study's aim is to create a special book to explain the importance of vehicle dynamics, which has an important place in the automotive and vehicle world and to direct more attention to autonomous vehicles.

The book chapters were created by experts in their fields and blended with the aim of both vehicle dynamics and modeling, testing, and modeling in different vehicles, and presenting the main information.

This book presents to the readers crucial phenomenon about the autonomous vehicles of the future and how important the vehicle dynamics is.

Conflict of interest

"The author declares no conflict of interest."

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Section 2

Modelling

Chapter 2

Modelling and Dynamic Analysis of a Vehicle

Burak Can Çiçek

Abstract

In this topic, modelling of vehicles, dynamic analysis and verification of both vehicle model and dynamic analysis will be elaborated. Vehicle modelling can be performed by either using simple discrete models, finite element models or rigid bodies that are connected with elastic elements. Element types of each modelling method and in which circumstances can be used will be explained. Advantages and disadvantages will be encompassed. After that, vehicle model will be evaluated in terms of dynamic behaviours such as mode shapes and natural frequencies. Moreover, damping parameter selection methodology will be elaborated. Consequently, model verification methodologies will be handled such as modal tests and dynamic load tests. How the model can be updated according to the tests will be briefly explained.

Keywords: finite element model, modal analysis, dynamic analysis, verification test, vehicle

1. Introduction

In this chapter, modelling of vehicle, methods of dynamic analysis of a vehicle and verification tests of the methods will be explained. Moreover, industrial experience in modelling, analysis and verification will be shared.

The vehicle market evolution requires reduction of time to market. Moreover, it is inevitable to decrease the time of concept to mass production. Furthermore, new vehicle models are revealed every couple of years in order to the survival of vehicle companies. It is merely possible by performing most of the verifications by analyses. Building models and relying on analyses for verification requires experience. Therefore, modelling methods, verification of models, analysis methods, verification of analysis and test methods are elaborated to share theoretical and industrial experience with the readers.

2. Modelling of a vehicle

In order to produce a vehicle, design phase is required to be completed. After the vehicle design verification, production phase starts. Some modifications will be needed to be performed before the final product such as design improvements, customer requests, etc. Performing verification tests after every modification will cause overbudget. Moreover, the production of each prototype will cause overschedule. Therefore, other verification methods will be needed such as verification of models and analyses. Models should be created before analyses are performed. There are two types of models such as analytical models and finite element models.

2.1 Analytical models

In analytical methods, there are two methods such as creating simple discrete models and creating flexible models. After creating these two mathematical models, analytical solutions can be calculated.

Advantages of analytical methods can be summarized as follows:

1. Analytical methods provide faster solutions due to the fact that it has fewer degrees of freedom when compared with finite element methods.

2. Modification of the mathematical model is faster for analytical methods when compared with finite element methods.

3. Modeling and solving an analytical model requires less computational cost.

4. Analytical methods provide insight into the solution and provide an order of magnitude for the solution.

Disadvantages of analytical methods can be summarized as follows:

1. Analytical methods provide less accurate solutions due to the fact that it has fewer degrees of freedom when compared with finite element methods.

2. Analytical methods require more assumptions and simplifications when compared with finite element methods.

3. Analytical methods are inadequate for detailed analysis.

2.1.1 Simple discrete model

Simple discrete models can be used at the beginning of the design phase. Simple discrete models are particularly utilized for a quick and approximate solution since they have tens of degrees of freedom. Rigid body and flexible joint assumptions can be utilized in order to obtain analytical model. Chassis and the upper structure of the vehicle can be modelled as a single rigid body that has mass and inertia or a set of point masses that have inertia. In this approach, suspension systems and tires can be modelled as point mass and inertia with their stiffness and damping. Dynamic behaviour of a vehicle can be calculated by using Lagrange's equation shown in Eqs. (1) and (2) [1].

$$\frac{d}{dt}\left(\frac{\partial \pounds}{\partial \dot{q}_r}\right) - \frac{\partial \pounds}{\partial q_r} = Q_r^* \ \ \mathrm{r} = 0, \dots, \mathrm{n} \tag{1}$$

$$\pounds = E_k - E_p \tag{2}$$

where,
£ is Lagrangian
q_r, r=1, … ,n are generalized coordinates
Q_r^*, r=1, … ,n are generalized forces representing all non-conservative forces
E_k is Kinetic Energy
E_p is Potential Energy

There are three types of simple discrete vehicle modes such as quarter vehicle model, half vehicle model and full vehicle model. Quarter simple discrete vehicle model, which is one-fourth of the whole vehicle, is shown in **Figure 1**. Quarter simple discrete vehicle model is the simplest version of a vehicle model. It contains only one tire, suspension system and one-fourth of the vehicle mass as a point mass.

Half simple discrete vehicle model, which is more complicated, is shown in **Figure 2**. It contains left or right half of the vehicle model.

Full simple discrete vehicle model is the most complicated version of the simple discrete models and is shown in **Figure 3**.

In simple discrete models, M represents the mass of the vehicle body without suspension system and tires, I represents the inertia of the vehicle without suspension system and tires. m_{i2} and I_{i2} represent relevant suspension system's mass and inertia, respectively. m_{i1} and I_{i1} represents relevant tire's mass and inertia, respectively. Suspension system's and tire's stiffness and damping properties are represented with k and c, respectively. In this simple discrete model, main body of the vehicle is represented by a rigid body that has a single mass and inertia. Each one of the four suspension systems is represented with a point mass and inertia. Similarly, each one of the four tires is represented with a point mass and inertia. Suspension system and tires

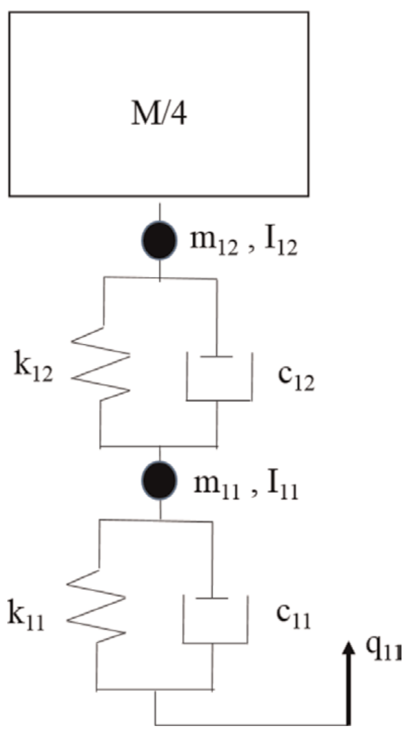

Figure 1.
Quarter simple discrete vehicle model [2].

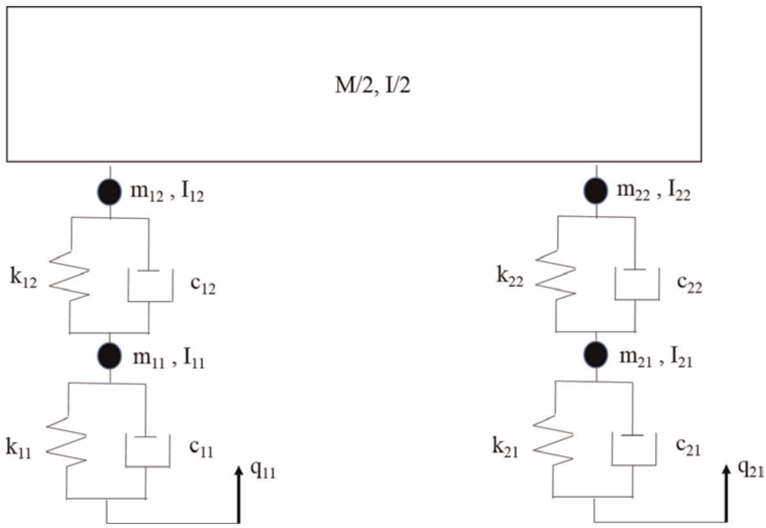

Figure 2.
Half simple discrete vehicle model [3].

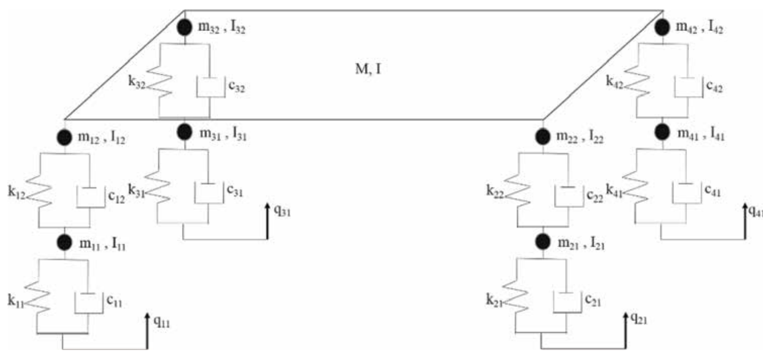

Figure 3.
Full simple discrete vehicle model [4].

are represented by single stiffness and damping coefficients. Q_{i1} is the excitation applied from the road [5, 6].

Quarter simple discrete vehicle model should be used for initial analysis. For further analysis, a half simple discrete vehicle model should be used for more accurate results which are also closer to the full simple discrete vehicle model when compared to dynamic responses [2]. Subsequently, a full simple discrete vehicle model should be used for more accurate results. MATLAB can be preferred as a solver of equations of motion.

2.1.2 Flexible multi-body model

Flexible multi-body models are more complicated when compared with simple discrete models since they have rigid and flexible bodies. In this method, system is modelled with rigid and flexible bodies connected by joints. In this method, solution can be calculated by deriving below fundamental equations [7].

Newton's equation using D'Alambert's principle for particle i is shown in Eq. (3).

$$\overrightarrow{F_i} - m_i \overrightarrow{\ddot{r}_i} = 0 \tag{3}$$

where,
$\overrightarrow{r_i}$: Position vector of particle i
$\overrightarrow{F_i}$: Sum of forces acting on the particle
Virtual work which is done by these forces is also zero.

$$\delta V_i = \left(\overrightarrow{F_i} - m_i \overrightarrow{\ddot{r}_i}\right) \delta \overrightarrow{r_i} = 0 \tag{4}$$

where,
δV_i: Virtual work
$\delta \overrightarrow{r_i}$: Virtual displacements of the particle i

$$\overrightarrow{F_i} = \overrightarrow{F_i^e} + \overrightarrow{F_i^s} + \overrightarrow{F_i^r} + \overrightarrow{F_i^d} \tag{5}$$

where,
$\overrightarrow{F_i^e}$: External forces acting on the particle i
$\overrightarrow{F_i^s}$: Internal forces from other particles in the same body
$\overrightarrow{F_i^r}$: Joint reaction force from another movable body through a joint
$\overrightarrow{F_i^d}$: Reaction forces due to joints with the fixed frame

$$\sum_{i=1}^{\infty} \left(\overrightarrow{F_i^e} - m_i \overrightarrow{\ddot{r}_i}\right) \delta \overrightarrow{r_i} - \sum_{j=1}^{n} \delta s_j = 0 \tag{6}$$

where,
n: number of flexible bodies
$\overrightarrow{F_i^e}$: External forces acting on the particle i
m_i: Mass of the particle i
$\overrightarrow{\ddot{r}_i}$: Acceleration vector of the particle i
$\delta \overrightarrow{r_i}$: Virtual displacements of the particle i
δs_j: Virtual change in strain energy of flexible body j
Lagrange form of D'Alambert's principle is shown in Eq. (7).

$$\sum_{j=1}^{n} \left(f_j + f_j^s\right) \delta q_i + \sum_{i=1}^{\infty} \overrightarrow{F_i^*} \delta \overrightarrow{r_i} = 0 \tag{7}$$

where,
f_j: Generalized external force corresponding to general coordinate j
f_j^s: Generalized structural stiffness forces
δq_i: Virtual displacement in independent coordinate i
$\overrightarrow{F_i^*}$: Inertia method of particle i
$\delta \overrightarrow{r_i}$: Virtual displacements of the particle i
For a system of rigid or flexible bodies generalized inertia forces can be calculated as follows.

$$f_j^* = -\sum_{k=1}^{N} \int \rho \ddot{\overrightarrow{r^k}} \frac{\partial \dot{\overrightarrow{r^k}}}{\partial \dot{q}_j} dV \quad (8)$$

f_j^* : Generalized inertia forces j
N: Number of bodies
ρ: Density
$\overrightarrow{r^k}$: Position vector of an arbitrary point in body k
q_j: Independent coordinate j
V: Volume

2.2 Finite element model (FEM)

After analytical models created and detailed analyses are required, detailed models should be created such as finite element models. Finite element method is a powerful and popular method that provides numerical solutions of differential equations. In this section, finite element method will be handled for dynamic and structural analysis. FEM divides whole domain into smaller divisions which are named finite elements in order to solve the problem. This method converges a solution by minimizing an error function.

Advantages of FEM are as follows:

1. FEM represents a complicated model more accurately.

2. FEM represents the total solution of the whole model more accurately.

3. FEM provides more detailed solutions for structural and dynamic analysis.

4. FEM requires less assumption and simplification.

Disadvantages of FEM are as follows:

1. FEM causes more time and computational cost.

2. FEM causes more modelling effort.

FEM of a vehicle can be classified in three groups such as simplified FEM, reduced degrees of freedom FEM and detailed FEM. At the beginning of the design phase, obtaining faster results is the most important thing since lots of iterations are needed to get the final design. Therefore, simplified and less degrees of freedom models should be preferred at the beginning. When desired response is achieved, detailed and more degrees of freedom models should be used for more accurate results. Detailed models are particularly required for structural analysis. Simplified and approximate models are inadequate for structural analysis. On the other hand, detailed models are not convenient for iterative solutions.

2.2.1 Simplified FEM

Simplified FEM generally consists of simple beam, truss, shell elements (As a rule of thumb smallest dimension is at least 20 times less than the largest dimension), point masses and rigid body elements to bind them. When creating shell elements, mid-surfaces should be created at first. Then mid-surfaces should be attached to each other at the same level for continuity. Subsequently, shell elements should be created by defining the thickness and mid-surface layer position. This process is critical for creating shell models.

The purpose of creating simplified FEM is to obtain quick and approximate results to anticipate how close the first approach to the final one is. Dynamic response of the vehicle can be approximately calculated by using these models. Moreover, simplified FEM has particularly huge advantage over detailed FEM when the past experience over vehicle design is weak or the dynamic load acting on the system is quite new.

Simplified FEM should be created by using an automated code since making modifications for every iteration will take time. Therefore, simplified FEM should be built as parametric. Easily modifiable parts should be modelled as parametric, and modelling and post processing codes should be automated.

Cicek et al. [8] created a simplified FEM to investigate the individual effects of a heavy vehicle's design parameters. Simplified Fem is shown in **Figures 4** and **5**.

There are other ways to create and analyse the system response such as gathering mass and stiffness matrix of a vehicle by using a FEA software and calculate system response by using analytical methods and these matrices. This method should be preferred for much simpler models since gathering these matrices will be much harder according to the complexity of the vehicle model. These matrices can be used to perform modal analysis only which is the first step of figuring out of the dynamic behaviour of the vehicle. On the other hand, computation time will increase due to matrix inversion when vehicle model has more degrees of freedom. Moreover, for further dynamic analysis numerical approach is better.

The other way is using superelements. A superelement is a special type of finite element which consists of a group of finite elements. It is particularly employed to simplify the model when most of the model remains the same after modifications. A simple example of a superelement is shown in **Figure 6**. Left part of the example represents the parts that will be modified during design iterations. Right part of the

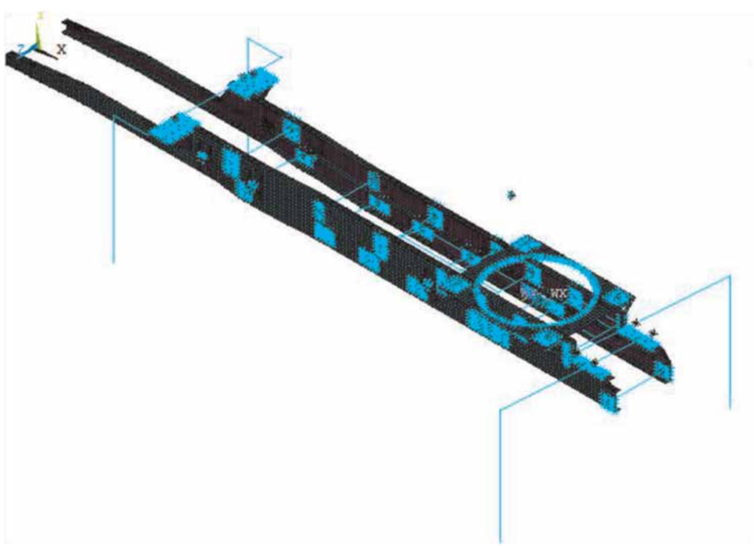

Figure 4.
Simplified finite element model [8].

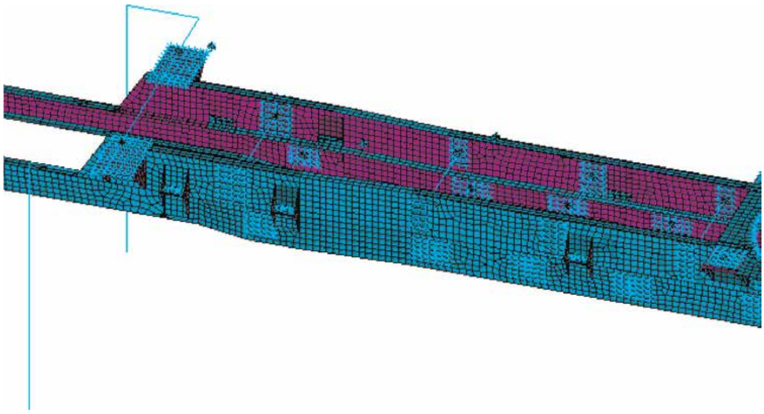

Figure 5.
Simplified finite element model's mesh [8].

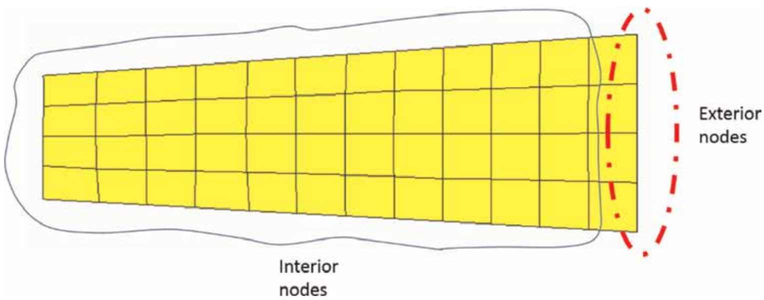

Figure 6.
A simple superelement example [9].

example represents the superelement that will remain the same during the design iterations. Exterior nodes represent the connection points. By using superelement approach, the number of degrees of freedom of the superelement part will be reduced which will provide a significant computation time due to the fact that analysis of the superlement part will not be calculated for every iteration [10]. This will provide a huge advantage during the first part of the vehicle design phase. On the other hand, reduction process will cause a computation cost. Superelement approach is applicable when the number of exterior elements is much less than the interior elements in the superelement. Furthermore, this method can be only utilized for figuring out the dynamic behaviour of the vehicle system like other simplified models. Moreover, the theory behind this technique should be comprehended before deciding to employ it.

2.2.2 Reduced DOF FEM

Reduced DOF FEM is another method to obtain faster results since it has hundreds of DOF when simplified FEM has thousands of DOF. Therefore, component modal synthesis (CMS) [11] which is the most popular reduction method is handled. This method employs highly truncated mode set by converting finite element model's equations of motion into modal domain in other words generalized coordinates space. The usage of this method is an improved version of superelement method. CMS is developed by using Craig Bampton method [12].

$$u = Tq \tag{9}$$

where,
u: System response which consists of many DOF
T : Transformation matrix
q: Modal coordinates consist of less coordinates

$$u = \Phi q \tag{10}$$

where,
Φ: Mode shape matrix which is obtained by below equation

$$\det\left(K - \lambda^2 M\right) = 0 \tag{11}$$

$$M\ddot{u} + Ku = F \tag{12}$$

where,
M: Mass matrix
K: Stiffness matrix
F: Force matrix

$$\Phi^T M \Phi \ddot{q} + \Phi^T K \Phi q = \Phi^T F \tag{13}$$

By using above equations, N DOF finite element model can be converted into n DOF model where N is much greater than n. The main issue is defining n since if it is selected closer to N, reduction will be pointless. When n is selected as smaller there is risk for truncated model that cannot represent the main model adequately. Therefore, modal effective mass approach can be utilized. This method calculates the contribution of each mode on rigid body motion. As a rule of thumb, modal effective mass should be more than 90%. Moreover, highest natural frequency should be selected more than 2 or 3 times higher than excitation frequency for reduction. Furthermore, number of attachment nodes should be taken into account when calculating the minimum number of modes required for reduction. It should be noted that reduction will bring truncation some errors [13].

Semi-trailer finite element model is shown in **Figures 7** and **8** as an example.

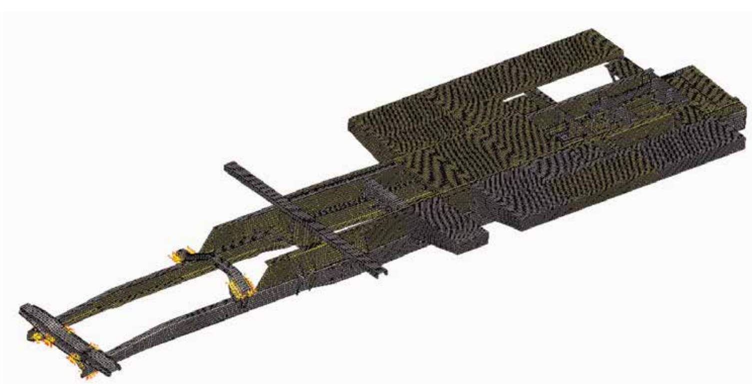

Figure 7.
Semi-trailer finite element model.

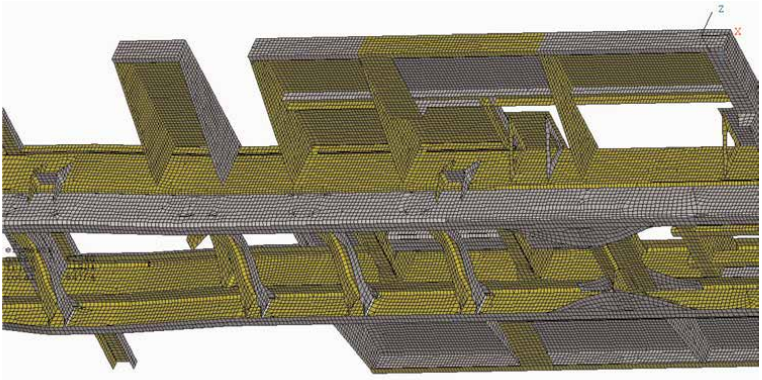

Figure 8.
Semi-trailer chassis finite element model.

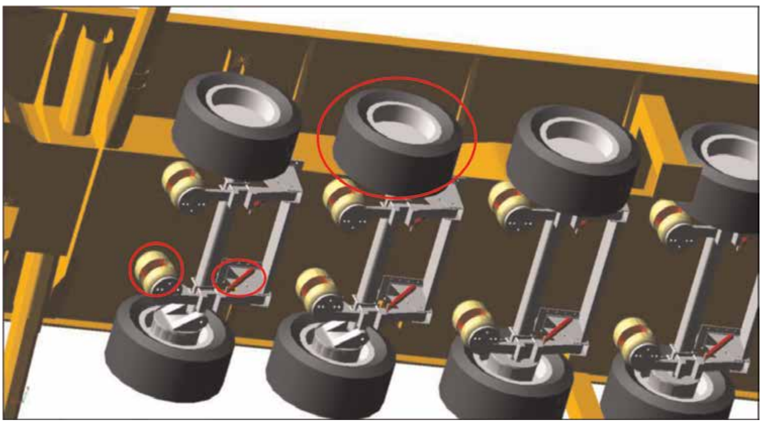

Figure 9.
Reduced degrees of freedom finite element model.

In semi-trailer finite element model, suspension system will be fixed to the lower chassis.

In this example semi-trailer model, suspension system is connected from reduced DOF FEM from its external nodes. Suspension system is modelled as rigid bodies in this example that is shown in **Figure 9**. Moreover, spring, damper and tire elements are utilized to represent stiffness and damping characteristic of the suspension system and tires. Tire properties can be acquired from the producer or can be obtained by conducting tests. Furthermore, road should be modelled for a complete dynamic analysis. Road can be modelled as 2D or 3D. Tire and road properties and their total dynamic behaviour should be verified for more realistic results. Pure and coupled reaction forces applied from road to tire and slip conditions are also should be taken into account when defining road and tire properties for an analysis model.

3. Dynamic analysis of a vehicle

After modelling of a vehicle process completed dynamic analysis process starts. All assumptions, simplifications and modifications effect on the dynamic response of the system. Therefore, after verification of the dynamic analysis models should be reviewed and next iteration should be initiated after necessary modifications made on the vehicle model.

Particularly for the finite element models, at the very beginning of the dynamic analysis vehicle model should be elaborately reviewed such as finite element mesh continuity, common nodes, element shape and size, material properties, thickness definition for the . In order to reveal that firstly free-free modal analysis should be performed. As a result of the modal analysis local modes appear if mesh continuity could not accomplished. Moreover, rigid body modes can be seen if connection of some parts are missing. As a result of modal analysis, aforementioned mistakes should be resolved for a proper dynamic analysis.

When the finite element model is convenient for the dynamic analysis, modal analysis should be performed. Modal analysis will provide overview about dynamic characteristic of the vehicle model [14]. Bending mode of a truck chassis is shown in **Figure 10**.

Furthermore, modal analysis results should be compared with the analytical model results. Natural frequency order of magnitude and mode shape should be close to the analytical model results particularly for the first bending mode. After getting experience about the vehicle, the need for the analytical model will disappear. Moreover, modal effective mass results should be reviewed. This will give the idea of which mode will contribute when reduction is applied.

After modal analysis, static analysis should be performed by applying boundary conditions and gravity load on the system. Static analysis is commonly considered the first step of the structural analysis. The static analysis of vehicle parts is utilized to obtain the effects of constant gravity loads on the vehicle without taken into account the inertia and changing dynamic loads. After static analysis stress, strain and deformation of the parts can be obtained under a constant load. To figure out the deformation results better exaggerated views can help. Simple discrete models and simplified models can talk less about the static analysis results since they have less details. On the other hand, detailed finite element model should be employed to investigate stress, strain and deformation of the parts. In the detailed FEM, elaborated structural analysis can be performed on parts such as bolts, nuts and welding points. Every detail will

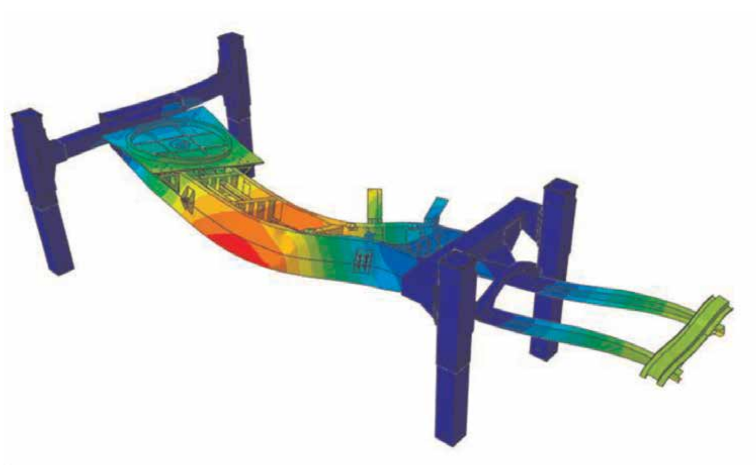

Figure 10.
Modal analysis of a truck chassis.

take some time for modelling and will cause a computation cost. Therefore, static analysis of the detailed FEM should be performed for the last iterations.

Up to now, natural frequencies and mode shapes are calculated by using simple discrete model and simplified FEM. Modal analysis results are compared for the simple discrete model and simplified FEM. Modifications on the simplified FEM are applied if needed. Static analysis is performed for the simple discrete model and simplified FEM. Results are compared. Now we are sure about our models, assumptions and simplifications and it is time to perform dynamic analysis.

First step of the dynamic analysis is to model the dynamic load on the vehicle. Dynamic load can be caused by the road, engine, transmission and etc. Dynamic load can be acquired by test results or can be modelled. After dynamic load is acquired, damping characteristic of the vehicle should be defined as a second step. Damping characteristic can alter material properties and joints of the vehicle model. For a linear elastic system proportional damping can be employed [8].

$$[C] = \propto[M] + \beta[K] \tag{14}$$

where,

$[C]$: Damping matrix

$[M]$: Mass matrix

$[K]$: Stiffness matrix

$\propto$ and β are the constants of proportionality

Dynamic analysis should be performed by using simple discrete model, simplified FEM and reduced DOF FEM as a third step. Dynamic analysis results should be compared to figure out the dynamic response of the system. Simple discrete model and simplified FEM can provide dynamic response of the system as an order of magnitude. For a more realistic solution reduced DOF FEM should be used. In order to use the reduced DOF FEM, vehicle model should be continuous, linear elastic and deformations should be small (about 10%) due to the fact that CMS is based on linear theory. Reduced DOF FEM is a commonly preferred model to calculate the dynamic response of a vehicle. On the other hand, for larger deformations and nonlinear structures, reduced DOF FEM is not valid. Moreover, to calculate stress and strain, detailed FEM should be preferred since reduced DOF FEM is not a powerful method since it solves the matrices in modal domain.

After reduced DEF FEM dynamic analysis is performed, dynamic characteristic of the vehicle is obtained and for elaborated analysis detailed FEM should be utilized. Detailed FEM and reduced DOF FEM dynamic analysis results should be compared in terms of deformation, reaction forces and transmissibility. Transmissibility is the ratio of the output to the input. Transmissibility equals to 1 when the model is rigid body. However, our vehicle model has some damping, transmissibility will change according to the frequency. Therefore, reduced DOF FEM and detailed FEM should be compared in terms of transmissibility in order to obtain more realistic results. According to the system response of a vehicle, some modifications can be required to decrease the deformation and transmissibility. Same rule applies here, too. Detailed FEM should be created, and dynamic analysis should be performed as multi body simulation particularly for the last iterations. Multi body simulation is a dynamic analysis method where multi body model has all necessary structural elements. Multi body truck model is shown in **Figure 11**.

As a last step, dynamic structural analysis results should be obtained by using detailed FEM. Deformations, stress, strain, transmissibility and reaction forces should

Figure 11.
Multi body truck model [15].

be calculated by using detailed FEM. Particularly for stress results, mesh size and mesh quality should be reviewed. In some situations, stress results can change according to the mesh size. As a rule of thumb, big mesh size causes bad results and small mesh size causes more computation time. Therefore, different mesh sizes should be compared to have experience on the vehicle FEM. Likewise, mesh quality is another factor that causes misleading results. Thus, mesh quality should be kept high particularly in stress concentration areas.

4. Verification of the analysis

In order to rely on the analysis results, models should be verified. Testing is the most common method to verify the models. Verifying modal analysis results is the first step of the verification of dynamic analysis. Modal updating is the mostly applied method to verify the modal analysis. Modal updating works by updating mass, stiffness and damping parameters of the model to decrease the difference between the analysis and the test results. Decreasing the difference between analysis and test results more will provide a better and more realistic models. Therefore, modal test should be performed. Modal testing is applied to determine the natural frequencies, mode shapes, modal masses, modal damping ratios of a system under a test condition. Modal testing is a method that is used for characterizing the structure by delivering a known force to the structure and measuring both the force and the response of the structure. Structure's response should be measured from multiple locations to figure out the response of the system. After acquiring the measurements, the data should be processed to determine the natural frequencies and the movement of the structure. There are two famous ways to perform modal analysis such as impact hammer modal testing and shaker modal testing.

The hammer impact test is a cost efficient and the simplest method to gather the system's frequency response functions (FRFs). The main purpose of the impact hammer modal testing is to apply the structure a perfect impulse that will cause all modes of vibration by exciting the structure with equal energy. On the other hand, the hammer impact test has some restrictions. The acquired data may have noise that cause inaccurate calculations of modal parameters. It is impossible to perform a perfect impulse since there is a duration of contacting the hammer with the structure. This time period effects the frequency content of the impact. Therefore, this impact should be measured and recorded with a load cell. Impact hammer testing is more convenient for small and lightweight structures. Thus, small parts of the vehicle should be preferred instead of the whole vehicle for impact hammer testing. Hammer impact test set-up is shown in **Figure 12**.

For complicated structures and obtaining more accurate results modal shaker testing is better than the impact hammer testing to identify coupled modes for closer frequencies. Full vehicle modal test set-up is shown in **Figure 13**.

After modal updating procedure is completed, static test verification should be performed. Reaction forces of the structure under its own weight should be calculated and reaction forces of the structure should be compared with the test results. Load cells are mostly used test equipment for the static tests. Moreover, deformations should be measured and compared with the static analysis results.

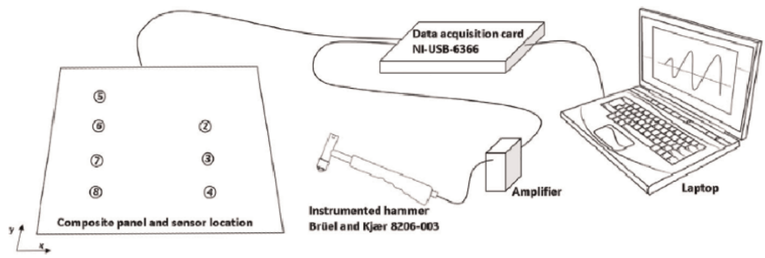

Figure 12.
Hammer impact test set-up [16].

Figure 13.
Full vehicle modal test set-up [17].

After static analysis, dynamic load can be applied on the vehicle. Different dynamic load scenarios that are generated from user experiences and use cases should be applied to the vehicle model to assess subsystems and components effects on the whole vehicle model. Vehicle performance is obtained by applying these scenarios. Dynamic load can be either driving loads or dynamic force that acts on the static vehicle. Dynamic load is advised directly applied on the structure by omitting tire and road effect as a first step. Deformations and strain data should be acquired to figure out the system's dynamic response. After that, dynamic test results should be compared with the dynamic analysis results. Modifications should be made on the vehicle model for verification. As a second step, tire and road effects should be added to the tests. Tire and road models are critical for verification. Therefore, tire and road model should be verified separately and together before dynamic analysis. Commercial analysis software's experience can be utilized to model tire and road. However, some modification may be needed for verification. During dynamic tests load, torque, velocity and displacement data can be acquired. Measurement locations is the critical point for verification. Therefore, main target and other aims of this vehicle should be determined at the beginning. If the main target of a vehicle is to carry passengers then comfort of the passengers should be maximized. Vibration acting on the passengers should be measured, and design should be modified to minimize the disturbance of the passengers. In this scenario, vehicle design should be modified according to passenger riding comfort and verifications should rely on riding comfort. Moreover, control algorithms can be added to the vehicle dynamics to increase passenger's riding comfort. In another scenario, vehicle can be truck that carries critical cargo. In this situation, main target of the vehicle is cargo. In another scenario, vehicle can be a working machine. In this case, dynamic load applies on the vehicle when vehicle is static. As a result, dynamic test measurements should be both acquired by considering verification of the analysis model and verification of the targets of the vehicle. Once the vehicle model and analysis results are verified, modifications on the design or test conditions can be changed and there will be no need to verify vehicle model again unless these modifications are out of verification. Dynamic test of a vehicle is shown in **Figure 14**.

In this chapter, modelling of a vehicle, implicit dynamic analysis with linear elastic deformation assumption and verification of the model and analysis is examined. Explicit analysis, fatigue analysis, buckling analysis, large or non-linear deformations

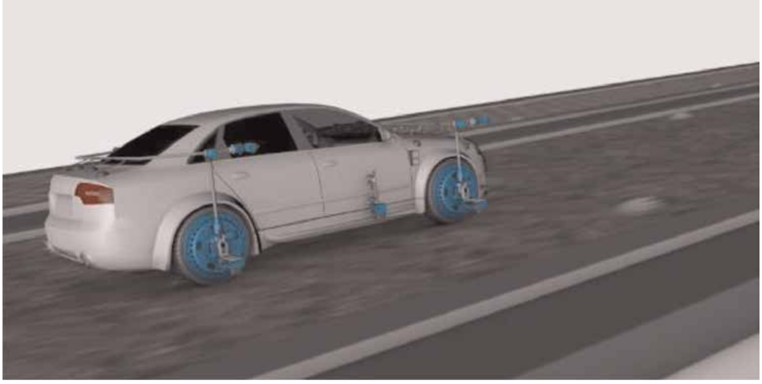

Figure 14.
Dynamic test of a vehicle [18].

are out of scope of this chapter. In order to solve these analyses, different kind of mathematical equations must be solved, and different kind of assumptions must be made. Moreover, verification of these analyses and test methods of these conditions are totally different.

5. Conclusion

In this chapter, modelling of a vehicle, dynamic analysis methods and verification of both models and analysis are investigated. Modelling methods of a vehicle are classified in two types such as analytical models and finite element models. Analytical models are grouped as simple discrete model and flexible multi-body model. Finite element models are classified as simplified FEM, reduced DOF FEM and detailed FEM. Aforementioned models are examined before dynamic analysis process. After that dynamic analysis methods of a vehicle are elaborated. Modal analysis, static analysis and dynamic analysis of a vehicle are elaborated. Furthermore, verification methods of models and analyses are examined. Industrial experiences are employed when assessing the methods.

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Replace the entirety of this text with acknowledgments. Usually, the acknowledgments section includes the names of people or institutions who in some way contributed to the work, but do not fit the criteria to be listed as the authors.

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Nomenclature

£	Lagrangian
q_r	r = 1, … ,n are generalized coordinates
Q_r^*	r = 1, … ,n are generalized forces representing all non-conservative forces
E_k	kinetic energy
E_p	potential energy
M	mass of the vehicle without suspension system and tires
I	inertia of the vehicle without suspension system and tires
m_{i2}	relevant suspension system's mass
I_{i2}	relevant suspension system's inertia
m_{i1}	relevant tire's mass
I_{i1}	relevant tire's inertia
q_{i1}	excitation applied from the road
k	stiffness coefficient
c	damping coefficient
$\vec{r_i}$	position vector of particle i
$\vec{F_i}$	sum of forces acting on the particle
δV_i	virtual work

$\delta\overrightarrow{r_i}$	virtual displacements of the particle i
$\overrightarrow{F_i^e}$	external forces acting on the particle i
$\overrightarrow{F_i^s}$	internal forces from other particles in the same body
$\overrightarrow{F_i^r}$	joint reaction force from another movable body through a joint
$\overrightarrow{F_i^d}$	reaction forces due to joints with the fixed frame
n	number of flexible bodies
$\overrightarrow{F_i^e}$	external forces acting on the particle i
m_i	mass of the particle i
$\overrightarrow{\ddot{r}_i}$	acceleration vector of the particle i
$\delta\overrightarrow{r_i}$	virtual displacements of the particle i
δs_j	virtual change in strain energy of flexible body j
f_j	generalized external force corresponding to general coordinate j
f_j^s	generalized structural stiffness forces
δq_i	virtual displacement in independent coordinate i
$\overrightarrow{F_i^*}$	inertia method of particle i
$\delta\overrightarrow{r_i}$	virtual displacements of the particle i
f_j^*	generalized inertia forces j
N	number of bodies
ρ	density
$\overrightarrow{r^k}$	position vector of an arbitrary point in body k
q_j	independent coordinate j
V	volume
u	system response which consists of many DOF
T	transformation matrix
q	modal coordinates consists of less coordinates
Φ	mode shape matrix which is obtained by below equation
M	mass matrix
K	stiffness matrix
F	force matrix
$\propto$	constant of proportionality
β	constant of proportionality

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Section 3

State of Art in Vehicle Dynamics

Chapter 3

Perspective Chapter: Future Perspectives of Intelligent Autonomous Vehicles

Yuan Yin

Abstract

The chapter explains the effects of intelligent autonomous vehicles from future perspectives. The chapter gives readers an overview of the future intelligent autonomous vehicles and promotes the development potential on intelligent. To be specific, the chapter first gives the readers an overview of the development of autonomous vehicles. Then, the chapter introduces the potential of intelligent autonomous vehicles, key technologies that are needed for future intelligent autonomous vehicles, and how intelligent autonomous vehicles affect the future. Finally, the chapter discusses barriers in intelligent autonomous vehicles development. The chapter will be contributed as a start point for people who want to keep working on intelligent autonomous vehicles and help them understand the general condition of future intelligent autonomous vehicles.

Keywords: autonomous vehicles, autonomous driving, self-driving, future, intelligence

1. Introduction

Autonomous driving is a field with a promising future [1, 2]. The human society is extremely dependent on transportation. According to statistics, there are about more than 1.4 billion vehicles in the world [3]. Tens of millions or even hundreds of millions of drivers manipulate vehicles around the world every day, which is a very large consumption of manpower [4]. Intelligent autonomous vehicles, including driverless vehicles, have become a hot topic of concern for regulators and industry in recent years. Intelligent autonomous driving has been defined as the direction of development in the next 10 years [5].

Based on the degree to which dynamic driving tasks that the intelligent automation driving system can perform, the role assigned in the execution of dynamic driving tasks, and with or without the design operating condition restrictions, the driving automation is divided into levels 0–5 (**Table 1**).

Level 0 (No Automation): Drivers are in full control of the vehicle. The automation driving system cannot continuously control vehicle motion in dynamic driving tasks, but has the ability to continuously detect and respond to partial target and event in dynamic driving tasks. Typical vehicles currently on the road are classified as Level 0.

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Level		Vehicle motion control	Targets and events detection and response
Level 0	No Automation	Driver	Driver
Level 1	Driver assistance	Driver and system	Driver
Level 2	Partial Automation	Driver and system	Driver
Level 3	Conditional Automation	System	Driver or system
Level 4	High Automation	System	System
Level 5	Fully Automation	System	System

Table 1.
The automotive driving division elements.

Level 1 (Driver assistance): The automation driving system continuously controls vehicle motion in dynamic driving tasks within its designed operating conditions and has the ability to appropriately detect and respond to partial targets and events that related to vehicle motion control. In other words, Level 1 automated systems are sometimes able to assist the driver in certain driving tasks.

Level 2 (Partial Automation): The driving automation system continuously controls vehicle motion in dynamic driving tasks within the conditions for which it is designed to operate and has the capability to detect and appropriately respond to some of the targets and events that are related to vehicle motion control. In other words, the automation system is capable of performing certain driving tasks, but the driver needs to monitor the driving environment and complete the remainder. Also, drivers need to take over driving when problems arising at any time. At this level, the automation system asks the driver ready to correct errors in perception and judgment, which has been able to be provided by most of car companies. Level 2 condition can be split by speed and environment into different usage scenarios, such as low-speed traffic jams on ring roads, fast travel on highways, and automatic parking with the driver in the car [6]. Most of the new vehicles on the market are classified as Level 1 or Level 2. These new vehicles are equipped with assisted driving features such as lane centering and speed control, which are useful for both parking and driving [7]. However, the car remains in the hands of the driver.

Level 3 (Conditional automation): The automation system is capable of both performing certain driving tasks and monitoring the driving environment in certain situations, but the driver must be ready to regain driving control when they are requested to do it by the automated system. At this level, drivers are still unable to sleep or take a deep rest. Currently, the highest level that commercial vehicles can reach is at Level 3 at most [8]. Conditional automation requires that the vehicle be able to drive autonomously under ideal conditions, such as at a given speed and road type, but there are many limitations when these conditions are exceeded. The meaningful deployments seen so far are upgraded high-speed road condition.

Level 4 (High Automation): Automation systems are able to perform driving tasks and monitor the driving environment in certain environments and under specific conditions. Specifically, the driving automation system performs all dynamic driving tasks continuously and takeovers dynamic driving tasks under the designed operating conditions. Under this stage, in the range of automatic driving can operate, all tasks related to driving and the driver have nothing to do. The perception of external responsibility is all in the automatic driving system. Level 4 vehicles are almost fully automated, but their automation systems can only be used in known use cases. They cannot be applied in driving off-road or in extreme weather conditions. In these unknown situations, the driver must steer the vehicle. Most of deployments of Level 4 are currently set in urban-based condition [9]. It is expected for fully automated valet parking or can be done directly in conjunction with a taxi service.

Level 5 (Fully Automation): The automation system can perform all driving tasks under all conditions. Specifically, the driving automation system continuously performs all dynamic driving tasks and takeovers dynamic driving tasks under any drivable condition. Level 5 vehicles are truly driverless cars. To reach Level 5, a vehicle must be able to navigate autonomously through any road condition or hazardous obstacle.

Level 1 and Level 2 cannot be considered autonomous driving; instead, they are Advanced Driver Assistance Systems (ADAS) [10]. Level 3 and above can be called autonomous driving. The majority of Level 3 vehicles is still test vehicles and is not really commercially available [11]. The current autonomous driving is still not perfect. Although the car is in automatic situation, the driver must be alert and ready to take over the vehicle to deal with accidents. It can be phased, in the future, autonomous driving will become a mature and reliable technology. It is not yet mature, but it will have a bright future.

2. The development of autonomous vehicles

2.1 Development history

In August 1925, a radio-controlled car called "American Miracle" was unveiled by Francis P. Houdina, a U.S. Army electrical engineer [12]. By radio control, the steering wheel, clutch, brakes, and other parts of the vehicle can be remotely controlled. According to the New York Times, the radio-controlled vehicle can start its engine, turn its gears, and honk its horn like a phantom hand at the wheel. It's a long way from "automation driving," but it was the first documented self-driving vehicle in human history.

In 1939, General Motors exhibited the world's first self-driving concept vehicle—Futurama—at the New York World's Fair [13, 14]. Futurama is an electric car guided by a radio-controlled electromagnetic field, which is generated by magnetized metal spikes embedded in the road. It was until 1958, however, that General Motors brought this concept vehicle to life [14]. General Motors embedded sensors called pickup coils in the front of the car. The current flowing, which goes through the wires embedded in the road, could then be manipulated and tells the vehicle to move the steering wheel to the left or right [15].

During the next close to 20 years, the development of autonomous driving technology hit a bottleneck and developed more slowly, with no significant progress. It was until the 1970s, especially after computers and IT technology began to develop at a rapid pace, that autonomous driving technology again ushered in a period of rapid development. In 1977, Japan's Tsukuba Mechanical Engineering Laboratory improved the pulse signal control method previously used by General Motors. They used a camera system that forwards data to a computer to process road images. This allows the car to follow white road signs at 30 kilometers per hour on its own, though it still needs the assistance of steel rails. A decade later, the Germans improved the camera and developed VaMoR. A vehicle equipped with the camera could drive safely at 90 km/h [16]. As technology has advanced, the environment detection and reaction ability of self-driving cars also has been improved.

In 1984, the Defense Advanced Research Projects Agency (DARPA), in partnership with the Army, launched the Autonomous Ground Vehicle (ALV) program [17]. The goal of this program is to give vehicles full autonomy and allow them to detect terrain through cameras and calculate solutions such as navigation and driving routes through computer systems. The second DARPA Challenge in 2005 was the first time in history that five driverless cars successfully navigated a desert track with rough road conditions using a recognition system.

Since 2009, Google has been secretly developing a driverless car project, which is now known as Waymo [18]. In 2010, it was reported that Google was testing self-driving cars at night on Highway for 1000 miles without human intervention and that occasional human intervention had been required for a total of more than 140,000 miles [19]. In 2014, Google demonstrated a prototype of a driverless car without a steering wheel, gas or brake pedal, resulting in 100% self-driving [20]. As driverless program steadily advances, the potential and opportunities of "autonomous driving" are being discovered by more and more people.

2.2 Industrial

In recent 10 years, self-driving cars have become a key area of concern for many companies [21]. There are two evolutions of autonomous driving industry. The first-time evolution is triggered from the expectation of autonomous-driving industrialization. There are many landmark events, such as Waymo's spin-off, General Motors' acquisition of Cruise, Ford's investment in ArgoAI [22]. The background of this evolution is that artificial intelligence technology has improved tremendously, and deep learning has started to be applied on a large scale in the field of perception technology, such as image recognition [23]. Also, sensor technology has developed greatly [24]. However, at that time, the long tail problem has become an important constraint for the implementation of high-level autonomous driving. Specific challenges exist in the robustness of hardware, redundancy of the system, and perfection of testing [25].

The second evolution comes from the commercialization of autonomous driving. After 3–4 -year development of technology, the core technologies of autonomous driving such as LiDAR, chips, perception, and decision algorithms have further developed [26, 27]. Autonomous driving in specific scenarios (such as mines, ports, and airports) has been able to be commercialized.

At present, the global autonomous vehicle industry is developing in a better trend. However, few areas can achieve mass production [28]. Autonomous vehicle technology is developing together with 5G communication technology and related technology of new energy vehicles.

3. Why intelligent autonomous vehicles have a huge potential

Autonomous vehicles technology has the potential to transform commuting and long-distance travel experiences, take people away from high-risk work environments, and allow for a higher degree of development and collaboration across industries. It is also the key to building our cities of the future.

3.1 Living

In the future, human's relationship with vehicles will be redefined from reducing carbon emissions and paving the way for more sustainable lifestyles levels. It is estimated that 30% of greenhouse gas emissions in the United States come from transportation [29]. Autonomous vehicles will be able to travel more efficiently on the road than vehicles operated by human drivers. This will lead to a reduction in greenhouse gas emissions. Also, vehicles can be grouped into "platoons" and reduced number of accidents. These can keep traffic flow continuously. Less congestion means that passengers can get to their destinations faster and spend less time on the road, which in turn makes more fuel efficiency and reduces CO2 emissions. Vehicles will also likely communicate with road infrastructure, such as traffic signals, to adjust fuel consumption and emissions accordingly.

Cab services, car sharing, and public transportation will become faster and cheaper as the autonomous vehicles revolution progresses. The cost of these services is therefore expected to decrease as maintenance, gas, and labor requirements decrease. In this way, the cost gaps between purchasing one's own car and using these travel services will be stretched to a degree that will redefine how people travel. More importantly, the reduced cost of transportation services will drive economic mobility for vulnerable populations. Geographic locations that previously have been inaccessible to certain populations due to commuting costs will become accessible, resulting in some new beneficial effects on the working population.

When autonomous vehicles become available, navigation will be more efficient and traffic congestion will be reduced. Also, because cabs and car-sharing services will be cheaper than purchasing a car, there will be fewer cars on the road. These will ultimately improve commuting efficiency. The saved commute time can be spent on work, socializing, and relaxing. This thus reduces the anxiety commuters when they arrive at work and being able to work in a better condition. In addition, the reduction in travel time also helps to improve daily productivity.

3.2 Human nature

Laziness is often the first driver of technological progress. Looking back at the history of technological progress, people have invented home appliances in order to reduce the labor of household chores. To save the pain of walking, human beings have made carriages, bicycles, motorcycles, cars, trains, and airplanes. Humans hate repetitive and inefficient tasks. They are too lazy to do it themselves. Therefore, they let the tools do it and automate the repetitive tasks. Driving is a relatively repetitive and inefficient task. Developing tools to achieve automation is clearly in line with the trend of technological development. From efficiency perspective, the popularity of intelligent autonomous vehicles can improve efficiency and save time.

3.3 Safety

Safety of intelligent autonomous vehicles is defined as their ability to keep people safe and reduce the accident rates when autonomous vehicles are operating properly. Research shows that intelligent autonomous vehicles are safer than the average human drivers [30]. Firstly, machines are much better at perception than humans. The autonomous vehicle has various sharp sensors, radar, and cameras, which can perceive a wider range than the human when driving. The hardware upgrades allow vehicles to "see" the world that humans cannot see in a farther, wider, and clearer way. Also, it can see many different angles at the same time, which is beyond the range of human perception. For example, Tesla has eight cameras mounted around the body (two in the front, two on the left and right side, and two in the rear), providing a 360-degree view and a range of 250 meters [31]. Front-enhanced radar is installed to provide clearer and more accurate detection data in adverse weather conditions (such as rain, fog, and smog). All of these are beyond the ability of human perception. Therefore, autonomous vehicles can make decisions earlier than humans and react faster, which makes driving safer. Furthermore, for, autonomous vehicles, vehicle-to-vehicle communication will be possible. There will be more communication in various scenarios and further improve safety.

Secondly, autonomous vehicles are more energetic than humans. Globally, fatigue driving has become one of the major causes of traffic accidents. According to the National Highway Traffic Safety Administration, there are about 100,000 traffic accidents on U.S. roads each year due to drivers going to sleep while driving [32]. Studies show that approximately 94% of crashes are caused by human error. The World Health Organization estimates that more than 1.3 million people die in road traffic accidents each year [32]. The number of deaths and injuries from car accidents caused by distracted drivers continues to increase [32]. Autonomous vehicles do not need a human driver. Instead, the driver is a microcomputer, which runs a large amount of computer code and connects to different sensors inside and outside the vehicle. The data and sensors are connected to the cloud and can simulate the external environment around the vehicle real time. In this way, the intelligent autonomous vehicles can anticipate the actions that need to be taken based on the current surrounding traffic conditions. These actions are performed normally regardless of the climate, environmental, and traffic conditions. People get fatigued while autonomous vehicles do not. Thus, safety levels of autonomous vehicles driving are higher than human drivers.

Thirdly, autonomous vehicles are more rational than humans. People have emotions. They may make dangerous actions because of panic and rage. Autonomous vehicles do not make these mistakes, which is a major advantage of autonomous vehicles. At present, autonomous vehicles may be worse than humans in making decisions, especially in the face of various extreme situations and uncertainty. However, this piece is constantly improving. One aim of intelligent autonomous vehicles research is to improve the ability of intelligent autonomous vehicles to deal with various extreme situations and cover a variety of possible extreme cases to increase safety of intelligent autonomous vehicles. In addition, the optimal future situation is that all vehicles are intelligent autonomous, which makes most of the driving behavior predictable.

It is also acknowledged that autonomous vehicles cannot guarantee a 100% safety rate. They will have failures and flawed algorithms. However, humans cannot achieve a 100% safety rate either. As long as intelligent autonomous vehicles outperform humans, intelligent autonomous vehicles will help reduce the deaths in traffic accidents worldwide each year.

4. Key technologies needed for future intelligent autonomous vehicles

From the future perspective, intelligent autonomous vehicles will develop from low speed to high speed, from carrying goods to people, from commercial to civil use. Autonomous vehicles are a complex engineering system that requires the integration and precise cooperation of various technologies, which include algorithm, client system, and cloud platform [33]. The algorithm includes sensing, which is used to extract meaningful information from the collected sensor raw data; positioning, which is used to precisely control the driving direction of the intelligent autonomous vehicles; perception, which is used to understand the surrounding environment of the vehicle and provide safe and reliable planning for the vehicle's travel and arrival. To achieve these algorithms, professionals are expected in the following areas: computer vision (including image classification, target detection, target recognition, and semantic segmentation), Kaman filtering (including vehicle position prediction, measurement, updating, and multiple sensor data fusion), Markov localization (including vehicle motion models for vehicle localization, Markov processes, Bayesian principles and position filtering, target observation localization, and particle filtering), vehicle control decisions (PID control; including lane departure error control, PID hyperparameter adaptive adjustment), model predictive control (MPC; including vehicle dynamics, vehicle trajectory prediction, finding optimal execution parameters such as steering angle and acceleration) [23, 34, 35]. Client system consists of operating system and hardware system, which can cooperate with the algorithm part to meet the requirements of real-time, reliability, safety, and green energy consumption. Cloud platform provides offline computing and storage functions to support testing of continuously updated algorithms, generating high-precision maps and large-scale deep learning model training.

4.1 Scenario operation

The future of intelligent autonomous vehicles driving also requires the cooperation of technology and scenario operation. The structured scenario can already realize Level 4 intelligent autonomous vehicles operation. However, different scenario has different requirements for technical details. Mining scenario has magnetic field interference, poor GPS signal, and harsh working environment with more dust [36]. Port scenario often encounters rain and wet weather [37]. Airport logistics needs to require high security [38]. Under these conditions, intelligent autonomous vehicles need to be connected to the overall operation management and dispatching system. Therefore, a deep understanding of the scenario and targeted changes to the algorithm are expected to achieve the implementation of intelligent autonomous vehicle driving. Also, continuous data acquisition through operation is needed to continuously iterate on the technology.

4.2 Machine learning

Machine learning behind autonomous driving is an interesting problem. Dataset of autonomous driving is on-policy, meaning that it changes with the driving strategy. Also, not all data are useful. For autonomous driving, a lot of data are monotonous and repetitive, such as nice weather, and no cars or pedestrians around, which do not help much to improve the driving strategy. How to overcome the shortcomings of each sensor to provide real-time, accurate, and non-redundant environmental information is a further requirement of deep learning.

Another area that future needs to solve is the learning improvement of driving strategy. Assuming that the driving strategy performs poorly at the beginning and requires human intervention every kilometer, for every kilometer some important data are collected, such as video and radar data, which are associated with a few seconds before the accident. Then, data are used to train the current model and learn a better strategy to avoid accidents. With better strategies, manual intervention is reduced once for every 10 kilometers. Then, the data are used to train the current model again. The learning cycles thus are built up. From the learning, it will be found that the better the quality of the driving strategy it is, the less frequent the manual intervention occurs, the less effective training data can be gotten, and the harder it is to continue improving. As the quality of driving improves, the decay in the rate of manual intervention is very slow. The key question then is whether it can surpass the level of a real driver? The real scenarios have a variety of strange and bizarre situations. There will be some corner case never seen by the algorithm [39]. As long as the machine learning algorithm still needs a lot of data, the driving strategy seems difficult to achieve human levels. Some people think that the problems can be solved by adding more sensors [40]. However, with the increase of sensors, at first the effect of signals will raise. But then the deployment, maintenance, and coordination costs will rise significantly.

The current research on perception algorithms is mainly focused on vision. The research on applying deep learning for target recognition, segmentation, and tracking is very hot [41, 42]. However, what will happen if there is a person wearing a t-shirt painted with a stop sign on the road? More problems happen on the counter-sample. Stop-sign with a few sticky notes may be recognized as yield sign. Printing a few special patterns on the clothes may be stealthy. These are still considered counter-sample on the visual level. In the future, strategy-level counter-sample problems may generate with more self-driving cars becoming available.

Using artificial intelligence to make decisions is also imperative. At present, a series of research studies on decision making such as deep augmented learning, predictive learning, and imitation learning are gradually carried out.

4.3 Sensors

Autonomous vehicles require the use of multiple sensors. This at the same time is the challenge for autonomous vehicle—how to balance these different sensing modalities [43]. To overcome this challenge, an intelligent way is expected to combine the various sensors to provide a safe, high-quality autonomous driving system without significantly increasing size, weight, power, or cost [6]. The improvement of vehicle sensing focuses on collecting data from individual sensors and applies sensor fusion strategies to maximize complementary and compensate the weaknesses of different sensors in various conditions [6]. For example, cameras are excellent at recognizing signs and colors, but perform poor in bad weather or low light environments. These weaknesses can be compensated by radar [44]. However, the current systems are mainly independent, with little interaction between individual sensing systems. Also, no single sensing approach can be applied to all applications or environmental conditions.

4.4 Road condition recognition

For road condition recognition, vehicles need to control and recognize surrounding obstacles, traffic signals, pedestrians, and other vehicle states. Inertial Measurement Units (IMUs) can detect sudden jumps or deviations caused by potholes or obstacles. Through real-time connectivity, these data can be sent to a central database and used to warn other vehicles about potholes or obstacles [45]. The same is true for camera, radar, LIDAR, and other sensor data [46]. These data are compiled, analyzed, and fused so that the vehicle can use it to make predictions about its driving environment. This allows the vehicle to become a learning machine and is promised to make better and safer decisions than humans. To date, however, very few intelligent autonomous vehicles have been able to achieve it.

4.5 Storage

The data of intelligent autonomous vehicles are massive. Data of intelligent autonomous vehicles are mostly images, sound, and other natural information. They are unstructured data, whose data volumes are much larger than structured data. In addition, intelligent autonomous vehicles require a very high level in real time. According to calculations, the amount of data collected by autonomous driving technology is as high as 500GB to 1 TB per hour per vehicle. The core of data flow in vehicles is the storage of data. The memory capacity of general computers is in a few or dozens of GigaByte (GB). The memory capacity of large servers is in hundreds of GB. It is nearly impossible to store all the data into the computer of intelligent autonomous vehicles considering the memory for computing capabilities under the existing hardware system. A potential solution is to load the data into high-efficiency hard disk storage and send it to the memory and CPU or GPU for computation when needed [47].

Another problem encountered in data storage for autonomous vehicles driving is environment [36–38, 48]. A computer hard drive is a fragile component. However, vehicles are often used in harsh environment. When the vehicle is on the road, it will experience constant vibration, extreme weather, and even sudden power outages or accidents. The hard drive, which is the "data tank" for autonomous driving, must ensure efficient and stable operation under all these circumstances. Otherwise, the data will not be sent to the computing unit, which will lead to serious consequences.

4.6 Electromagnetic interference (EMI)

There are two types of electromagnetic interference (EMI) emissions: conducted and radiated [49]. Conducted emissions are connected to the product through wires and alignments [49]. Since the noise is limited to a specific terminal or connector in the design, in the early development process, with the help of a good layout or filter design, it usually can be relatively easy to ensure compliance with the conducted emission requirements [50]. However, radiated emissions are in a different condition. Anything on a circuit board that carries current radiates electromagnetic fields. Every alignment on a circuit board is an antenna, and every copper layer is a resonator. Things, other than a pure sine wave or DC voltage, will generate noise across the signal spectrum. The power-supply designer does not know how bad the radiated emissions will be until the system is tested. To make things worse, radiated emissions can only be tested formally after the design is essentially complete. People often use filters to attenuate a specific frequency or a certain frequency range of signal strength, in this way to reduce EMI [51]. In addition, the energy of radiation, which goes through the space propagation, can be attenuated by adding metal and magnetic shielding. EMI cannot be eliminated, but can be attenuated to a level acceptable to other communications and digital devices. This is what the future needs to further detect.

4.7 Chips

Under the trend of "software-defined car," chips, operating systems, algorithm, and data form the closed loop of intelligent autonomous vehicle computing ecology. Chips are the core of intelligent autonomous vehicle ecological development. This also gives rise to a strong demand for autonomous vehicles chips. The value of chips in the autonomous vehicles is not small. The value of all the chips in a cell phone is a hundred dollars, but the value of all the chips in autonomous vehicles is up to hundreds of dollars. At the same time, there are many kinds of chips above the autonomous vehicles. Family cars need hundreds of chips, such as tire pressure monitoring, sunroof, lights to back-up camera, back-up radar, and remote control keys. When any chip misses, the car cannot be delivered.

In 2022, the global "chips shortage" still has not been effectively alleviated. The most shortage of chips is MCU chips, which is the most common chip on the autonomous vehicles. Window control, seat control, and Electronic Control Unit (ECU) are inseparable from it. MCU accounts for about 30% of the total number of autonomous vehicles chips. A car needs dozens to hundreds of MCU chips [52]. Chips shortage prompts many dealers under the temptation of high profits, which makes the market situation of chips shortage become more and more serious.

Chips are a piece that contains integrated circuit components. Chips can be roughly divided into two categories—functional chips (such as CPU and communication base station processing chip) and storage chips. To manufacture a chip, the industry first needs to design the chip. Which function that the chip can have has been determined in the design of this step. This requires professionals to carry out the design of the circuit. Next is the production. This step is also the most tedious. Finally, it is the packaging. The finished chip is mounted into a saleable product. Among these three steps, the most difficult is the design, while the easiest is the packaging.

The chip crisis is bringing a change to reshape the autonomous vehicles business model. The "0 inventory" management can no longer adapt to the development. The pursuit of supply chain costs brings a greater risk of hidden danger. Secondly, cooperation with chip foundries needs to be more open. Previously, vehicle chip foundries were relatively closed. They were unable to respond unexpected situations flexibly. How to cooperate with more chip suppliers on an equal footing in the future is a problem that must be faced. Finally, autonomous vehicle chips need to follow the chip industry upgrade. Now, the vehicles chip is mainly used in 8-inch production line. However, from a technical point of view, 8 inches compared with 12 inches is "past tense"; from the economic efficiency point of view, the 12-inch production line is more efficient than the 8-inch production line.

Autonomous vehicles driving also makes the E–E architecture of vehicles a new trend. The EE architecture of vehicles refers to the layout of the electrical and electronic systems in the vehicle scheme. This concept was first proposed by Delphi in 2007. The electrical architecture is dedicated to providing integrated electrical system layout solutions for automakers to address the development of electrification of vehicles. The original EE architecture was a distributed architecture. Each controller targets one function, which makes add an additional function simple and quick by adding a controller. In the stage of mechanical vehicles, because there are not many electrical and electronic components, the distributed architecture is still comfortable to use. As the level of automotive intelligence increased, distributed architecture began to be caught off guard by the explosive growth of electrical and electronic components.

Today's autonomous vehicles do not only need abundant acceleration, but also need to be able to see and hear all directions and realize human-machine interaction at any time. With so many functions to achieve, the number of ECUs has increased dramatically; the complexity of the wiring harness in the car has risen; and the maintenance of electrical equipment has become cumbersome to update. How to ensure these functions do not become "congested" in the process of use, and how to call different ECU functions at the same time to react quickly when dealing with complex instructions? The wave of vehicle electrification makes these problems even more difficult.

The new architecture of EE-Centralized Architecture has emerged. It divides the whole vehicle into several domains according to the functions of electronic components (such as powertrain domain, vehicle safety domain, intelligent cabin domain, and intelligent driving domain). Then, a domain controller (DCU) with better processing power is used to unify the control of each domain. The emergence of a centralized architecture has led to a significant increase in the integration of vehicle functions. The role of individual ECU is integrated by integrated management. Complex data processing and control functions are unified in the DCU. With the signals received and analyzed become more complex, the EE architecture will also evolve to multi-domain controller MDC. Because of the new trend of automotive EE architecture, the integration of controllers and the introduction of domain controllers will affect the chip market simultaneously. DCUs, ECUs, and other electronic devices will also be further developed.

The centralized EE architecture also puts new demands on the automotive software architecture. With the centralization of automotive EE architecture, domain controllers and central computing platform deploy in a hierarchical or service-oriented architecture. The number of ECUs is significantly reduced. The underlying hardware platform needs to provide more powerful arithmetic support. The software is no longer based on a fixed hardware development, but to have portable, iterative, and scalable features. Therefore, at the level of software architecture, automotive software architecture is also gradually upgraded from Signal-Oriented Architecture to Service-Oriented Architecture to better achieve hardware and software decoupling and rapid software iteration.

4.8 Navigation

In the future, more advanced driver assistance features that can be synchronized with navigation and GPS systems will be developed. Each situation's data that a self-driving car might encounter will be collected and accumulated. Mapping companies need to enhance 3D mapping data of cities. Automakers and high-tech automotive system suppliers need to work closely with each other to ensure that light detectors, LIDAR, radar sensors, GPS, and cameras work together.

4.9 Iteration

There are currently two types of iterations: evolutionary and revolutionary. The evolutionary route enables accumulation of more perception and driving data (such as scenario road conditions). These data (such as calibrated image data and corner case driving road conditions) and decision algorithms can be migrated to Level 4 intelligent autonomous vehicles. Revolutionary aims to develop fully autonomous vehicles directly. It remains unclear which path alone will be successful. However, the more likely outcome is a symbiotic fusion of the two.

5. How intelligent autonomous vehicles affect the future

The automobile was invented in 1886. More than 100 years after the invention of the automobile, the human social life has been changed. Life, living, working, and entertainment have changed dramatically. Therefore, autonomous vehicles may change human life living once again in the following areas.

The value chain of the automobile industry will be reconstructed with the development of intelligent autonomous vehicles. Nowadays, vehicles are mainly hardware devices, and safety is the core. However, the core of the vehicles is changing from hardware equipment to IT services, including autonomous driving system and vehicle networking system. In addition, automobile insurance is being changed. In the future, insurance for human driving may be not needed. Without the needs on insurance for human driving, the insurance companies need to seek new business. Insurance for autonomous vehicles, such as network security and system failure, may become a new trend.

Because of the installation of cameras, radar, LIDAR, and artificial intelligence systems, the cost of autonomous vehicles will be high. This means intelligent autonomous vehicles will be more likely to be firstly used for specific traffic industries and groups [53]. The senior and disabled people may be first group people that use intelligent autonomous vehicles. Intelligent autonomous vehicles give them the freedom to travel without relying on friends and family. Car-hailing, buses, cabs, logistics vehicles may be the first group services that adopt autonomous vehicles. This will significantly reduce traffic congestion and environmental degradation. Because of the changing public transportation [54], the offline shopping mall will be subverted too. From small street stores to the large shopping malls, there are usually large parking lots underneath the malls. However, in the future, after the popularity of self-driving, the vacancy time of the car almost does not exist, and people travel and shopping simply do not need to consider whether there is a large parking lot near the mall. This will have a direct impact on shopping malls.

6. Barriers in intelligent autonomous vehicles development

In the future, it is inevitable that autonomous driving may replace human driving in most cases. However, new technologies have not been tested over a large amount of time and are not guaranteed to be free of pitfalls. These pitfalls mainly include reliability, legal, and ethical issues. The two pitfalls may barrier the development of intelligent autonomous vehicles.

Reliability of intelligent autonomous vehicles is defined as the ability to perform a given function without failure for a given period of time and under certain conditions. Failures can come from various directions such as control system failures and being hacked. Generally, the more complex the system is that the more automated and intelligent it is, the greater risk of potential stability it will meet. For example, in Arizona, USA, a self-driving road test vehicle struck and killed a cyclist. There was a person behind the wheel of the autonomous vehicles at the time of the accident, but that person was not actually steering the vehicle. These types of accidents reduce public confidence in the ability of autonomous vehicles.

Ethical and legal are one of the most serious issues that autonomous vehicles need to solve if they want to go forward in the future, especially involving the definition of responsibility for accidents. It includes a few of sub-questions. Firstly, the question is related to whether an autonomous driving system can be a legally recognized driver or not? The function of driving a vehicle has historically been assigned to a licensed human driver. This determination will have a direct impact on whether self-driving cars can be considered as a legal driver. Secondly, the issue is related to liability. If autonomous vehicles malfunction and cause damage to the owner, whether the owner can seek compensation from the insurance company, and how liability will be allocated between the human driver and the manufacturer in an accident. Legislation on intelligent autonomous vehicles depends on the simultaneous development of technology, regulations, and public consensus building. Thirdly, the issue is related to ethics. In times of emergency condition, whether self-driving cars protect the people inside the car or the people outside the car? Traditional cars are centered on protecting the drivers and passengers for it is decided by human drivers. But self-driving cars can face such ethical controversies because they can be prEEngineered. Moreover, the ethical issues related to the condition that when facing the necessity of hitting one of the two persons in certain situations, who should be the victim? Due to Moore's law, self-driving technology will continue to mature and safety. The legal and ethical issues will become the biggest obstacle for the development of intelligent autonomous vehicles.

7. Conclusion

Under the impetus of automated driving, artificial intelligence, and other technologies, the major reform of automobile industry has become an inevitable trend. The integration of information communication and automobile industry has become an inevitable move. As an important product reflecting the country's industrial strength, intelligent autonomous vehicles are a new representative of the potential growth of the national economy. Also, it is a manifestation of the integration of the country's industrial manufacturing sector with new technologies. At present, the development space of intelligent autonomous vehicles is getting bigger and bigger, and with the penetration of this type of vehicles, the proportion of autonomous vehicles in the future automobile market will continue to increase.

The chapter reviews the autonomous driving levels and the development of autonomous vehicles first. Then, the chapter explains why autonomous vehicles have huge potential, key technologies that are needed for future intelligent autonomous vehicles, and how intelligent autonomous vehicles affect the future. Finally, barriers in intelligent autonomous vehicles development are discussed. This chapter contributes as a start point for people who want to keep working on intelligent autonomous vehicles and help them understand the general condition of future intelligent autonomous vehicles.

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Chapter 4

A Comprehensive Review on Hybrid and Electric Vehicle Energy Control and Management Strategies

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Abstract

We show a new technology to manage solid waste services through optimization methods (on sectoring, routing costs, and resources). This technology is called optimized planning and integrated logistics management (OPILM). It is being applied to Brazilian municipalities as it attends to their major natural features. The technology is formed by a framework of computational systems that uses optimization methods from sector arc routing and scheduling, fleet and staff scheduling, using also mobile smartphone apps. We present some of the results of real cases evaluated for residential refuse collection and selective waste collection in two Brazilian cities (Petrópolis/RJ and Bom Jesus dos Perdões/SP). The plan implementations achieved 17.9% from actual fixed and variable cost savings for sectors (vehicles and workers) and routes (time and distances) for residential refuse collection in Petrópolis/RJ. For the selective waste collection, we detail how we made our project to Bom Jesus dos Perdões/SP. We also present the returns considering costs involved in the management of the operational level and amortized by the investment required to use and apply the proposed technology for Petrópolis/SP.

Keywords: regenerative braking, energy management and control, driving cycles, hybrid electric vehicles, thermal management system

1. Introduction

The continuing falloff of fossil fuel reserves, in addition to strict emission rules around the world, has made even more critical the need for improved vehicular fuel economy [1–5]. Due to the worsening effect of climate greenhouse gasses and the limited fossil fuels, electric and hybrid electric vehicles (EHEVs) are carrying large responsibilities to freeze the drawback of defective environment and energy degradation in the recent years. Power management and control strategy is important innovation to boost the EHEV performances. Regeneration of electric energy from braking is the foremost important features of hybrid and electric vehicles. During braking, the motor can function as a generator to recover the vehicle's kinetic energy and potential energy to convert it into electrical energy, which can then be restored to the energy storage devices. Meanwhile, the motor will be controlled and will provide sufficient torque for braking.

Some research on the regenerative brake control approach has been published in the literature, although most of it is limited to flat driving cycles. Despite this, domestic and international researchers have done minimal research on downhill regenerative braking control. The ability to downsize the original internal combustion engine while fulfilling the power demand at the wheels in the case of HEV is the most popular of these benefits. This benefit is due to regenerative braking's capacity to transfer power to recharge the battery from both the internal combustion engine and the electric motor at the same time, resulting in lower fuel consumption and greater driving range [6–10]. The use of an electric drivetrain in a HEV allows kinetic braking energy to be recovered that would otherwise be lost owing to mechanical brakes in conventional vehicles. Accomplishing the aforementioned advantages in a real-time control method by coordinating the onboard power sources, it is a key to enhancing fuel efficiency and minimizing emissions. Various energy controls and management solutions have been advocated in the literature up to this point. This presentation presents a complete analysis of the literature, with a focus on offerings in the area of energy efficiency improvement control and management for electric and hybrid electric vehicles. Available research gaps and future works are also mentioned in this section of the discussion. The following is a list of the offerings in this chapter: First, strategies for HEV modeling, control, and management are briefly addressed in order to emphasize the relative relevance of each approach. Following that, two levels of HEV management and control strategies are examined in depth: HEV offline control strategies and HEV online control strategies. This in-depth analysis focuses on the control structure of the techniques under consideration, as well as their novelty and contributions to the achievement of several improvement goals, including but not limited to: reduced fuel consumption and emissions, charge sustenance, optimization of braking energy regeneration, and improved vehicle drivability. Finally, exploitable research gaps are identified and discussed within the research domain.

1.1 Approaches to HEV Modeling

In the current development of HEVs, there are at least three stages of computational modeling. The following are the stages:

- Detailed modeling is carried out during the HEV's research and development stages. Single powertrain components like an internal combustion engine and an electric motor are the focus of this type of modeling. This type of modeling aims to provide detailed information about the component being modeled's specific characteristics [11].

- Software-in-the loop (SIL) modeling occurs later in the HEV development cycle, but usually before any hardware is built. In the development of HEV control systems, SIL is now widely used [11].

- Hardware-in-the loop (HIL) modeling is done after the controllers have been manufactured and validated. At the detailed modeling stage of the development process, there are three common ways for HEV modeling: the kinematic or backward approach, the quasi-static or forward approach, and the dynamic approach [11].

1.2 Kinematic approach

The kinematic approach, as depicted in **Figure 1**, is a backward methodology in which the input variables are the vehicle's speed and the road's slope angle. This method calculates the engine speed using basic kinematic connections based on the wheel revolution speed and the total transmission ratio of the driveline. From the major vehicle characteristics, the tractive torque that needs to be applied to the wheels to drive the vehicle according to the selected speed range may be computed (e.g., vehicle mass, aerodynamic drag and rolling resistance).

To obtain an immediate fuel consumption or emissions rate estimate, the calculated engine torque and speed are combined with a statistical fuel consumption model [12]. The kinematic technique implies that the vehicle matches the goal performance; hence, the vehicle speed is purportedly known a priori [13]. As a result, the kinematic approach has the benefit of simplicity and cheap computational cost. The kinematic modeling method, also known as backward modeling, ensures that the driving speed profile is followed exactly. There are no guarantees that the given vehicle will be able to complete the specified speed trace because the power needed is immediately generated from the speed and not checked against the actual powertrain capabilities. A "fail-safe" component is usually included in the kinematic approach, which terminates the simulation if the required torque exceeds the maximum torque available (from the electric motor and engine). Another issue in this modeling technique is that it ignores engine thermal transient activity, which is seen after a cold start. Because transient situations are simplified into a series of stationary states, this modeling method is only useful for estimating vehicle fuel consumption and emissions in the first stages [11].

1.3 Quasi-static approach

Figure 2 depicts, the quasi-static technique of HEV modeling uses a driver model, usually a PID, which compares the desired speed of the vehicle (driving cycle speed) with the vehicle's real speed profile and then generates the power demand profile necessary to meet the target speed of the vehicle profile. The vehicle's differential motion equation is used to construct this profile of power demand [14]. After determining the engine's propulsion torque and speed, instantaneous consumption of fuel can be calculated using a statistical engine model, as stated in the kinematic or backward approach. The applicability and precision of the quasi-static modeling

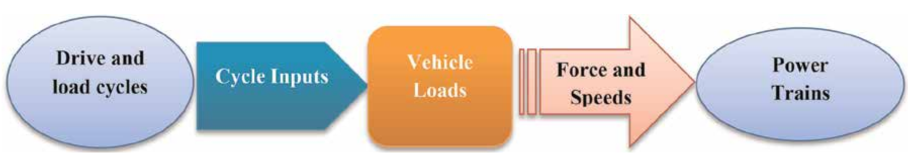

Figure 1.
Information flow in a kinematic or backward HEV model [11].

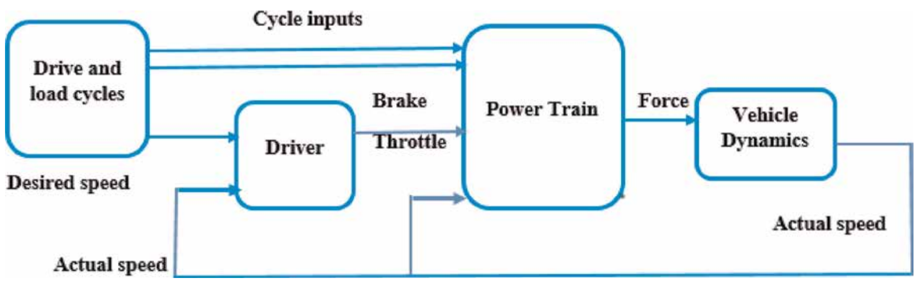

Figure 2.
Information flow in a quasi-static powertrain model [7, 11].

approach are highly dependent on the type of simulation models to be performed. When it comes to estimating the consumption of fuel and NOx of a car with a conventional powertrain, the quasi-static modeling approach delivers reasonable accuracy. Acceleration transients and related "turbo-lag" phenomena make a significant contribution to cycle cumulative emissions for pollutants like soot, demanding a more complex engine simulation model capable of adequately representing engine transient behavior [13].

1.4 Dynamic modeling approach

The internal combustion engine behavior during transient conditions is also taken into account in the dynamic modeling technique, in addition to longitudinal vehicle dynamics. The engine's transient behavior is represented by a complete one-dimensional fluid dynamic model. In a dynamic modeling technique, an internal combustion engine engine's suction and discharge systems, for instance, are represented as a network of tubes connected by connections that reflect either physical joints between the tubes, such as area changes or volumes, or subsystems, namely the engine cylinder. A finite difference technique can then be used to find solutions to the equations governing mass, momentum, and energy flow for each element of the network. This enables highly dynamic events, such as rapid vehicle accelerations, to be correctly simulated. Dynamic modeling is often restricted to study areas requiring internal combustion engine development because it involves a substantial amount of time and calculation [15, 16]. The quasi-static technique is preferred for control development because it preserves the physical causality of the vehicle system and enables the use of the identical controller inputs/outputs in the simulator as well as on the real vehicle.

2. Power split configurations and HEV modes

HEVs have been shown to improve automotive fuel efficiency and emissions while meeting vehicle power demands, preserving vehicle performance, and offering a better driving experience [12]. Regardless of the HEV configuration in question, effective power distribution across the energy sources is required to achieve improved fuel efficiency and reduced emissions (ICE and electric motor). As part of this endeavor, several power split control systems have been suggested, evaluated, and applied to various HEV configurations. HEVs' power-split controller gets inputs from the global positioning system (GPS), including vehicle power demand, vehicle speed or acceleration, battery state of charge, current road load, and, on occasion, "intelligent" future traffic circumstances. A set of control decisions are contained in the controller outputs signal, which governs which of the following modes the HEV should operate in:

1. The regeneration mode (for kinetic energy recovery electric motor is used).

2. Charge with a trickle (for charging the battery engine power is used).

3. Only use the electric motor (electric motor operates alone).

4. Engine-only operation (ICE operates alone).

5. Assist function (electric motor and ICE operates).

2.1 HEV management and control strategies

Minimization of fuel consumption and emissions without compromising of vehicle performance, and battery state of charge are often the main control objectives of most HEV control strategies. As illustrated in the control strategy classification chart in **Figure 3**, HEV control techniques may be divided into two categories: online control strategies and offline control strategies. Although various papers and research publications have contributed to the compilation of reviews on HEV control tactics, this field of research is always expanding, and there is a need for an up-to-date review with the introduction of novel methodologies. This section's major goal is to highlight important research gaps in the field as well as contribute to the increasing list of review debates. On the basis of **Figure 3**, all HEV management and control solutions were discussed.

2.1.1 HEV offline energy management strategies

Control signals are determined using optimization-based control algorithms that minimize the sum of the goal function over time (global optimization) or minimize the objective function instantly (instantaneous optimization) (local optimization). Because the effectiveness of a global optimal control technique is solely dependent on a priori knowledge of the entire driving cycle, which is often difficult to determine in real time, global optimal techniques are often referred to as "non-causal," meaning they cannot be used in real time but can be used as a control benchmark against which all other causal real-time controllers can be compared. For optimal energy management of HEVs, global optimization approaches such as linear programming, dynamic programming, genetic algorithms, and others have been used.

2.1.2 Linear programming

The nonlinear fuel consumption model of an HEV is approximated and solved for a global optimal solution using linear programming [11]. Automotive energy management challenges have been effectively solved using linear programming.

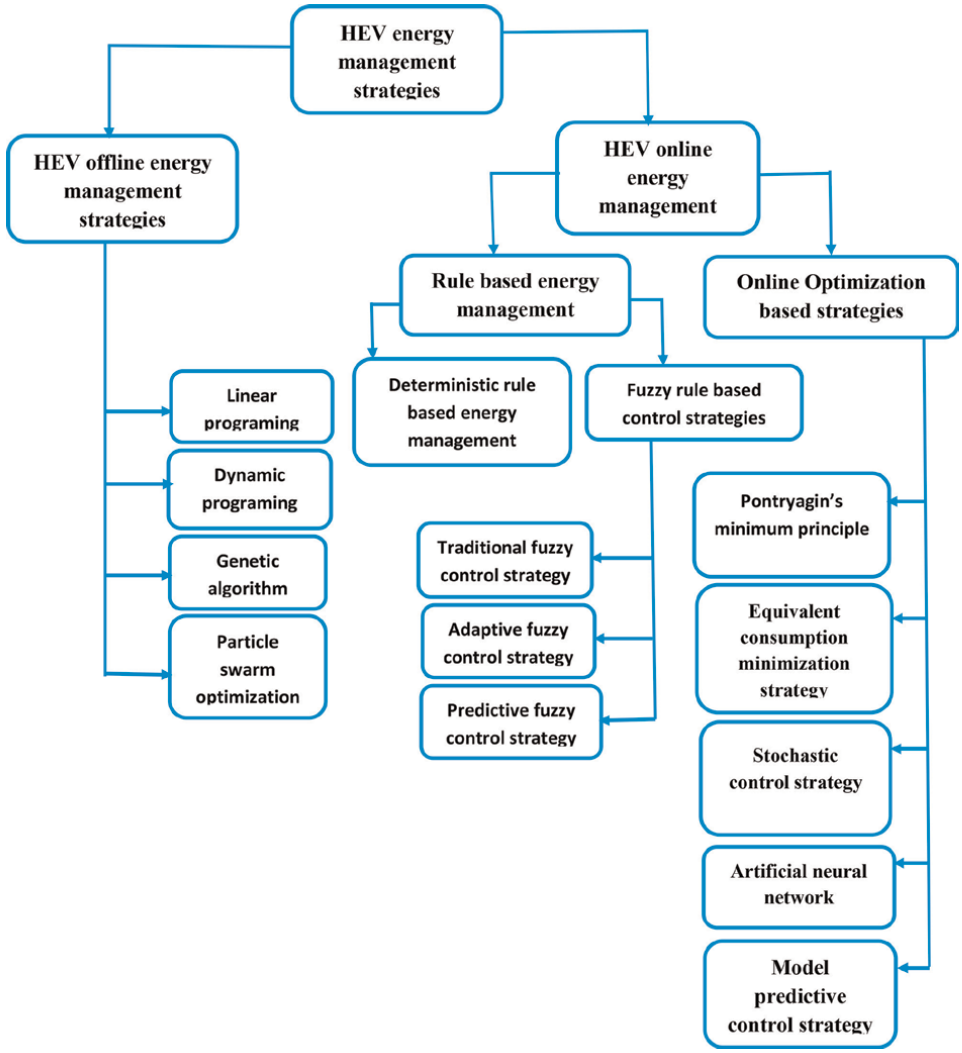

Figure 3.
HEV control strategy classification redrawn from [12].

2.1.3 Dynamic programming

The dynamic programming technique was invented by Richard Bellman and is used to determine optimal control policies through a multi-stage decision process. An ideal control policy, as described by Bellman, has the property that no matter what the prior decision (i.e., controls) was, the remaining decisions must comprise an optimal policy in terms of the state resulting from those previous decisions [17]. A discrete multi-stage optimization problem in which a decision based on the optimization criterion is taken from a finite set of decision variables at each time step is known as a dynamic programming algorithm. The backward recursive method and the forward dynamic programming methodology can both be used to implement Bellman's dynamic programming algorithm. The best sequence of control variables is found by working backward from the final state and selecting the path that minimizes the cost-to-go at each time step in the backward recursive technique (integral cost from that time step until the final state).

2.1.4 Genetic algorithm

The genetic algorithm (GA) is a heuristic search algorithm for developing optimization solutions. Darwin's theory of evolution inspired this branch of artificial intelligence. GA starts with a population of preliminary solutions (chromosomes) to find the best solution to a problem. Each population's solutions are picked based on their suitability for forming new and enhanced versions. As a result, the most suited solutions have a better chance of growing than those that are less suitable. The method is performed indefinitely until the desired optimization conditions are met. The genetic algorithm is a reliable and practical global optimization method with a large search space that may be used to solve complex engineering optimization problems with nonlinear, multimodal, and non-convex objective functions.

2.1.5 Particle swarm optimization

Dr. Eberhart and Dr. Kennedy created particle swarm optimization (PSO) in 1995 [18, 19]. This method is based on the social behavior of flocking birds, which optimizes a problem by iteratively trying to enhance a candidate solution in terms of a specific quality metric. Particles in PSO travel about a search space, directed by the search space's best known positions as well as the swarm's best known position. When better sites are located, the swarm particles will move. PSO is a meta-heuristic method for searching a large number of candidate solutions. PSO does not require the optimization problem to be differentiable, despite its non-causal character, and is thus well suited to optimization problems with some degree of noise or irregularity. In HEVs, particle swarm optimization has proven to be effective.

2.2 HEV online energy management strategies

HEV online control strategies, in contrast to HEV offline control strategies, are causal and implementable in real time. Heuristic control rules (rule-based control strategies) or an instantaneous optimization of a stated objective function can be used to create HEV online control techniques (online optimization-based strategies).

2.2.1 Rule-based energy management strategies

The most typical method of establishing real-time supervisory control in a HEV is using a rule-based control scheme. The control rules are frequently based on heuristics, engineering intelligence, or mathematical models, and they are designed to allow the ICE to function at high-efficiency levels while still allowing for energy recovery via regenerative braking. The development of rule-based HEV control approaches is typically divided into two stages: the formulation of appropriate powertrain control rules and the calibration of the strategy, which is commonly accomplished through simulations on a vehicle model. In most cases, rule-based control approaches fail to guarantee the optimality of the solution or to fulfill the required final integral constraint (charge sustainability). To correct this, the control rules must ensure that the integral constraint state of charge (SOC) remains between the lower and upper boundaries as specified. There is no standard approach to forming control rules in rule-based control strategies, and there is no way to know a priori whether a certain set of rules is adequate for a given application. However, the control rules could be designed deep and complex enough to handle any exceptional event that might occur [20].

The fundamental benefit of rule-based HEV control approaches is their simplicity, which makes them very simple to comprehend and execute on actual cars [11]. Rule-based control techniques have monopolized the production vehicle industry due to their minimal computational demand, natural adaptability to online-applications, high dependability, and reasonable fuel consumption outcomes. Despite their extensive use, rule-based HEV management systems still face considerable obstacles. Due to the lengthy rule definition and calibration process, developing a rule-based HEV management approach typically necessitates a significant amount of time and investment in competent labor. This scenario is exacerbated by the necessity to change the rules for each new driving circumstance and engine, raising concerns about the robustness of rule-based HEV control schemes. Furthermore, current research investigations reveal that rule-based HEV control approaches offer lower but acceptable fuel consumption results when compared to optimization methods. Deterministic rule-based control strategy and fuzzy rule-based control strategy are two types of rule-based controllers [11].

2.2.2 Deterministic rule-based control strategy

The rules for the deterministic rule-based control method are determined using the engine's fuel economy or emissions map. The rules are frequently implemented using pre-computed look-up tables. The concept of a hybrid optimum line for a parallel HEV with continuously variable transmission (CVT) was introduced by Kim et al. [21], who used a deterministic rule-based control technique. The best values of CVT gear ratio, motor torque, and engine throttle were effectively determined and applied in real time using this method. The electric assist control approach is one of the most widely used deterministic rule-based HEV control strategies. The ICE is employed as the sole source of power in this technique, and the electric motor is only used to provide additional power when the vehicle requires it. Another type of deterministic rule-based control is thermostat control technique. The electric motor and ICE are employed to generate the electrical energy that powers the car in this manner. By simply turning on/off the internal combustion engine, the battery state of charge is always maintained between specified high and low values. The thermostatic control technique was employed by Jalil et al. [22] to turn the engine on/off based on the battery state of charge profile. When compared to a deterministic rule-based control technique, the obtained outcomes were shown to be considerably sub-optimal. The following rules apply to several of the most extensively used rule-based control systems [13]:

1. When the vehicle's power demand falls below a specified threshold, the vehicle operates solely as an electric vehicle (EV), with the electric motor supplying the whole power requirement. This rule is usually applied to prevent the engine from operating at low-efficiency levels. The applicability of this rule, however, is contingent on the size of the HEV's electric engine and batteries.

2. When the vehicle power demand exceeds the maximum engine power, the electric motor is engaged for power-assist.

3. During regenerative braking, the electric motor charges the battery.

4. When the battery SOC falls below the defined minimum value, the ICE is activated to generate extra torque.

2.2.3 Fuzzy rule-based control strategy

Rule-based controllers are the forerunners of fuzzy rule controllers. In the fuzzification and defuzzification process, the linguistic representation of the control inputs is turned into a numerical representation with membership function in a fuzzy rule controller. The fuzzy rule-based control strategy's underlying logic is a type of multivalued logic derived from fuzzy set theory, which is designed to deal with reasoning that is approximate rather than precise. The relative simplicity of fuzzy rule controllers allows for tuning and adaption as needed, hence increasing the degree of control flexibility. Because of its nonlinear structure, it is very useful in complicated systems like modern powertrains. The battery level of charge, desired ICE torque, and intended mode are often inputs to fuzzy rule controllers, which output the ICE operating point. Driver command, battery SOC, and motor/generator speeds were treated as fuzzy sets for the creation of a fuzzy rule-based control strategy considered by [23, 24]. A power notification system was added to the fuzzy control framework, allowing the engine to operate in its high-efficiency region. In most cases, the electric motor compensates for the gap in power demand and ICE power. Traditional fuzzy control strategy, adaptive fuzzy control strategy, and predictive fuzzy control strategy are some of the current varieties of fuzzy rule-based control [13].

2.2.4 Traditional fuzzy control strategy

Traditional fuzzy control is frequently used to improve fuzzy efficiency, allowing the ICE to run more efficiently. This is accomplished by load balancing, which involves using the electric motor to push the engine to operate in its most efficient region (low engine speed, high engine torque) while maintaining the battery charge level. In a parallel HEV, Sulaiman et al. [25] presented a fuzzy logic controller to optimize fuel usage. The proposed strategy is centered on improving the efficiency of the vehicle's most important components, such as the internal combustion engine, electric motor, and battery.

2.2.5 Adaptive fuzzy control strategy

Fuzzy control that adapts because it potentiates simultaneous optimization of fuel efficiency and emissions, strategy is becoming increasingly popular in automotive applications on HEV. Because fuel efficiency and emissions are frequently at odds, an optimal solution cannot be found that meets all of the goals. However, utilizing the weighted-sum approach, where appropriate weights are modified over different driving situations for fuel efficiency and emissions, a sub-optimal solution is possible. The weights are relative, reflecting the importance of the particular objectives (fuel usage, NOx, CO, and HC emissions) [13]. As a result, adaptive fuzzy controllers can control specific objectives by modifying the weights given to them.

2.2.6 Predictive fuzzy control strategy

Prior information about a planned driving trip is used by a predictive fuzzy controller. This information is frequently obtained *via* a global positioning system (GPS), which provides information on the kind of impediments that the vehicle is likely to encounter, such as heavy traffic and a steep incline, among other things. Vehicle speed, speed state in the look-ahead window, and elevation of sampled places along a specified route are all common inputs to the predictive controller. The predictive fuzzy controller calculates the optimal ICE torque contribution for each vehicle speed based on the available history of vehicle motion and the speculation of its possible future motion, and outputs a normalized signal in the order of 1 to +1, indicating whether the battery should be charged or discharged. Fuzzy controllers have drawn a lot of interest from heuristic control professionals in the research and automobile industries due to their simplicity and robustness.

2.3 Online optimization-based strategies

Online optimization-based solutions break down global optimization problems into a series of smaller problems, lowering the amount of time and effort required to solve them. This eliminates the requirement for future driving data, allowing for real-time implementation. Local optimization procedures have gained the most research interest in HEV management, although producing marginally sub-optimal results when compared to global optimization strategies. The most widely used strategies are ECMS (Equivalent Consumption Minimization Strategy) [26] and PMP (Pontryagin's Minimum Principle) [3, 21]. Artificial neural networks, particle swarm optimization (PSO), and model predictive control (MPC) are some of the other online optimization-based methodologies now being investigated.

2.3.1 Pontryagin's minimum principle

Pontryagin's minimal principle (PMP) is a specific instance of the Euler-Lagrange equation of the calculus of variations, which was formulated in 1956 by Russian mathematician Lev Pontryagin and his students. The optimal solution to the global optimization issue must satisfy the criterion of optimality, according to the principle. The performance of the PMP controller was shown to be particularly sensitive to the estimated co-state value after studying the state of energy evolution for various co-state values. The model-based PMP control technique was discovered to compel the vehicle to deplete the battery for a co-state value larger than 10, and then transition to a charge-sustaining mode when the lower SOE (State of Energy) bound is achieved. Likewise, when the co-state value is 6, the model-based PMP technique allows the battery to be progressively reduced during the cycle, reaching the lower SOE boundary only at the end of the driving pattern and avoiding any charge maintaining activities. This process, known as blended mode, enables the achievement of the lowest possible vehicle fuel usage throughout a set of driving cycles. According to the findings of Stockar et al. [27], PMP is a shooting approach for solving a boundary value optimization issue. As a result, the optimal control technique that emerges is non-causal and cannot be executed in real time.

2.3.2 Equivalent consumption minimization strategy

The Equivalent Consumption Minimization Strategy (ECMS), which was first devised based on the heuristic assumption that the energy consumed to operate a vehicle over a driving cycle ultimately comes from the engine, is a more easily implementable local optimization strategy. As a result, the hybrid system just acts as a buffer for energy [13]. The instantaneous minimization of a cost index, which is the sum of a number of operation metrics weighted by equivalence factors, is the basis for this technique. Engine fuel cost and battery fuel cost are two often utilized metrics in ECMS HEV regulation. It can be implemented online because it does not require prior knowledge of driving patterns. The optimum power split is biased using a nonlinear penalty function of the battery state of charge divergence from its goal value to impose the global constraint of charge-sustaining operation.

2.3.3 Stochastic control strategy

For the power management of a series HEV, a stochastic model predictive control (SMPC) framework was created. The driver's power demand was simulated as a Markov chain, evaluated over numerous driving cycles, and utilized to generate SMPC control law scenarios. When compared to deterministic receding horizon control techniques, simulation results reveal that the SMPC solution drives engine, motor, and battery operations in a causal, time-invariant, state-feedback manner, resulting in enhanced fuel economy and vehicle performance.

2.3.4 Model predictive control strategy

Over a finite horizon, model predictive control is the solution to a basic optimal control problem. It is done online with the help of a model that predicts the impact of control on the system output. It works by calculating the optimal control for the prediction horizon in real time but only applying the first element; the prediction horizon is then shifted forward at the next time step. MPC's operation is based on high model accuracy and prior knowledge of reference trajectories, both of which are not directly possible in-vehicle applications. When combined with a navigation system, however, MPC has been proven by Salman et al. [28] to be an effective real-time predictive optimum control technique.

2.3.5 Artificial neural network (ANN)

An artificial neural network (ANN) is a computing system composed of a number of simple, highly interconnected processing components that process data based on their dynamic state responses to external inputs. Mc Culloh and Pitts created the ANN concept in 1943, and Hebb enhanced it in 1949 by adding the first learning rule. By modifying weights to minimize the difference between the actual and anticipated output patterns of a training set, neural networks can be trained to learn a highly nonlinear input/output relationship. The backpropagation method aids this type of guided learning.

The neural network's adaptable structure makes it ideal for HEV energy management applications. The nonlinear correlations between inputs and outputs of a well-defined energy management network can be learned and replicated using neural networks. For varied drivers and driving patterns, Baumann et al. [29] devised a control approach that blends artificial neural networks and fuzzy logic to create a load-leveling technique for increased fuel economy and lower emissions. A dynamic model is utilized [30] to explain the driver-vehicle interaction for a general transient and to simulate the vehicle driveline, internal combustion engine, and electric motor/generator (EM). Vehicle load is assessed in real time using a time delay neural network (TDNN) and used to optimize the supervisory control approach in the absence of traffic preview information.

2.4 Energy regeneration through the braking system

According to Chen et al. [31], the included regenerative braking system (RBS) recovers the vehicle's kinetic energy during deceleration, considerably boosting fuel economy. According to studies, a traditional braking system in urban driving scenarios wastes around a third to half of the power plant's energy in the form of heat to the atmosphere during deceleration. And this squandered energy was originally in the form of kinetic energy, or motion energy. As a result, it is critical to be motivated to recuperate this wasted kinetic energy in order to increase electric power demand and expand driving range. From a practical standpoint, recovery of vehicle kinetic energy by converting it to thermal, mechanical, or electrical energy setup is a viable option.

Hydraulic regenerative braking, which has a high power density and energy conversion efficiency, has been used in heavy vehicles, but control strategies for hydraulic regenerative brakes are difficult to fully utilize the regenerative potential due to the low energy density of the hydraulic accumulator, which forces a tradeoff between performance and cost to solve this new control strategy, which will be used as a blended brake control and energy efficacy. High regeneration efficiency and nice braking sensation can be attained if the regeneration and frictional brakes are well synchronized.

2.4.1 EV energy control with hydraulic brake system (HBS)

Based on the study shown in **Table 1**, Chen et al. [31] observed that electric vehicles with blended brake control with the purpose or objective of discussing the mechanism and evaluation of electric vehicle regenerative energy efficiency

Authors	Purpose	Similarity	Unique feature
Liang et al. [32]	To improve the efficiency of electric vehicles	Energy generation and control	Concerned about HEV with HBS
Chengqun [33]			
Wei et al. [34]			
Chengqun et al. [17]			
Chen et al. [31]			

Table 1.
Electric vehicle energy control with HBS.

improvement. The methodologies followed were vehicle tests carried out on chassis dynamometers under typical driving cycles. Three different control strategies were used, namely, the system design, blended brake control, and energy efficiency evaluation. In addition to this, by using the energy flow analysis, two different evaluation parameters were also used: the contribution ratio to energy efficiency improvement and the contribution ratio to driving range extension. In comparison with non-blended regenerative brake control, the contribution ratios made by regenerative braking to energy efficiency improvement and driving range extension were up to 11.18 and 12.58 percent, respectively, under the new European drive cycle (NEDC). Finally, the report identifies future research needs based on the following gaps:-

- Evaluation method of regenerative braking contribution for other types of electrified vehicle, road tests of the evaluation parameters under different driving cycles should be conducted since the test is only made on chassis dynamo meter.

- From the experiment, different mechanism analysis and practical implementation methods were not discussed adequately to get more accurate and better results.

The similarity of this study with other related comprehensive review is efficiency improvement through control and management of regenerative braking energy. The study made by Qiu and Wang [33] same purpose or objective is followed to improve energy regeneration efficiency but the methodology used for the experiment under this study for mechanical and evaluation methods analyzed by energy flow is:

- Proposals have been made to calculate the contribution of regenerative brakes.

- A new regenerative braking control method, known as "serial-2 control strategy," is introduced.

- Two control strategies, known as "parallel control strategy" and "serial-1 control strategy," are proposed as the comparative control strategy and vehicle road testing are conducted.

To do such an experiment, the parameters used to get the desired result are two, namely, the contribution ratio for regenerative braking energy transfer efficiency improvement and the contribution ratio to regenerate driving range. The energy consumption of a vehicle with regenerative braking. Then, EmDrive calculated the efficiency of the axle with the RB energy efficiency of a vehicle, with the RB average efficiency of a battery during charging and the energy consumption of hydraulic braking situations obtained. The serial-2control technique produces a significantly higher regeneration efficiency than the parallel and serial-1 strategies. Regenerative braking contributes up to 41.9 percent to improved energy transfer efficiency and 24.63 percent to an increased regenerative driving range, respectively. Finally, the study identifies areas where more research is needed in order to improve the process of evaluating regenerative braking contributions for different types of powered cars.

The torque optimization control of electric vehicles with four-wheel motors equipped with regenerative braking is addressed by Xu et al. [34].with the objective of having better safety and increasing energy regeneration efficiency. The method followed was model predictive control (MPC) theory, with the issues of multiple objectives and constraints of the regenerative braking system well addressed. Hence, a real-time test is demonstrated through the parameters of four in-wheel motors mounted to each wheel, determining the hydraulic braking torque and motor braking, alternating electric motor AME/sim software to verify the advantages of the proposed model predictive controller, motor model, and vehicle dynamics model is effective in the study. The simulation results show that optimizing braking torque distributions improves energy recovery performance for electric vehicles. The study has its own gaps concerning the MPC and should be tested with another strategy to see and compare for a better result.

Chengun et al. [17] is a second study next to Chengun et al. [33] with the same author and objective but with different methodology. This study focuses on novel control strategies (NCS) of regenerative energy braking systems, and its main objective or purpose is to focus on the control strategy of a regenerative braking system of an electric braking system under safety critical driving conditions to ensure the electric vehicle's stability in various types of tire-road adhesion conditions. The method proposed was to investigate using a serial control strategy to utilize proportional integral derivative control to utilize proportional brake force as an antilock brake system (ABS) operation. Three control strategies were developed in this study:

- "the model following control"
- "Frequency selection by filter"
- "PQ method" strategies

This study considers a regenerative braking system that is electrically controlled according to the techniques of conventional hydraulics. The ABS is studied and a control algorithm harmonizing the ABS control function and braking energy regeneration has been developed. A representative passenger car outfitted with a central electric motor is chosen for the case study. Road tests were carried out under various types of road adhesion conditions, and the results were then compared. The simulation test results on the basis of a quarter vehicle model show that "Regenerative ABS" is useful during the critical braking procedure. To see the effect on the ICE road test, the contribution ratio to stable and dynamical braking energy efficiency is enhanced by up to 58.56 and 69.74 percent, respectively, under the serial control technique. According to the ICE road test results, mean deceleration has improved by 4.41 and 14.7% separately in comparison with the bench mark. The study still has its own gaps to be filled by future research work and further recommends that:

- The regenerative braking system's controls performance in different types of electric automobiles.
- The impact of various battery kinds and their degradation mechanisms on the suggested control strategy's performance.
- The impact of various vehicle dynamics modes on the suggested control strategy's performance.

Last but not least is the use of an electric car in conjunction with hydraulic braking system downshifts to improve the efficiency of regeneration energy in electric vehicles. Cooperative strategies (HB, EM) with a hierarchical control approach were proposed by Li et al. [32] to realize cooperative control of regenerative and hydraulic braking during the downshift process. To achieve the ideal down-shift point, an off-line calculation, and an on-look-up table approach are employed to classify the upper controller. A nonlinear sliding mode observer is built for the medium controller to obtain the actual hydraulic brake torque. Cooperative control of regenerative and hydraulic braking is provided for the lower controller to ensure brake safety during the downshifting process, and a pulse width modulation method similar to pulse width modulation is proposed to regulate the hydraulic brake torque using three degree of freedom (DOF) vehicle model to illustrate the vehicle dynamics.

The results obtained from simulation and hardware in-loop tests show that the proposed algorithm is effective in improving the energy efficiency of electric vehicles. The study is most similar to my topic, but it has its own future work recommendation since it faces gaps. Therefore, future research will focus on the tradeoff between dynamic performance and energy efficiency during the braking process. The energy efficiency is only higher at medium speeds and with medium braking strength, which means not at lower speeds and higher speeds in accordance with braking strength. The purpose, similarity and unique features of the authors are indicated in **Table 1**.

2.4.2 EV with super-capacitor compared with other storage devices

The concept behind super-capacitor under power regeneration system.

Energy regeneration system is classified into three categories:

- Fly-wheel energy storage system
- Hydraulic energy storage system
- Electrochemical energy storage system

Among the three electrochemical energy storage systems, electrochemical energy storage system proved to be promising energy storage for regenerative vehicles [35]. When an electric car is driven at high speeds, the transient current generated by brake feedback in the motor bus can reach 200 A or more, causing significant damage to traditional batteries like lead acid and lithium-ion batteries. Super capacitors, in contrast to typical batteries, have high power densities, making it more acceptable for a substantial quantity of braking energy to be quickly transferred to the super capacitors through proper conversion from kinetic to electrical energy. The super-capacitor can greatly enhance energy savings and consequently extend the driving range. Super-capacitors could output huge current instantaneously and then reduce the power output of the batteries. The accelerating capability of electric vehicles and battery life will also be improved accordingly as such installing a super capacitor as an auxiliary power source. Electric vehicles with super capacitor have become the latest research focus at this time. Faggioli et al. [36] suggested various energy system topologies with super-capacitors for electric vehicles, demonstrating that the use of super-capacitors in electric traction systems can result in significant improvements in terms of electric performance, battery life, and energy economy. As may be shown in **Table 2**,

Energy storage devices	Charging time	Life Cycle	Efficiency (%)	Specific energy (WH/Kg)	Specific power (W/Kg)
Super-capacitor	0.3–30 sec	>500,000	85–98	1–10	6000–9000
Ni-Hydride	6 hr	1000–2000	70	60–80	200–300
Li polymer	6 hr	5000	90	150–200	350
Li ion	1–6 hr	5000	95	80–130	200–300
Lead-acid	6–12 hr	500–1000	80	30–50	150–400

Table 2.
Comparison between various electric energy-storing devices [37].

Authors	Purpose	Similarity	Unique feature
Pezhman et al. [14]	To improve the performance of EV power efficiency through using battery and SC to store and supply energy as synergy	Better storage of energy and control	Concerned with battery and supper capacitor
Long et al. [38]			
Vivekumar et al. [37]			
Zhongyue et al. [39]			

Table 3.
Electric vehicle with battery and super-capacitor.

super-capacitors outperform other chemical batteries. The purpose, similarity and unique features of the authors are indicated in **Table 3**.

3. Comparison between various energy storing devices

As shown in **Table 2**, Vivek et al. [37] investigated comparisons of various energy storing devices that the lesser charging time required to fully charge is supper capacitor with a higher specific power of 6000–9000 (W/Kg), greater than 500,000life cycle, and 85–98% efficiency among other alternative storage devices. The least other alternative is the lead acid battery which exhibited a maximum charging time of 6–12 hr. and a life cycle of 500–1000 with a specific power 150–400 (W/Kg).

Electric vehicles (EVs) are gaining popularity these days due to their unique characteristics such as high efficiency, quiet operation, and minimal emissions. EVs have improved their efficiency in recent decades, and several researchers have cited them as an interesting issue. However, several elements of these vehicles, like as limited ranges due to limited capacity, may make a single energy storage technology insufficient to meet the requirements of EV applications.

The idea of adopting a semi-active hybrid energy storage system (HESS) is appealing since it allows for the use of each storage technology's operating benefits. Chemical batteries have long been the primary energy storage systems in many industrial applications. Newer batteries (e.g., Li-ion) give improved discharge efficiency at higher energy storage density, but they have a low power density and a number of drawbacks, including:

- Limited cycle life as well as high cost

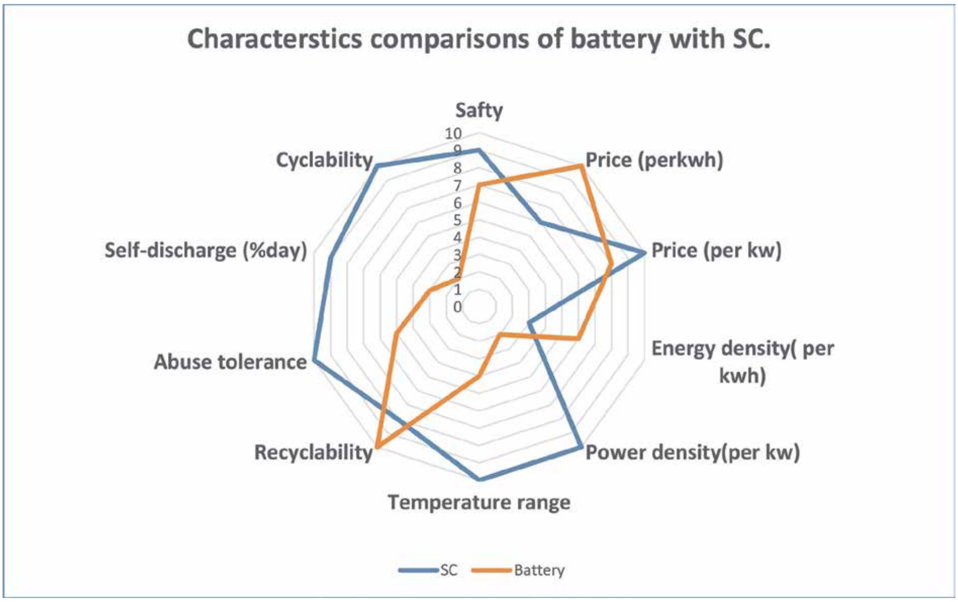

Figure 4.
Characteristics comparison of battery with SC taken from (Pezhman et al. [36]).

- Super capacitor (SCs) are being actively studied and unanimously envisaged as a promising energy storage technology further see **Figure 4**, owing to their desirable merits including:-
- low internal resistance
- High cycle life
- high efficiency
- High power density
- High degree of recyclability
- It works at high temperature range

Based on **Table 3**, electric vehicle, battery, and super-capacitor energy management and control-related reviews for the case of Pezhman et al. [36], a combined storage system is designed to boost or improve the performance of energy supply efficiency, that is, battery and super-capacitor, using a hybrid sliding mode controller (HSMC) with a manufactured model electric vehicle equipped with the proposed controller through a practical test in the case of stochastic EV driving cycle as a parameter. According to the study, the practical and simulation results show that the proposed method can effectively improve the performance of an EV. The study also has a gap and recommends future research work that may concentrate on:

- Investigating control methodologies for three port DC-DC converter with multiple operating modes.

- Exploring advanced and intelligent control methodologies for the DC hybrid power systems.

- Determining how to guarantee system stability and maintain system performance for three port DC-DC convertors with two input sources.

As a disadvantage the model has its own gaps concerning about cost of the additional SC and weight addition on the system which will compromise the efficiency.

The other electric vehicle with super-capacitor for rail used as additional power storage sources as Long et al. [38] studies that its main objective or purpose is to reduce the battery and SC loss or to utilize the recovered regenerated energy without loss through using SC since there are power voltage fluctuations from the main supply system leads to battery power loss. The approach utilized to manage is a rule-based EMS (RB-EMS), which gives the SCs charging priority over the batteries when the car is braking, and this way was finally tested with a conventional SC through simulation and testing findings. The suggested EMS is compared to SOC penalty-based cost function optimization to evaluate losses, and the final result shows that when compared to SOC penalty-based cost function optimization, and it reduces losses by 7.5 percent and prevents SOC from reaching the discharge limitations. Even though the study has acquired this much recovery, more optimization research is needed in the future for a greater energy loss recovery.

When it comes to SC and battery, Vive kumar et al. [37] investigated regenerative braking for an electric vehicle using a hybrid energy storage system, with a focus on the battery and super-capacitor, with the goal of reducing unnecessary energy waste, high power demand, and stresses on the battery by using a super-capacitor to recapture energy from regenerative braking. The method followed an intelligent electronic control strategy for the whole process, using an intelligent electronic buck-boost transformer (IGBT) Buck Boost convertor to control the energy stored in the super-capacitor bank storage with the parameters of the application of the super-capacitor as a power buffer to minimize rapid power fluctuation under acceleration and deceleration. Then finally, the result from the model shows that a large amount of energy can be recovered with minimum losses of energy and stress on the battery pack. Within this area of strategy, regenerative braking energy for super-capacitor vehicles' mechanisms is to improve the efficiency of energy conversion and increase the driving range of electric vehicles.

Zhongyuo et al. [39] conducted an experimental study under various braking conditions and the result verified the higher efficiency of energy regeneration systems using super-capacitors and the effectiveness of the proposed measurement method. A maximum regenerative energy conversion efficiency of 88% was obtained.

3.1 Electric vehicle (EV) power management and control with the state of art

Table 4 shows the state of the art in terms of electric vehicle regenerative braking control and management strategy (battery, super capacitor, motor, and so on), and it can be seen that all of the topics discussed have similar purposes or objectives, such as storing more and efficient energy from regenerative braking to extend (prolong) driving ranges or to maximize the efficiency of electric vehicles using better and improved models and systems. And the methodology [23, 40] employed comparable methodological control strategies, such as a fuzzy logic control strategy, and their end results were similarly tested using Matlab/Simulink. However, the former parameters

Authors	Purpose	Similarity	Unique feature
Siddharth et al. [24]	To store more energy during regenerative braking for extending driving rage	Better energy utilization, storage and control	Concerned on state of the arts (Motor torque) electric energy is generated from waste braking force (kinetic energy)
He et al. [40]			
Jian et al. [23]			
Shiva et al. [41]			
Bo-Chiuan et al. [42]			
Md Shumiur et al. [43]			
Jiejunyi et al. [44]			
Laiqing et al. [45]			
Liang et al. [46]			

Table 4.
Electric vehicle with power management and control with the state of art.

employed are nonlinear factors such as soc., speed, and brake force, while the latter uses a single pedal regenerative braking control strategy (RBCS), COS, GOS, Kg, and relative energy recovery rate (RERR) calculations to make driving more easy and intelligent. The average power stored by the battery is raised by 2.5 times as a result of the result achieved in the case of the former, and the vehicle comes to a halt faster. The later topic has a lot greater energy recovery than the first, with (RERR) of 65.99 percent and 55.40 percent, respectively, which is effective in energy recovery when compared to the first. However, they both share the same principle and concept with this reviewing topic and they both consider electric vehicle side only. Concerning future work and the gap between the two processes, the former is ambiguous and difficult to explain SOC, P, I (since they are constantly changing with time). So far, the latter situation is concerned about future work, and the gap is, to some extent, a waste of motor braking energy characteristics.

Though it was mentioned that they all have similar objectives or purposes, the methodology used and the results obtained are different, so to see each one from numbers 3 to 9 in **Table 2**, you should be able to easily understand that a feedback hierarchical controller, a methodology for which was proposed as a methodology, and estimated longitudinal velocity and input-to-state stability theory were used as parameters [23]. The results after the simulation test show that the effectiveness of the proposed method in tracking the velocity and improving the energy recovery of vehicles compared to non-regenerative braking. The four-wheel independently actuated motor mounted on each wheel, which adds weight, complexity, and cost to the given model of electric vehicle, is one of the gaps considered.

A novel control strategy for regenerative braking is proposed as a method and for validation as a final test, Matlab/Simulink test is made parameters based on slope information [41]. The front and rear axles are presented in addition to this based on a logic threshold control algorithm with input Z and I (relationship between electrical and mechanical braking). The study’s findings suggest that the improved management approach works well on roads with varying slopes. The regenerative braking control strategy is capable of recovering energy and improving brake stability.

The gap obtained is the aerodynamic stability during downshifting, which is one factor influencing the driving range in the case of modified direct torque control and adaptive control theory used a method for this particular study [42]. A modified direct torque control (MDTC) is proposed to generate electrical energy from the kinetic energy and also an adaptive controller is designed to improve tracking error and torque ripple. The parameters used for conventional direct torque control (DTC), MDTC, SOC of the DTC with the modified DTC combined, and model reference adaptive system (MRAS) controller was obtained. The result is that the new switching pattern improves the speed and torque tracking signals the torque ripples. The different feature on the motor is that it uses less direct current (BLDC) for study power converter is not necessary.

The proposed strategy is then proposed as a power management strategy (RE-EV) with DP to evaluate both power management strategies, and the results are extracted from the Matlab/Simulink test. The proposed strategy can approach approximately 70% control performance of DP results compared to the thermostat control strategy (TCS). The computation power of the multi-mode switch strategy increases by 8, 11, and 10%, respectively, when compared to TCS for three untrained driving patterns. To finalize the findings, the results indicate that the proposed strategy can require lower computation efforts in exchange for better control performance of fuel economy and battery protection. This result is obtained by using the parameters of two design criteria; battery energy losses for battery protection and fuel energy losses are for addressing fuel economy and considering driver comfort, battery life, limitations of noise, vibration, harshness, and battery charging currents, which are expressed as the gaps that are not yet solved, but maybe for future work.

The electric vehicle study conducted by a novel coordinated control strategy is proposed in order to facilitate the V2G capability of 3p AC and DC type EV charging stations in an island commercial hybrid AC/DC microgrid [43]. The whole system is designed in Matlab/Simulink with respect to the parameters followed is a three-layered coordinated control to incorporate three-phase (3p) alternating current AC type electric vehicle energy storage system (EV-ESSs) for the improved hybrid AC/DC microgrid operations, bus RMS voltage regulator, respectively. Based on the comparative case studies, improved voltage regulation and power sharing performance have been with the presence of homogeneous single-phase EV charging, and better energy conversion is obtained. This research must integrate market operations and investigate the effects of the distributed control approach to reduce communication dependency in the future.

Jiejunyi et al. shown in [44] a method used a 4-speed transmission system with corresponding control strategies is proposed and investigated in order to achieve power on shifting during regenerative braking. A detailed mathematical model is built on an advanced multi-speed transmission power on shifting strategy is proposed. The parameters adopted for the system are based on the full-size sedan, in which regenerative braking is more significant. Based on the selected vehicle specifications, a systematic choice of suitable gear members is made. The results obtained from this show that with the proposed system, the regenerative braking efficiency can be improved by 45% in a typical NEDC cycle. A similar concept related to this topic is electric vehicle energy regeneration control and management. The difference and its unique feature is energy control in terms of power on shift control. The gaps for future work recommendations are weight, cost, and complexity of the model or system.

Laiqing et al. indicated in [45] the methodologies adopted in this system or model is a hierarchical control architecture that consists of three layers in the proposed strategy, which is a novel energy-saving control strategy for electric vehicles based on the movement of the preceding by forward radar. The parameters according to the relative motion between the Ego-vehicle and the preceding vehicle are designed and simulated under commission for the urban driving cycle (CUDC). From this, the average energy-saving percentage of the 90 groups of simulations under CUDC conditions is about 9.6%. The average energy consumption of the experimental bus under actual urban traffic conditions is reduced by 5.9%. The system uses an intelligent radar system to control the torque output energy and this creates a new and different experiment than the existing revision topic.

3.1.1 HEV regenerative braking energy management and control

When a hybrid electric vehicle (HEV) is combined with a hydraulic brake system (HBS), there is a tradeoff relationship in terms of regenerative braking efficiency. This means that when braking is performed by the motor torque, the vehicle will not come to a complete stop immediately, but will instead be a cause of an accident. On the other hand, when additional braking is applied by the hydraulic brake system by the driver to deter an accident, the regenerative energy efficiency increases. To reconcile these phenomena and to have both safety and regenerated energy efficiency, a program and model should be proposed to gain both. In this classification of **Table 5**, reviewed articles share a common goal or objective, which is to improve regenerative braking efficiency, fuel economy, and environmental concern through various control and management strategies.

Wisdom et al. showed in [11] the controlling models and their effects on various research topics in their modeling and control of HEV regenerative and sustainable energy review. The objective or purpose of the study was to develop a real-time control strategy capable of coordinating the onboard power source to maximize fuel economy and reduce emissions by using sample parameters of off-line and on-line control management strategies. The comprehensive review and discussion of various journals as a method to reach the findings or results of energy optimization on hybrid electric vehicles of different systems and state of the art to obtain energy optimization through using different proposed strategies leads to reduced emissions and fuel costs. But based on the review, tremendous gaps are faced and future work is also recommended. Exploitable research gaps in rule-based control methods, dynamic programming, the equivalent consumption minimization strategy (ECMS), and model predictive control (MPC) strategies have all been discovered as part of this dissertation. These study gaps indicate that present HEV control algorithms are still weak,

Authors	Purpose	Similarity	Unique feature
Wisdom et al. [11] Liang et al. [47] Jian et al. [48] Sulakshan et al. [49] Liang et al. [50] Zhang et al. [51] Lars-Henrik et al. [52] Grandone et al. [13]	• To store more energy during regenerative braking for extending driving rage • To maximize fuel economy and reduce emissions. The focus of the strategy is to maximize energy recovery in the battery using the motor as much as possible.	Better energy utilization, storage and fuel consumption control	Concerned with hybrid system power supply from both fuel cell engine and electric motor including regenerative braking

Table 5.
Hybrid electric vehicle energy management and control.

particularly in terms of optimizing brake energy regeneration and charge surviving sub-optimal control using partial and no route preview information. Future studies toward mitigating these research gaps are expected to yield control strategies capable of realizing the ultimate charge-sustaining fuel-saving potential of HEVs in real time.

The energy conservation improvement of down shifting to maximize the regenerative energy stored in the battery is the objective used in the study by Liang et al. [47]. The research platform was an HEV with an automated manual transmission (AMT), and simplified dynamic models of the HEV system were produced as part of the procedure. Based on the research, two innovative down-shifting strategies based on DP algorism are given, and the results are validated using Matlab simulation with single shaft HEV and HBS cars. Varying gear position regenerative braking effects are examined, as are differential initial speed braking severities. The study found that downshifting improves the energy conservation of the regenerative braking mechanism by 10.5–32 percent as compared to not downshifting. The DP-based technique provides global optimal solutions and enhances energy saving by 21–32.4 percent, demonstrating that regenerative braking's potential cannot be realized in practice, but rule-based strategies can. The rule-based technique provides instantaneous optimal solutions and improves energy conservation by 10.5–29.7%, with considerable fluctuations in improvement. The study found the following gaps, which should be addressed in future research:

- Down-shifting control during regenerative braking process is a problem with ABS

- The control strategies are not effective and stable enough to bring adequate energy conservation and efficiency so more effective and efficient control strategies are necessary.

Another similar study was conducted by the same author with the same objective but with different methodologies, parameters, and results. It was conducted by Liang et al. [50] to improve the stability concern raised by the previous study with the objective of recovering braking energy stability during emergency braking. To acquire the optimal distribution of braking torque, the modified nonlinear model predictive control (MNMPC) approach is proposed, with the particle swarm optimization (PSO) algorithm being used. For road conditions with varying road adhesion coefficients, simulation and hardware in-loop-testing (HIL) are also performed (to know the MNMPC accuracy result). As a result of the findings, the proposed technique may assure vehicle safety during emergency braking scenarios while also improving recovery energy by about 17% when compared to a traditional rule-based strategy in a general braking condition. A future research study might be conducted using the MNMPC strategy and the parameters employed in the proposed approach, which, when calibrated properly, could increase algorithm performance.

As illustrated in [51] by Jian et al., to overcome the problem, a hierarchical control technique is recommended (vehicle braking safety). The simulation experiments are used to show how regenerative braking affects battery aging and the effectiveness of the proposed method, while controller-in-the-loop testing is used to check the real-time computation performance. The parameters used to control the upper-level controller (general braking mode) and the lower-level controller (pneumatic braking and EM) are listed below. The proposed control strategy applies to the entire cycle of city busses on straight roads. The result of the proposed method can ensure the vehicle's safety in the braking process and mean while balancing the battery's aging and energy recovery. The study recommends future work for further research due to the still existing gap. It is hoped that the model will be extended with driving modes to investigate the influence of many cycles on battery life and energy recovery. The other one is a large recovery current that can cause damage to the battery and reduce its life.

As Sulabshan et al. pointed out in [52], an effective ABS controller is required to achieve high braking efficiency without sacrificing regenerative efficiency (to avoid trade-off). The intelligent sliding mode scheme (ISMS) uses a supervisory logic-based motor torque limiter and slip controller to achieve this. The plan has undergone extensive testing. The proposed controller is an effective ABS controller system, a slip controller, a magic formula, and a two-wheel model are used. From this effect, high braking efficiency and considerable energy regeneration without overcharging the battery are obtained. But the study still faces a challenge and encountered a research gap, and to recommend for future work, higher order SMC (HOSMC) will be explored with fuzzy logic or ANN to generate an HEV system to improve overall performance.

Zhang et al. pointed out in [51] a "modified control strategy" with "baseline control strategy" as a comparative control strategy and the results obtained by this strategy have been tested with simulation and hardware in-loop-test (HIL) carried out, and bench tests and road tests have been conducted to improve the regeneration efficiency problem in the HEV in combination with HBSs. The test was conducted with a rear-drive electrified minivan equipped with a rear motor as the parameter. The simulation and HIL test results reveal that the updated control approach has much higher regeneration efficiency than the baseline control strategy. The updated control approach had a regeneration efficiency of 47%, which was 15% higher than the baseline control method. The quantity of total recoverable energy is the modest because the target minivan is rear-driven and has little mass, according to the recommended future work for researchers in this field of study. As a result, regeneration efficiency would be limited.

- Because of the modulation of wheel pressure during regenerative braking, brake pedal sensation will be impacted, and it will be difficult to maintain an adequate brake pedal feel.

- Because of its low inertia, the target minivan is sensitive to changes in brake torque, making it difficult to ensure braking.

Lars-Henrik et al. illustrated [52]. The parameters used are GPS-derived speed and altitude data from real-world car-driving to estimate the overall potential for energy regeneration under car driving, and two drive trails are investigated on BEV and MHEV. And methods to solve the issue: the speed profiles of the new European drive cycle (NEDC) and worldwide harmonized light vehicle test procedures (WLTP) test cycles are used for comparison, and the results from real-world driving are compared to the NEDC and WLTP test cycles. The results or findings obtained indicate that regeneration of braking energy under current driving conditions could increase energy efficiency with average energy savings at the wheels of about 15% for a battery EV and up to 10% for a "milled" hybrid. The gap observed is energy savings by engine stop/start ability, which will contribute to its economic viability not considered in this study.

Grandone et al. in [13] studied the development of a regenerative braking control strategy for hybridized solar vehicles with the aim of developing the best braking strategy that allows the trade-off between mechanical and regenerative braking on hybridized vehicles. Methods followed to estimate the vehicle braking torque considering aerodynamics, vehicle friction, and engine passive losses in different gears have been developed and identified over road tests, for a vehicle hybridized with wheel motors on the rear wheels, so far the parameters considered. The model which is useful for real-time battery control has been developed based on this condition. Regenerative braking is installed on the rear brake axle with rear total torque ratio (RTTR) and driveline torque effect integration of state-of-the-art components (PVP, wheel motors, and batteries). The preliminary results show that the model is useful for designing real-time braking strategies, if properly combined with estimation of slipping coefficient and use of ABS system, and it will eliminate the trade-offs. The purpose, similarity, and unique features of the authors are indicated in **Table 5**.

3.1.2 Plugged in hybrid vehicles (PHEV) power generation and management

When energies are fully discharged, it is possible to obtain an external power supply from the power grid by plugging in a power supply cable (socket) into the power supply system while in a stationary position for energy control and management in the case of PHEV. The main goal is to obtain more energy supply during highway driving conditions at acceleration time, which helps with better fuel economy and emission reduction. So, in this regard, according to **Table 6**, some researchers are working hard to improve energy efficiency by employing various control strategies and models. For that reason, as Yu et al. indicated [53]. The suggested PHEV algorithm results are compared with the determinacy rule-based energy strategy for HEV with a similar battery capacity as PHEV. The proposed energy management method is implemented in the advisor on a PHEV model, which is then simulated using Mat Lab and Simulink. The parameters considered are for several numbers of drive cycles and the paper chooses nine words to describe Treq. The fuzzy set of Treq is the input and output (Tm) variables of the fuzzy set and its domain provision (NBB, NB, NM, NS, O, PS, PM, PB, PBB). The SOC is set up into three fuzzy subsets (L, M, and H) and the domain [0, 1]. The simulation results in the cycle of road conditions show that with an appropriate distribution of ICE and motor torque, the suggested energy management approach may successfully minimize exhaust emissions and improve fuel economy. The gap created by this experiment is that the basic fuzzy control model in adviser was built based on theory, and control rules in general have poor practicality.

Shown in YU-Hui et al. [55] the power management of a semi-active hybrid energy storage system (HESS) and an assistance power unit (APU) is proposed, with MPCS regulating output power between battery and ultra-capacitor packs and a rule-based strategy controlling output power between APU and HESS. To optimize the control approach, the dynamic programming algorithm will be used. Three typical cycles verify the following parameters:

- Manhattan Cycle
- CBD cycle
- UDDS HDV cycle (urban dynamometer driving schedule heavy duty vehicle)

In the model predictive control process, a period of the future velocity will be predicted.

Authors	Purpose	Similarity	Unique feature
Yu Zhang et al. [53]	• To maximize fuel economy and reduce emissions and to obtain more power torque in different driving condition • To store more energy during regenerative braking for extending driving rage	Better energy utilization, storage and fuel consumption control	Concerned on power is generated from plug-in-(external electric power) electric supply with hybrid power from both fuel cell engine, electric motor and -including regenerative braking
Shuo et al. [54]			
Zheng et al. [26]			
Yu-Huei et al. [55]			

Table 6.
Plugged in hybrid vehicles (PHEV) energy control and management.

The results show that the proposed control strategy can promote fuel economy compared with the original control strategy, especially in the charge-sustaining mode under the Manhattan driving cycle (21.88% improvement). The future work recommended by the study and considered as a research gap is the durability of the proposed control strategy, which needs a real driving cycle test on the street and then tested through bench testing.

As Zehng et al. [26] determine the engine fuel rate with respect to battery power in this paper, an intelligent algorithm based on the quadratic principle (QP) and simulated annealing (SA) methods is proposed for the energy management of series plug-in HEVs in order to reduce fuel consumption. The problem is solved by using quadratic programming and the simulated annealing method together to find the optimal battery power commands and the engine-on power. The simulations were performed to verify the proposed algorithm. The engine and generator inertia are analyzed to improve calculation precision, and the battery's health is taken into account as a parameter. The result, through simulations, is that the proposed algorithm is proven to be effective in improving the fuel economy regardless of the battery health status. Experimental validations, including the actual vehicle test or hardware-in-loop test, will be the focus of future work. The other work-related to this regard is YU-Hui et al. [55]. To solve the optimization problem of HEV fuel consumption and emission reduction, a robust evolutionary computation method called "Memetic algorism (MA)" to optimize the control parameters in HEV is used. The fitness function is linked with advanced vehicle simulation (Advisor) and its setup according to an electric assist control strategy (EACS) to decrease the vehicle engine's fuel consumption (FC) and emissions. The concerned parametric values are taken into account in order to complete the test with the specified model's driving performance parameter requirements. The new European driving cycle (NEDC), federal test procedure (FTP), European Commission for Europe +extra urban driving cycle (ECE + EUDC), and urban dynamometer driving schedule (UDDS) are the four driving cycles used. The results of the tests reveal that the proposed strategy effectively reduces fuel consumption and pollutants while maintaining vehicle performance. The purpose, similarity and unique features of authors concerned on PHEV were indicated in **Table 6**.

4. Thermal management system for EV/HEV/PHEV

Any batteries used in large power storage (utility-based, electric car) will very certainly require some type of temperature control, whether lithium- or nickel-based.

This is an evident need for high-temperature sodium-beta technologies. Electric-vehicle applications place particularly high demands on the technology required to regulate and control the temperature within the battery due to space and cost constraints. This hardware is commonly known as the thermal management system (TMS). To maintain the technology's high efficiency, the TMS must mitigate heat loss from the battery under normal operating conditions and idle periods while allowing sustained high-power discharge periods without reaching unacceptably high temperatures or creating unfavorable temperature differentials within the battery. The TMS in a sodium/sulfur battery typically consists of the following elements to meet these technical requirements: [17].

- A thermally insulated battery enclosure
- An active or passive cooling system
- A method of distributing heat within the battery enclosure
- Heaters to warm the battery to operating temperature and to maintain it at operating temperature during long idle periods, if necessary

The extent and kind of thermal insulation employed in the thermal shell (e.g., conventional, evacuated, or variable conductance) are determined by the intended application. The physical dimensions of the battery, the power-to-energy ratio, the duty cycle, and the duration of any "idle" intervals are all important application needs to consider. Utility-energy-storage applications, for example, are not as limited in terms of weight and volume as those associated with electric vehicles. As a result, utility batteries can use traditional composite material.

Batteries developed. To reduce thickness and weight, batteries designed for electric vehicles used evacuated insulation. Both ABB (ABB Ltd.) and ABB (ABB Ltd. is a Swedish-Swiss multinational enterprise headquartered in Zürich, Switzerland. In 1988, Sweden's Allmänna Svenska …) and SPL (Swiss Propulsion Laboratory) employed double-walled, evacuated thermal enclosures with either fiber board or microporous insulation to develop the firm. To maintain the required amounts of vacuum, chemical gettering agents were introduced within the cage. This was the only design that properly minimized heat loss while delivering the required load-bearing capability [55].

The need for a cooling system is determined by:

- The quantity of heat generated during sustained high-rate discharge,
- The thermal capacitance of the battery, and
- The upper temperature limit of the battery.

Direct and indirect heat exchange with the air, indirect liquid-based heat exchange, heat pipes, thermal shunts, latent heat storage, evaporative cooling, and variable conductance insulation systems are among the ways that have been utilized or are being considered. ABB used an active cooling technology in their EV battery series. The cells were placed on a flat-plate liquid heat exchanger, which transmitted surplus heat to a heat sink made of oil/air or oil/water. The thermal capacitance of the battery could accommodate the temperature rise suffered by the battery if the electrical resistance of the cells and their interconnections is suitably low. Although active cooling was included in later versions, this was the planned approach for SPL.

Battery safety. To ensure that the cell and battery designs were safe under both normal and accident settings, the strategy concentrated on preventing electrical short-circuiting and minimizing exposure to and interaction with any reactive materials. In the case of incidents involving mobile applications, the vehicle industry and different governing organizations have required a strict requirement: the existence of the battery cannot enhance the hazard (contribute to the severity or consequence). The following specific safety considerations were addressed in various sodium/sulfur cell and battery designs:

- Selecting proper construction materials (such as low reactivity and high melting point)
- Limiting the availability and flow of sodium to an electrolyte or seal failure site, thus reducing the potential for large thermal excursions (>100°C) in cells, which can cause damaging cell breaches
- Using components that minimize the effect of cell failure on adjacent cells (e.g., porous or sand filler between cells in stationary batteries)
- Including thermal and electrical fuses to eliminate the potential for catastrophic short circuiting
- Providing protection against the environmental hazards associated with each application; in the case of the sodium/sulfur technology, the thermal enclosure is effective against many of these factors
- Including functional redundancy to ensure that improbable or overlooked phenomena do not result in an unwanted consequence

Reclamation. All batteries, even sodium/sulfur, will eventually approach their end of life and must be recovered or disposed of in some way. Because of its corrosivity, sodium polysulfide, like sodium and sulfur, is classed as a hazardous material. Chromium or chromium compounds are still employed as confinement corrosion protection coatings. As a result, all sodium/sulfur batteries used in terrestrial applications must be sent to a processing facility for recycling, reclamation, or disposal.

Thermal Control Increasing the energy density of EV batteries or improving the energy consumption of the electric powertrain as well as the vehicle's auxiliary components has received a lot of attention in recent years. Heating and cooling the cabin of BEVs is a problem that many people have been working on for years.

Thermal management has the ability to significantly improve fuel economy and reduce emissions in HEVs and BEVs. Hence, battery heat control is critical for optimal functioning in all climates. Optimization of vehicle thermal management has become a significant commercial segment in recent years.

Thermal Management effects (compare **Figure 5**):

- fuel/energy consumption (e.g., friction losses, combustion process, recovery of energy losses, efficiency),

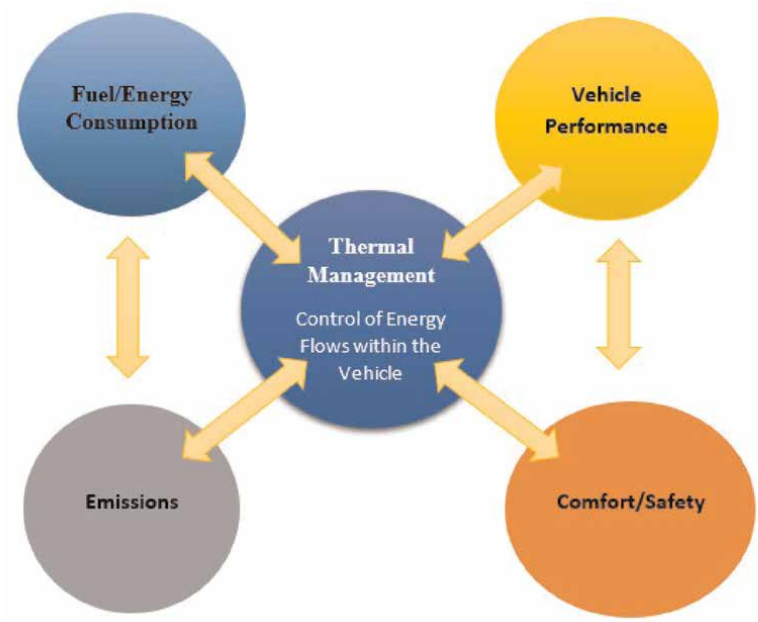

Figure 5.
Thermal management and its impact [56].

- emissions (e.g., cat-light-off, EGR/SCR strategies) (catalytic convertor off) (silicon controlled rectifier)
- engine performance (e.g., effective cooling, engine efficiency, reduction of friction losses),
- comfort and safety (e.g., cabin conditioning, windscreen defrosting)

In comparison with a traditional vehicle, an HEV has additional heat sources such as e-motors, power electronics, batteries, and so on that must be kept within a specified temperature range in order to create high efficiency and protect components from overheating. A complete simulation model is required for hybrid systems due to the interplay between several subsystems such as the combustion engine, e-motor/generator, energy storage, and drive train.

Figure 6 depicts several drive train arrangements, such as ICE, micro HEV, mild HEV, full HEV, and PHEV/BEV, and their requirements in terms of new vehicle constraints, new thermal needs, and new systems and components. This illustration highlights the necessity for additional heat monitoring systems.

Many companies and R&D institutions have recognized the need for thermal management solutions in recent years. As a result, two Task 17 workshops concentrating on Thermal Management Systems (TMS) and HEV concepts were organized in Chicago (2013) and Vienna (2014).

Organizations and research institutes such as ANL, AIT, Delphi, Fraunhofer, qpunkt, and Valeo presented their findings and thoughts. This section includes a list of the most commonly imported ones.

An overview of the impact of ambient temperature and driving behavior on energy usage in HEVs, PHEVs, and BEVs.

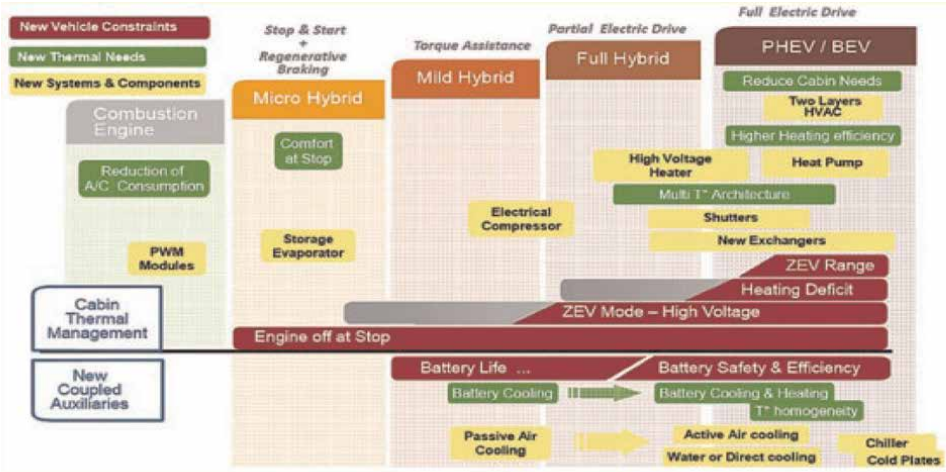

Figure 6.
HEV/EV thermal management activities [56].

The ANL emphasized the impact of ambient temperature and driving patterns on energy usage. As a result, they compared a BEV (Nissan Leaf 2012), a HEV (Toyota Prius 2010), and a traditional vehicle (Ford Focus 2012).

A comprehensive thermal study was conducted, with seven vehicles ranging from conventional vehicles (CV) (gas and diesel), HEVs (mild to full), a PHEV, and a BEV tested on cold start UDDS, hot start UDDS, HWFET, and US06 at ambient temperatures of 7°C (20°F), 22°C (72°F), and 35°C (95°F) with 850 W/m 2 of sun emulation (compare **Figure 7**). The findings of this investigation show the following facts:

Conventional Vehicles		Hybrid electric vehicles (HEV)			Plug-in Vehicles (PHEV, BEV)	
12 Focus	09 Jetta TDI	09 Insight	11 Sonata HEV	10 Prius	12Volt	12 Leaf
Conventional 2.OLDI6spd DCT Gasoline	Conventional 2.OLDI6spd DCT Diesel	Mild HEV 1.3L CVT 10kw motor	Pre-trans HEV 2.4L 6 spd auto 30kw motor	Full HEV 1.8LDI power split 60kw prim motor	PHEV EREV 1.4LDI 111kw prim motor	8EV single gear 80kw motor
Climate control: Mechanical	Climate control: Mechanical	Climate control: Automatic	Climate control: Automatic	Climate control: Automatic	Climate control: Automatic	Climate control: Automatic
Air conditioning: mechanical	Air conditioning: mechanical	Air conditioning: mechanical	Air conditioning: mechanical	Air conditioning: HV Electrical	Air conditioning: HV Electrical	Air conditioning: HV Electrical
Heater: Engine waste heat	Heater: Engine waste heat	Heater: Engine waste heat	Heater: Engine waste heat	Heater: Engine waste heat Exhaust heat redistribution	Heater: Engine waste heat HV electrical	Heater: Engine HV electrical
Battery thermal: N/A	Battery thermal: N/A	Battery thermal: forced air from cabin	Battery thermal: forced air from cabin	Battery thermal: forced air from cabin	Battery thermal: actively heated or cooled through coolant	Battery thermal: internal combustion but no active external cooling

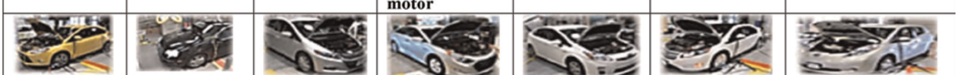

Figure 7.
Wide technology spectrum of research vehicle [56].

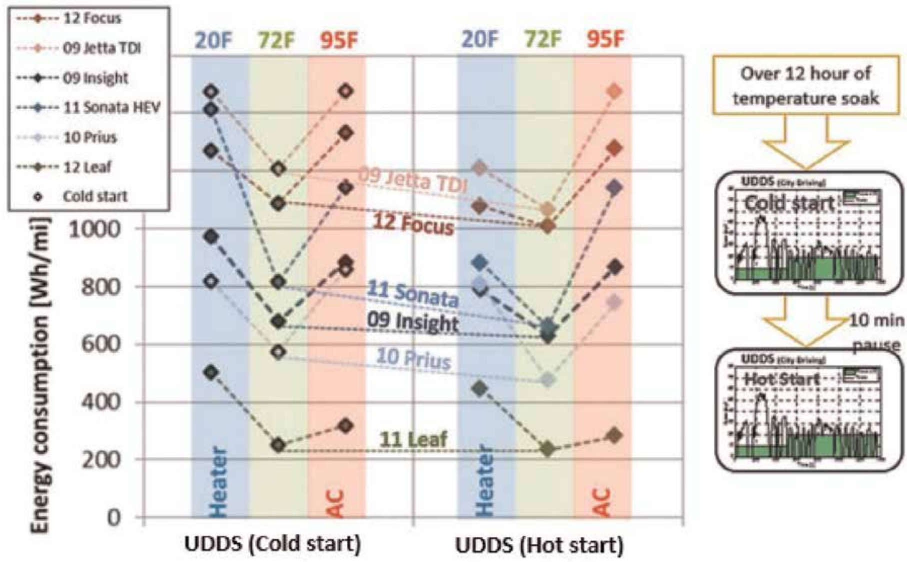

Figure 8.
UDDS energy consumption for cold and hot start [56].

- −7°C (20°F) cold start has the largest cold start penalty due to high powertrain losses and frictions. Once a powertrain reached operating temperatures, the energy consumption is close to the 22°C (72°F) results again (see **Figure 8**),

- 35°C (95°F) environment requires a constant A/C compressor load which impacts the energy consumption across all vehicle types on hot and cold starts,

- worst-case scenarios for the different vehicle types:

- CV: 35°C (95°F) environment due to 4–5 kW of extra air conditioning load,

- HEV: both −7°C (20°F) and 35°C (95°F) have a large range of increase due to a change in hybrid operation (fuel and electricity trade off),

- PHEV:−7°C (20°F) where the PHEV uses both the engine and the electric heater to warm up the powertrain and the cabin,

- BEV: −7°C (20°F) due to 4 kW of heater which can double the energy consumption on a UDDS,

- Battery system resistance doubles from 35°C (95°F) to −7°C (20°F) for all battery chemistries in the study

Looking more closely at the findings, as shown in **Figure 9**, utilizing the heater in an electric car can quadruple the energy use in city driving. **Figure 10** depicts how driving at faster speeds and more aggressively increases the energy consumption of an electric vehicle.

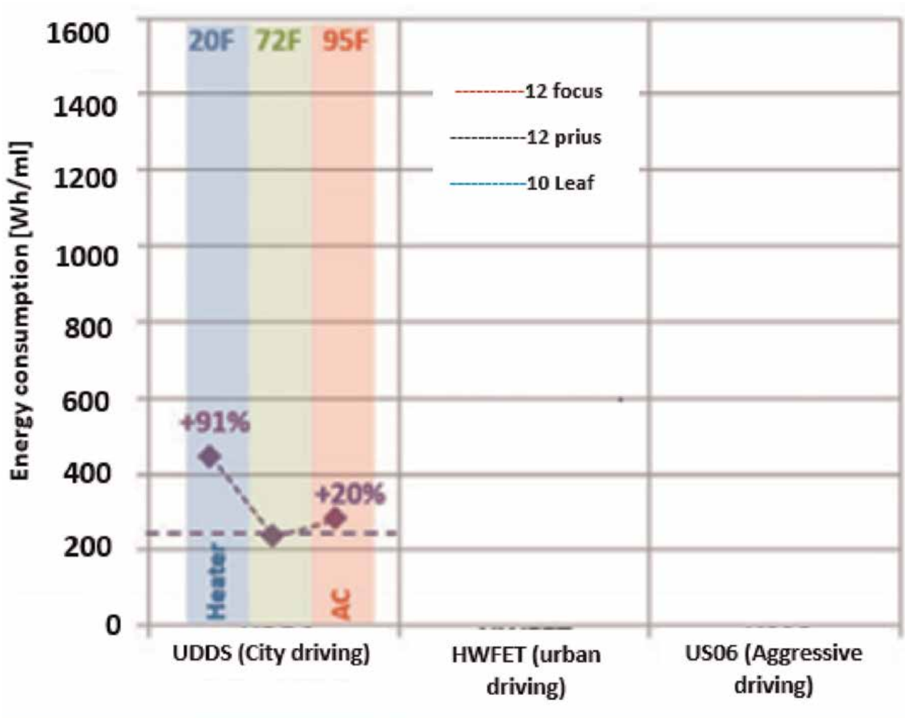

Figure 9.
Using the heater in an electric car may double the energy consumption in city type driving [56].

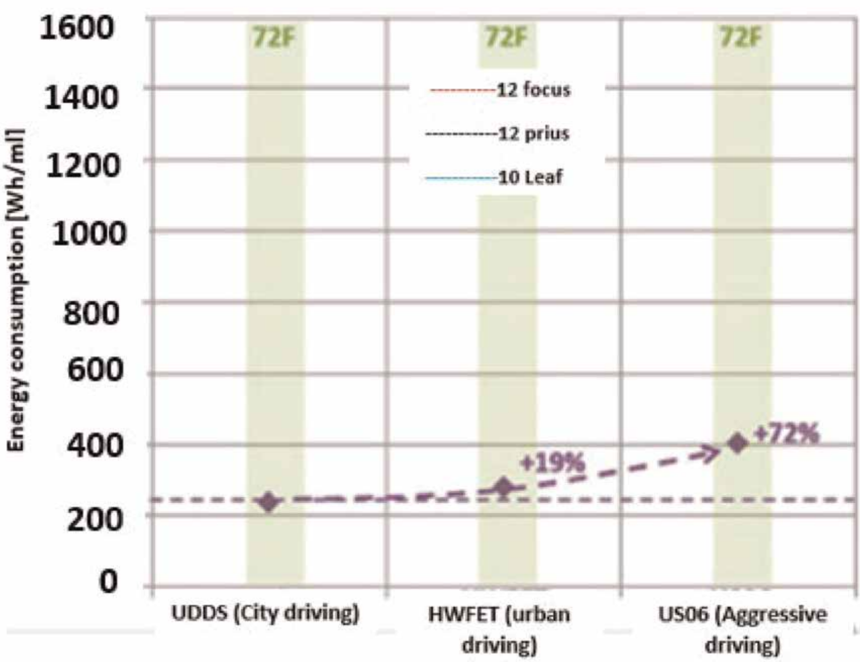

Figure 10.
Driving at higher speeds and aggressively will increase the energy consumption in an electric car [56].

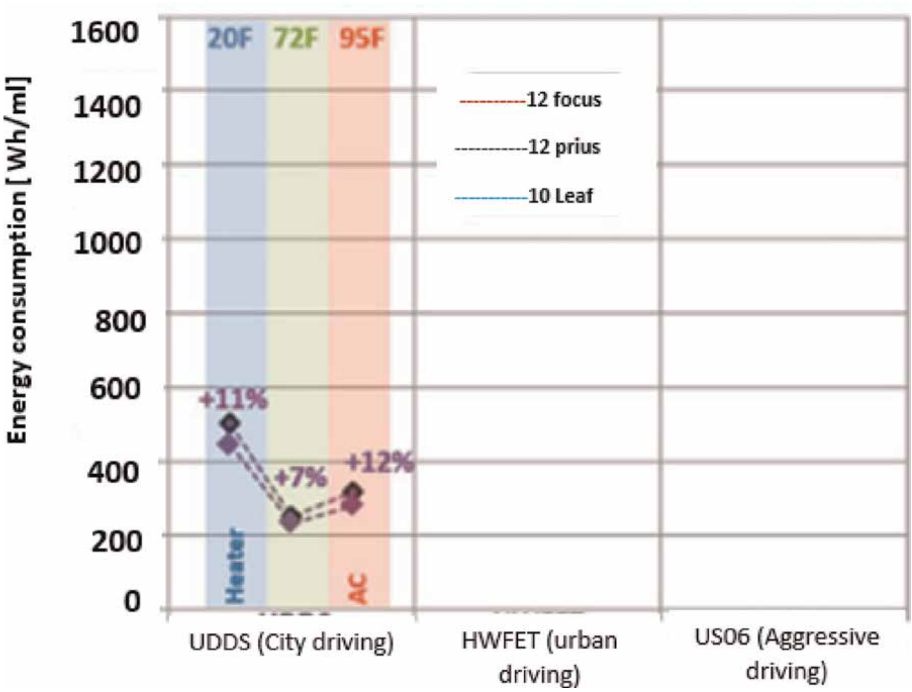

Figure 11.
Cold start energy consumption is larger than the hot start energy consumption [56].

When the cold start energy function and the hot start energy consumption are compared, it is clear that the cold start energy consumption is more than the hot start one (see **Figure 11**).

Figures 12 and **13** illustrate the highest increases in energy consumption for a BEV and a conventional vehicle. Hence, the highest increase in energy usage for an EV

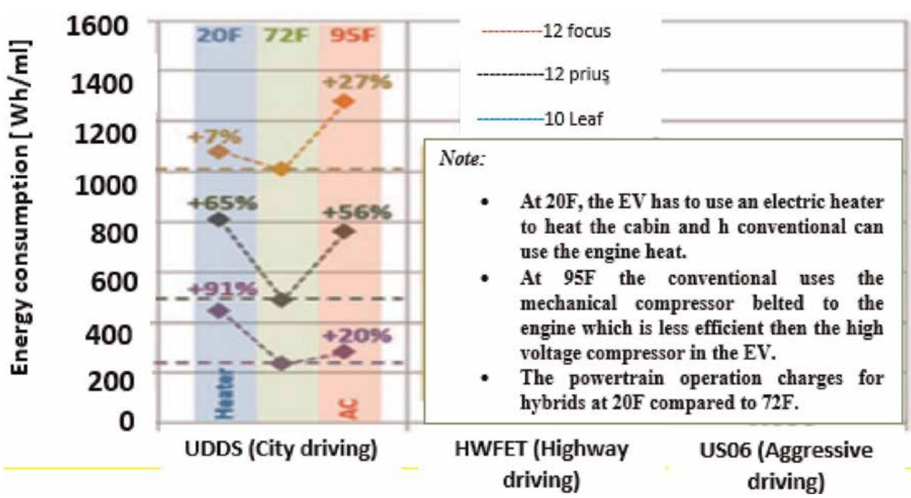

Figure 12.
Larger energy consumption increase for an EV occurs at -7°C (20°F) and for a CV at 35°C (95°F) [56].

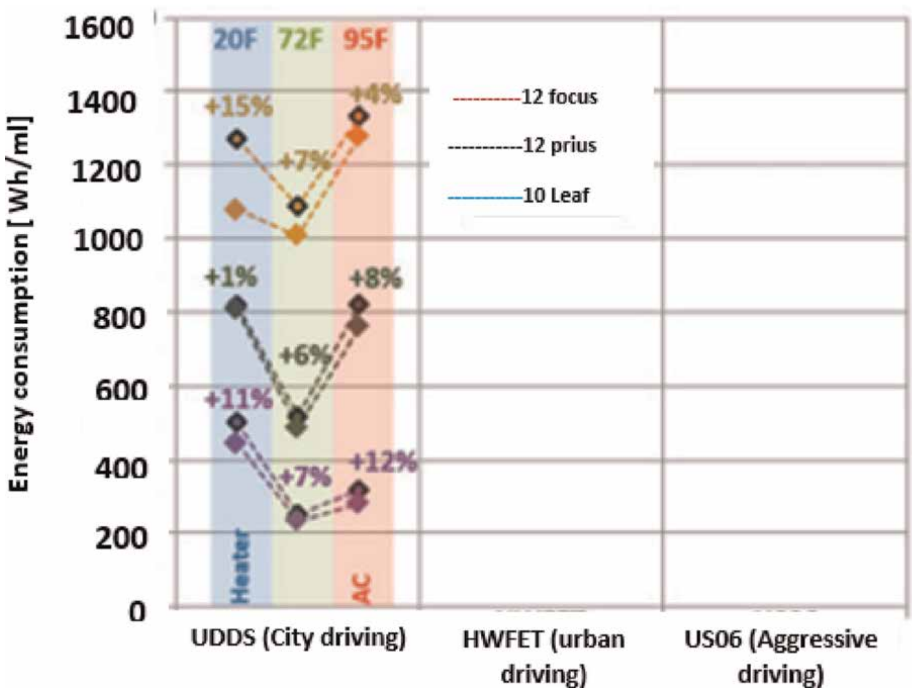

Figure 13.
A conventional vehicle has the largest absolute energy consumption penalty on a cold start [56].

happens at 7°C (20°F) and for a conventional vehicle has the largest absolute energy consumption penalty on a cold start at 35°C (95°F), respectively.

Figure 14 shows that, in general, higher speeds and accelerations result in higher energy consumption, with the exception of the conventional due to low efficiency in the city. Journal of Automotive Engineering has more information on this subject.

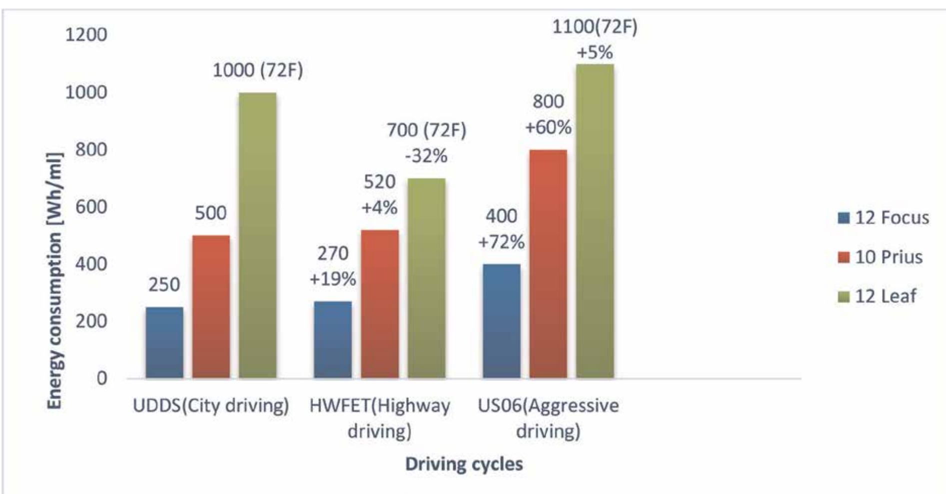

Figure 14.
Generally increased speeds and accelerations translate to higher energy consumption except for the CV due to low efficiency in the city [56].

Driving at higher speeds and more aggressively will increase an EV's energy usage. Cold start energy consumption exceeds hot start energy consumption. The greatest increase in energy usage happens for an EV at 7°C (20°F) and for a conventional at 35°C (95°F). For a cold start, a CV has the highest absolute energy usage penalty. Except for the typical because to low efficiency in the city, increased speeds and accelerations often translate to higher energy consumption.

5. Conclusion

HEVs are becoming more affordable and accessible than ever because of the likelihood of improved fuel economy, vehicle performances, and toward alleviating environmental concern.

To meet the energy demands of different HEV configurations, several power management strategies have been proposed in literature. This chapter presents a comprehensive review of relevant literatures pertaining to modeling and control of parallel hybrid electric vehicles. HEV control strategies were reviewed at depth on two main tiers: HEV offline and online control strategies. This in-depth analysis focuses on the control structure of the techniques under consideration, as well as their novelty and contributions to the achievement of a variety of optimization goals, such as reduced fuel consumption and emissions, charge sustenance, braking energy regeneration optimization, and improved vehicle drivability. Exploitable research gaps in rule-based control methods, dynamic programming, the equivalent consumption minimization strategy (ECMS), and model predictive control (MPC) strategies have all been discovered as part of this study.

For the case of HEV energy management and control, this complete evaluation is vital and necessary for researchers to quickly identify research needs for future research work.

HEV energy output can be managed and controlled by taking into account a variety of factors. Different control systems result in varying levels of efficiency, production, and emission control, but choosing the best and most dependable one is critical.

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Chapter 5

Inductive Power Transfer: Past, Current, and Future Research

Emanuel G. Marques, André Manuel dos Santos Mendes, Marina Mendes Sargento Domingues Perdigão and Valter S. Costa

Abstract

Electric vehicle (EV) technology has proven to be a propulsion technology of the future but urgently needs to address challenges such as lower-priced, reasonably sized EV for higher market penetration, higher life cycle efficiency, and increased power density. Range extension, in particular, in urban scenarios is critical. Inductive power transfer (IPT) technology solves simultaneously the electric hazard risks of conventional power cord battery chargers, but specially EV limited autonomy and related anxiety and even security. In this context, this chapter presents the past, current, and future research areas of IPT systems. A review of the main resonant compensation networks and prominent geometries of magnetic couplers is presented. Then, future research areas namely dynamic IPT and in-wheel IPT solutions are introduced along with their main challenges.

Keywords: wireless power transfer, inductive power transfer, magnetic coupler, electric vehicle, IPT systems development

1. Introduction

Electric vehicles (EVs) have clear advantages over internal combustion engine (ICE) vehicles like reduced noise, full torque capability of the motor from a standstill position, and smaller carbon footprint. However, they are still limited in range by the batteries storage capacity. The current state of EV lithium-ion battery technology has a specific energy (energy per unit mass) that placed them behind that of gasoline by a factor of almost 100. Manufacturers workaround this limitation using larger battery packs, a costlier and bulkier solution to a limitation that follows EVs since their first appearance. In addition, lithium-ion batteries can take up to several hours to charge which will undoubtedly affect the driving habits of the users. **Table 1** identifies some EVs and EV truck models and their corresponding battery storage capacities. On average, an EV requires 185 Wh per kilometer, whereas EV trucks requires 1250 Wh to travel the same distance. These values together with the battery capacity define the EVs range.

All commercial available hybrid and battery EV models have in-built sockets that can charge the battery pack from a few kilowatts, in domestic chargers, up to 250 kW

Model	Battery capacity	Range	Energy consumption
	(kWh)	(km)	(kWh/km)
BMW i3	33	200	0.165
VW Golf-e	35.8	190	0.188
Nissan Leak	39.5	240	0.165
Tesla Model 3	55	310	0.177
Chevy Bolt	65	417	0.156
Ford Transit	68	315	0.216
Toyota bZ4X	71.4	380	0.188
Cupra Born	77	450	0.171
Audi e-tron	95	360	0.264
Ford Mustang	99	539	0.184
Tesla Model S	100	510	0.196
Lucid Air	105	630	0.167
Mercedes EQS	107.8	640	0.168
Trucks			
Freightliner eM2	315	370	0.851
eCascadia	475	402	1.18
Tesla Semi	500	482	0.829
Volvo VNR	565	443	1.275
Nikola Tre	753	563	1.337

Table 1.
Battery specifications of different BEVs.

Operating level	Input voltage	Maximum current	Output power	Charging time
	(V)	(A)	(kW)	(h)
AC Level 1	120	12–16	1.08–19	6–24
AC Level 2	208–240	16–80	3.3–19.2	1–3
AC Level 3	208/480/600	150–400	≥19.2	0.5–1.5
DC Level 1	200–450	80	36	0.5–1.3
DC Level 2	200–450	200	90	0.3–1.3
DC Level 3	200–600	400	240	0.25–1

Table 2.
Power levels of EV chargers.

in supercharging stations. The vehicles can be charged from AC or DC power supply with different voltage and current values. According to Society of Automotive Engineers (SAE) standards, AC chargers can be divided into three different power levels, as depicted in **Table 2**. The AC levels 1 and 2 are intended for domestic use. The AC level 3 is directly supplied from the grid, and they are usually found in commercial locations. The DC charging systems require a dedicated infrastructure, and they are usually mounted at parking area or public charging stations. DC chargers regulate the voltage ratings according to the battery packs. Moreover, they bypass the vehicle on-board controller and charger the batteries at a higher current rate than AC chargers. The supercharger of Tesla is one example where this strategy is adopted, allowing a maximum charging power of 250 kW.

The high power rating of level 3 AC/DC chargers require large power demands from the grid simultaneously. Current grid infrastructures are not prepared for a wide-scale installation of theses chargers. As a consequence, the increase of EVs will create longer queues in existing charging areas. Additionally, the need of human intervention in the charging process increases the risk of shock hazard and electrocution. New wireless charging technologies are then being studied as viable replacements to conductive chargers.

Wireless power transfer (WPT) technology enables the energy transfer between two systems without any contact. The concept dates from the late nineteenth century where Prof. Heinrich Hertz demonstrated for the first-time electromagnetic wave propagation in free space using a spark to generate high-frequency (HF) power and to detect it in the receiving end. Nikola Tesla, in 1899, conducted a series of experiments in Colorado Springs where he devised the best approach for WPT. During its stay in Colorado Springs, Tesla reported power transfer capabilities over distances superior to 18 m between the transmitter and receiver coils. Tesla accomplishments in Colorado Springs mark the beginning of WPT technology.

WPT systems can be classified as far-field and near-field technologies [1, 2]. The first group includes radio frequency/microwave techniques that radiate energy isotropically or toward some direction through beam-forming. However, the high-frequency spectrum (300 MHz to 300 GHz) makes them undesired for EVs application due to the effects of electric fields in the human body. The near-field group includes the techniques that use variable magnetic or electric fields to accomplish power transfer between two coupled sides. Electric field coupling, also referred as capacitive power transfer, uses a pair of plates to form a capacitor with air as a medium. In this way, the electric field created between the two plates enables the energy transfer between both plates. One advantage of electric field coupling is the possibility of energy transfer through metallic materials, since a capacitor is formed between each conductor plate and the metallic surface. Moreover, they are less sensitive to lateral displacements as the electric field between the plates "bends" with the displacement value. However, the low capacitance between two plates at high air gap values limits the power transfer capabilities to a few kilowatts.

Magnetic field coupling techniques use a varying magnetic field to achieve power transfer, and it includes inductive coupling and magnetic resonance coupling (MRC) techniques. The second technique is based on evanescent-wave coupling that accomplishes energy transfer between two resonant coils through varying or oscillating magnetic fields. The two resonant coils are strongly coupled and operate at the same resonant frequency; thus high-power throughput is achieved with small leakage to nonresonant externalities. Several studies demonstrated the capabilities of power transfer over larger distances while charging multiple devices using MRC technique [3]. However, the high operating frequency (range of MHz) and the complex tuning of both sides are unsuitable for EVs charging applications.

Inductive coupling, also referred as inductive power transfer (IPT) system, transfers energy between two coupled coils. The transmitter coil generates a varying magnetic field which induces a voltage across the receiver coil, according to Faraday's law. To boost the quality factors of the coils at low operating frequencies (from 10 kHz to 250 kHz), compensation capacitors are added to the circuit. IPT systems gain popularity and its applicability in EVs are being investigated by the scientific community since the early twenty-first century. Since then, a lot of works present efficiency values as high as 97% and in line to conductive chargers [1, 4].

This chapter reviews IPT technology and its applicability to EVs. The use of electric propulsion systems in vehicles has formulated its construction methods and opened new opportunities. The shift of the powertrain into the wheels, the inclusion autonomous guiding systems is changing the dynamic of vehicles. IPT technology also plays an important role in the massification of EVs. Therefore, this chapters discusses the main research fields of IPT systems including past trends of research. Then, recent developments are reviewed along with future research areas.

2. IPT system and main development areas

This section explores the main constituents of IPT systems and main development areas. These areas are related to the electrical configuration of the compensation networks, power converters topology, and design optimization of the magnetic coupling structure.

2.1 Basic IPT system configuration

An IPT system, in its simplest form, uses two magnetically coupled coils, also known as power pads, to transfer energy between the off-board and on-board sides, as illustrated in **Figure 1**. The off-board side usually comprises a high-frequency power supply, a resonant compensation network, and the transmitter (Trm) power pad of a magnetic coupler (MC). The on-board side includes the receiver (Rec) power pad of the MC, a resonant compensation network, the on-board converter, and battery pack. An intrinsic characteristic of EV IPT systems is movement of Rec pad in relation to

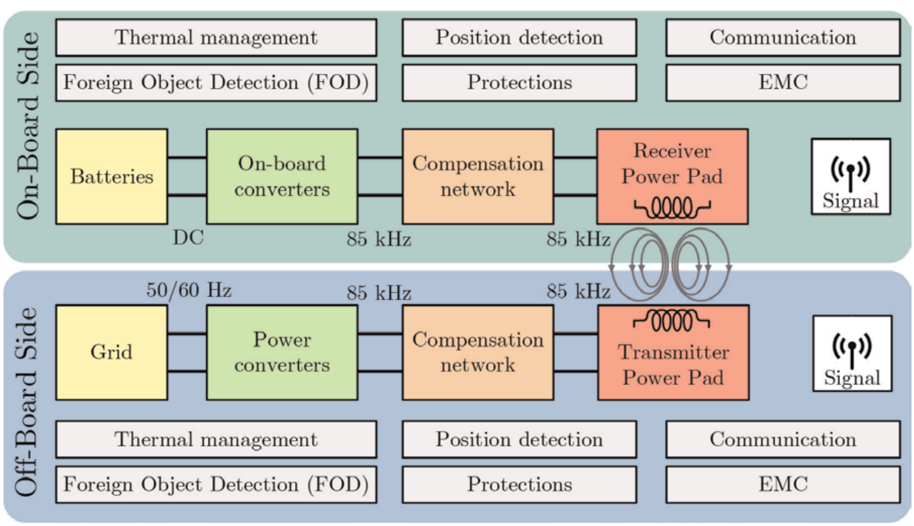

Figure 1.
Overview of a typical IPT system with its main components.

Trm pad due to the vehicle's movement. As a consequence, the coupling factor has a high variability which directly impacts the system power transfer capabilities. High operating frequencies together with resonant compensation networks are used to increase power transfer capabilities minimizing, at the same time, the volt-ampere rating and commutation losses of the power supply. The free-movement of the Rec pad together with the high operating frequency creates new challenges like vehicle position detection, stray magnetic fields compliance, and foreign object detection between the Trm and Rec pads. **Figure 1** summarizes the main concerns in both off-board and on-board sides.

IPT systems are divided into static (SIPT) and dynamic charging (DIPT) modes. In the first mode, the vehicle is charger in a fixed position whereas in second mode, the charging process occurs with the vehicle moving along the roadway. Nevertheless, four main research areas are found for IPT systems: magnetic couplers, resonant configurations, circuit analysis, and controllers and control. **Figure 2** illustrates the main research areas and subcategories of IPT systems. The first advancements in EV IPT occurred for static IPT mode. The energy transfer from a still position eliminates the variable coupling effect during the charging process and simplifies the analysis. Electrical circuit analysis for classical IPT systems is already well defined in the literature [5]. Controllers and control research areas have also well-established solutions. On the other hand, the study of new resonant network configurations and MC geometries were object of research over the last decades with new findings being reported in the literature on a weekly basis. The following subsections detail the main findings in resonant configurations and MC research areas.

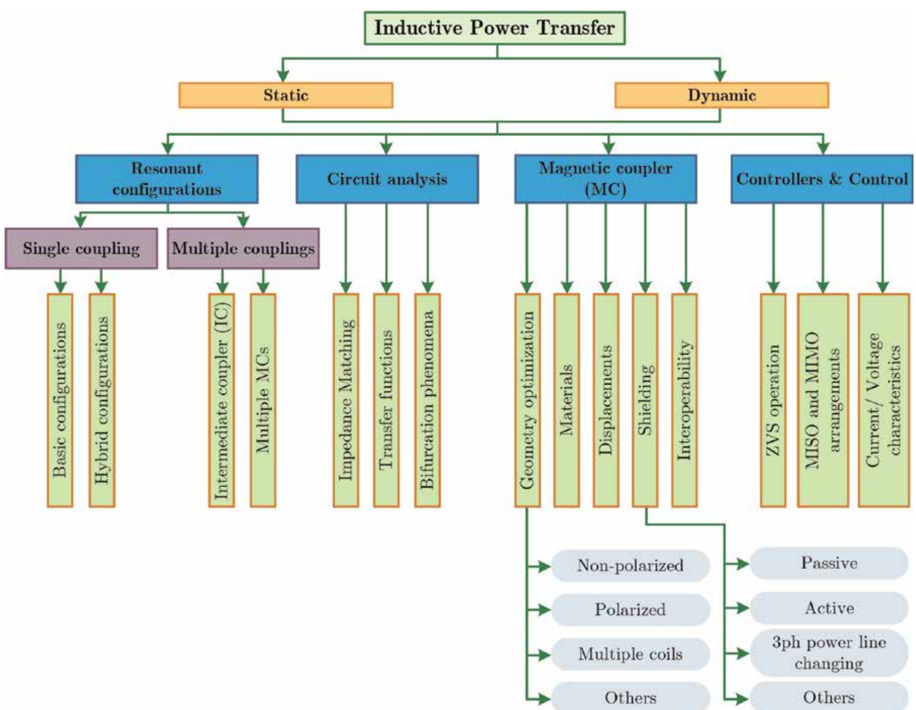

Figure 2.
Main research areas of IPT systems.

2.2 Research areas

2.2.1 Resonant configurations

Early single-coupling IPT systems had limited power transfer capabilities caused by the poor coupling between the transmitter and receiver power pads of the MC coupler [1]. The simplest way to compensate the self-inductance of the power pad coils is to place a capacitor in each side, either in series or parallel. Four classical resonant configurations can then be derived: Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), and Parallel-Parallel (PP), as illustrated in **Figure 3**. The positioning of the capacitor changes the intrinsic characteristics of the circuit and their response to coupling, load, and frequency variations [6, 7]. The SS configuration offers output current independence of load and resonant frequency, and it is preferable for high-power applications. PS and PP configurations, on the other hand, limit the input current in the event of total absence of the vehicle, and they are ideal for dynamic applications [8, 9].

Hybrid configurations use multiple reactive components to form high-order resonant configurations like the LCL-LCL, LCL-S, S-SP, and SP-S, as depicted in **Figure 3**. These new compensation networks offer power transfer capabilities over wider coupling range, load-independent zero-voltage switching (ZVS), zero-phase angle (ZPA), and voltage/current source characteristics. One of the first hybrid configurations used in IPT systems was the LCL configuration [10–12]. When applied in the off-board side, the LCL configuration offers load-independent current source characteristics in the second L, if both values of L are the same [10]. Therefore, this configuration is often used in dynamic applications, since the vehicle's absence does not compromise the integrity of the power supply [4]. The LCL configuration is also employed in the on-board side to provide a smooth power transition between fully-on and fully-off [13] or to keep an unitary power factor in the transmitter side [14]. The S-SP configuration offers mutual coupling and load-independent voltage gain. In addition, it can realize good output voltage stability and low circulating losses under the condition of wide parameters variations [15]. The SP/S configuration was proposed in [16]. This configuration combines the characteristics of SS and PS configurations and allows higher displacement tolerances. The studies [17–19] evaluate high-order

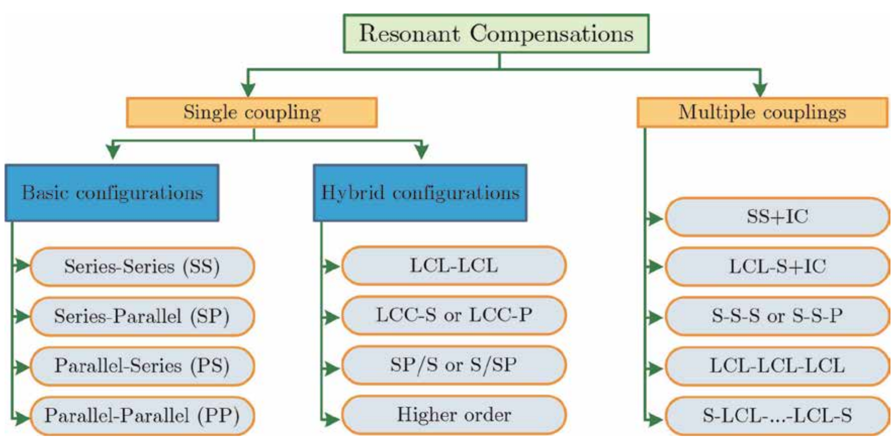

Figure 3.
Classification of resonant configurations in IPT systems.

configurations with different L and C arrangements in terms of soft-switching, system efficiency, and zero-phase angle. The S-CLC compensation network was proposed in [20]. The proposed configuration offers easier achievement of ZPA and ZVS. In addition, it offers CC and CV modes and simplifies the control circuit design.

Both classical and hybrid configurations have limited power transfer capabilities in charging scenarios where the vehicle has large ground clearances and is lateral displaced from the transmitted power pad. The low mutual coupling value requires high current values on the off-board side and as a consequence, higher magnetic fields which may lead to adverse problems in the human body. Intermediate coil (IC) systems, also known as multi-coil resonators or relay coil IPT systems, place resonators between the transmitter and receiver pads to enhance the magnetic link [21–24]. The resonators are formed by a magnetic coupled coil and a capacitor, usually tuned at a higher frequency than the operating frequency. Several studies show that ICs offer better efficiency values, less component stress, and better flux leakage control [25, 26]. The mid-air positioning of an IC is, however, incompatible with an EV IPT charger. Therefore, they are placed in proximity or even in a coplanar fashion with the Trm coil. In this configuration, ICs are often used as a replacement to the ferromagnetic core of the Trm pad, making them suitable for dynamic applications. The inclusion of IC with a classic or hybrid resonant configuration modifies its intrinsic characteristics altogether. As an example, the SS configuration with an IC exhibits both load-independent voltage and current source characteristics in different operating frequencies, while the Trm current is shifted to the intermediate circuit, thus reducing the commutation losses. Recent works use several ICs to increase robustness of EV IPT systems against the unavoidable lateral displacements [27]. This means the total number of admissible configurations increases drastically each time a new IC or a variant of a hybrid resonant configuration is proposed, meaning that multiple resonant configurations can satisfy a specific EV IPT application. Therefore, the selection of the most adequate resonant configuration can be decided in the smallest detail like voltage stress across the capacitors or even the configuration with the minimum number of components.

The use of multiple couplers connected with one another is also investigated for delivering power to multiple loads or for dynamic applications. **Figure 4** exemplifies a multicoupler configuration. The authors in [28] use a LCL-LCL-LCL configuration as a contactless interface for multiple Trms and Rec sides. The use of a parallel compensation in the intermediate circuit minimizes the VAr requirements. A n-coupler S-LCL- … -LCL-S configuration is investigated in [29] to power multiple loads. The proposed configuration ensures constant load current values regardless of load variations. The double coupling S-S-P and S-S-S configurations are analyzed in [30]. The S-S-S exhibits load-independent CV mode if all natural resonant frequencies match the switching frequency. On the other hand, CC mode is achieved in the same conditions for the S-S-P configuration. In addition, both configurations exhibit ZPA during CC or CV modes. Moreover, S-S-X double coupling systems limit the Trm current in the absence of the receiver, making them ideal for dynamic IPT applications.

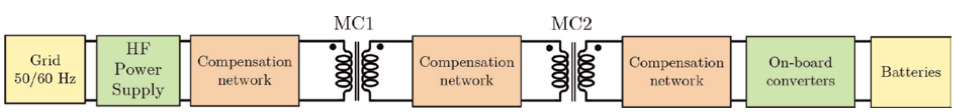

Figure 4.
Equivalent circuit of a double coupling system.

2.2.2 Magnetic couplers

Magnetic couplers (MCs) are considered the key element in IPT systems as they enable the energy transfer without physical contacts using a variable magnetic field. The MC resembles a conventional 50 Hz transformer with a Trm and Rec pads. A clear characteristic of IPT systems is the spatial freedom of the Rec pad toward the Trm pad due the vehicle's movement. The relative positioning of the Rec pad has a direct impact on the coupling factor, and it ranges between 0.05 and 0.3. The degrees of freedom that the receiver pad may be subject to are as follows:

- *Vertical Displacement*—corresponds to the ground clearance of the vehicle.
- *Lateral displacement*—corresponds to the lateral distance between the transmitter and receiver pad center points.
- *Tilt*—corresponds to the inclination angle of the receiver pad.
- *Rotation*—corresponds to the rotational angle between the transmitter and receiver pads along the horizontal plane (only applicable to in-wheel IPT system).

Figure 5 illustrates the different degrees of freedom in different perspectives. The vertical displacement and tilt degrees of freedom depend on the vehicle's type (Sedan, SUV, etc) and, in normal operation, these values remain approximately constant. The lateral displacement and rotation degrees of freedom, on the other hand, depend on the drivers ability to park the vehicle or driving it in a straight line. The guideline SAEJ 2954 suggests that a minimum lateral tolerance of ±150 mm is sufficient for an average driver to drive/park the vehicle correctly. Extreme charging positions with large vertical and lateral displacements reduce the coupling factor of the MC and increase the leakage magnetic fields. Over the years, many researchers have address these issues by proposing new coil and core arrangements with better materials and shield techniques.

2.2.3 Transmitter coil: track versus pad

MCs commonly have a unitary size ratio between the Trm and Rec pads, especially in SIPT. DIPT systems, on the other hand, require longer charging areas and elongated

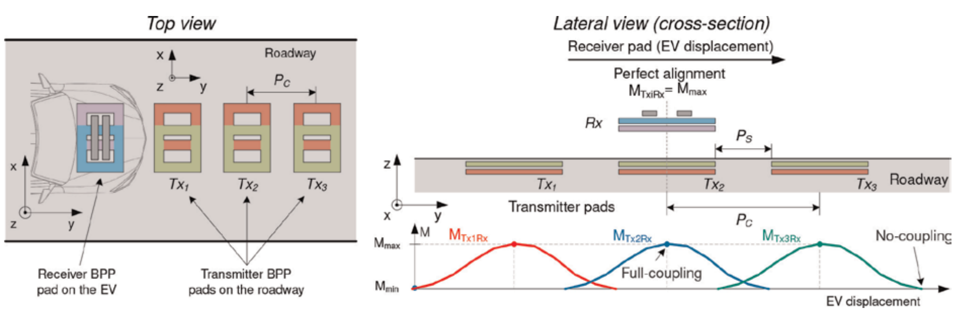

Figure 5.
DIPT system, top view (left side), and lateral cross-sectional view (right side).

tracks can be applied instead of a set of smaller Trm pads. The first option offers a continuous power transfer with constant coupling factor. The large inductance of the track, however, reduces the overall coupling factor and requires higher voltage levels to drive the necessary Trm current. Additionally, most power track systems prototypes operate with frequencies around 20 kHz instead of the 85 kHz recommended by the SAEJ 2954 standard. Furthermore, compliance with the ICNIRP guidelines to human exposure leakage magnetic field levels is only achieved at wider distances. The second option places several discrete transmitter pads along the roadway where the power transfer to the vehicle occurs, as illustrated in **Figure 5**. Since both approaches exhibit merits, there is still an open discussion on the appropriate solution for EV charging applications. However, the segmented solution is gaining terrain [4].

The impact of the EV movement in the mutual inductance (M_{12}) profile between the Trm and Rec pads in DIPT systems is visible in **Figure 5**. The bell-shaped pattern of M_{12} is caused by the lateral displacements between both pads. This behavior occurs for both static and dynamic IPT systems, and the difference resides in the range variation of M_{12}. For SIPT systems, M_{12} varies between a perfect aligned charging position, which corresponds to the peak of the bell shape curve, and a minimum M_{12} in the worst charging position in terms of vertical and lateral displacements. This minimum value also ensures that the rated characteristics of the overall system are not exceeded. Likewise, DIPT systems exhibit the same maximum value as static systems, but the minimum value is zero. This no-coupling charging position M_{12} = 0H) occurs right before the receiver pad enters the first transmitter pad (first point of the red curve) and soon after exiting the last transmitter (last point of the green curve). Therefore, DIPT controllers must cope with no-coupling scenarios and ensure that the limits for a safe operation are not exceeded.

2.2.4 Pad geometry

A power pad, in its basic form, is formed by a single coil, a ferromagnetic core and shield. Early designs used pot cores and U- and E-shaped cores but proved unfeasible for applications with large air gap and lateral displacements. The Auckland research group optimized the circular pad (CP) geometry back in 2009, by fracturing the ferromagnetic disk into several ferrite bars [31]. The construction simplicity makes it one of the most used MCs in current IPT systems. A limiting factor of CP is the total decoupling between the Trm and Rec pads when the lateral displacements exceeds the size of the CP by 40% or more and largers CPs are required to provide larger tolerances. To overcome this limitation, the same research group proposed several geometry alternatives with multiple coils including the solenoid pad (SP) in 2010 [32] and the double-D pad (DDP) and the bipolar pad (BPP) in 2011 [33, 34]. The aforementioned geometries are depicted in **Figure 6**. The SP corresponds to two solenoids connected electrically in series with a ferromagnetic core in the middle. This design exhibits high tolerance to both vertical and lateral displacements. Unfortunately, it produces unwanted magnetic fields in the back of the geometry and a shield is required to contain the stray magnetic fields. The DDP arose as a viable replacements to SP, by placing two D-shaped coils on top of a fragmented ferromagnetic core, as illustrated in **Figure 6**. The ferromagnetic core forwards the magnetic flux with little stray magnetic fields in the back of the pad. The DDP offers greater performance when compared with the CP in both vertical and lateral displacements with a smaller MC size. This geometry, however, has a poorer coupling pattern to displacements along the length of the DDP. To overcome this limitation the research group proposed

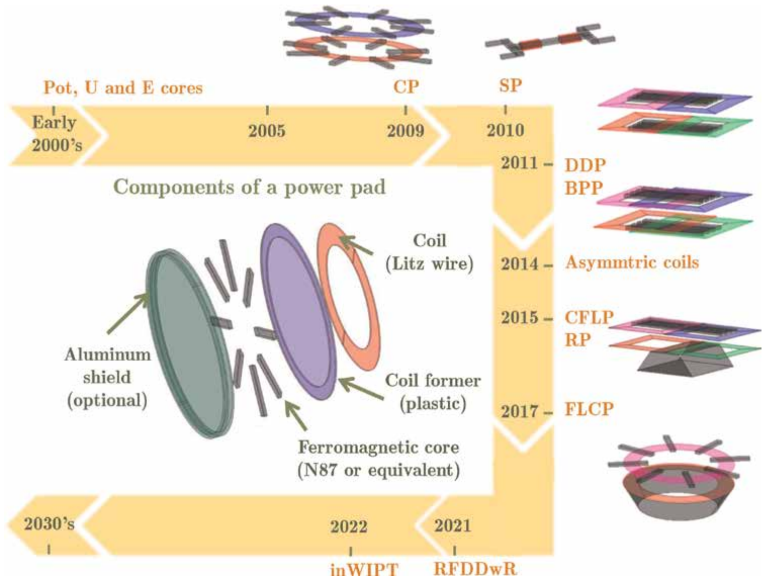

Figure 6.
Chronological evolution of MC geometries.

a 3rd coil, referred as quadrature coil (Q), and placed it in the Rec pad to improve the coupling. The Q coil is decoupled from the other two coils and captures the flux from the Trm pad in the event of lateral displacements. The BPP is formed by two slightly overlapped coils, decoupled from one another, and placed over a ferromagnetic core. The overlap coil design ensures the decrease of the induced power in one coil due to lateral displacement is compensated by the increase of the induced power in the other coil. This geometry has similar tolerance as the DDP + Q geometry using 30% less copper.

The Korea Advanced Institute of Technology (KAIST) introduces in 2014 the asymmetric coils geometry for SIPT systems. The geometry uses Trm and Rec pads with different size ratios to achieve large lateral displacement tolerances. The same group is also a reference on DIPT applications using elongated transmitter pads. The ultraslim S-type geometry, introduced in 2015, uses S-shape ferromagnetic cores along the roadway to channel the magnetic fields of an elongated wire. The solution allows a large lateral displacement of 300 mm with a compact Trm pad with the dimensions of 100x30x300 mm. In the same year, the research group from the Swiss Federal Institute of Technology (ETH) Zurich optimizes the rectangular pad (RP) geometry with a stripped ferromagnetic core. The optimized RP showed equivalent performance when compared with the DDP in terms vertical and lateral displacements for output powers up to 50 kW [35].

One major concern in DIPT systems is the cost of manufacturing the transmitter pads. The ferromagnetic core weights more than 50% in the total construction costs of the aforementioned geometries. The Auckland research group develops in 2015 a concrete ferrite-less pad (CFLP) geometry that uses a "pipe" coil instead of a ferromagnetic core to channel the flux in the backside of double-D coils [36]. The design offers reasonable coupling profiles and lateral displacement tolerances with vertical variations between 150 and 200 mm. Moreover, high currents can be tolerated in ferrite-less geometries, since there is no ferromagnetic material that can be saturated.

In 2017, the research group from University of Coimbra proposed a variant of the CP without the ferromagnetic core. The geometry, referred to as ferrite-less circular pad (FLCP), uses a cone-shaped coil to channel the magnetic flux in the backside of the Trm coil [37]. The coupling profile shows a reduction around 15% when compared with the CP in both vertical and lateral displacements. Another ferrite-less variant of circular geometries was presented in [38]. The new geometry, referred as circular non-ferrite pad (CNFP), uses a cancelation coil below the main circular coil to reduce the leakage flux around the geometry. The coils are wounded with one single wire in a series-opposing configuration that generates opposing magnetic fields. The turns ratio and height between the main and cancelation coils dictates effectiveness of the canceling field at a given lateral displacement. The coupling factors are lower than a CP but with reasonable values for dynamic operation.

Figure 6 summarizes the evolution of MCs since early 2000s. Most of the proposed discrete geometries appeared between 2010 and 2015. Since then, researchers have shift focus toward optimizing leakage magnetic stray fields using cancelation coils while avoiding entirely ferromagnetic cores [27, 39]. The advancements in IPT systems made in the last years paved the way to commercially available SIPT solutions. Their applicability ranges from simple parking lot IPT chargers for standard EVs to high-power (≈200 kW) solutions in transportation sector like city busses. Now, there are still many challenges to transit from SIPT into commercial DIPT systems.

3. Active and future research

3.1 Dynamic IPT systems

The movement of the vehicle creates additional challenges relatively to SIPT. Among them, the preferable Trm topology (elongated or segmented), vehicle positioning detection, road infrastructure, and communication system. **Figure 7** summarizes current and future developments regarding DIPT.

Early DIPT applications employed long-track coils, typically between 10 and 100 m long, allowing the simultaneous charging of multiple vehicles. Different magnetic core shapes were analyzed by KAIST researchers for long-track DIPT systems such as E, U, W, I, S, X-type (or cross-segmented) and, ultra-slim S-type. The last

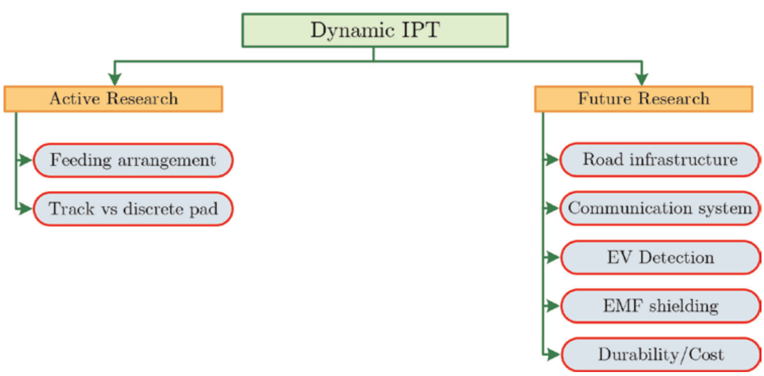

Figure 7.
Dynamic IPT current and future research.

two, ultra-slim S-type and X-type, present the best characteristics, low leakage EMF, and high efficiency with the ability for large air gap and lateral displacements.

Despite the core configuration, long-track coils still create unwanted leakage EMF, since the track is driven by a current during the vehicle's absence. Alternatively, the long-track coil can be divided into multiple subtracks, where each subtrack can be activated and deactivated by supplying them through a switch box fed by a HF inverter. Different types of switch boxes can be used including centralized switching, distributed switching, or auto-compensation switches.

Smaller segmented pads where the overall dimension of the transmitter is similar to the receiver, typically around 1 m, are an active focus of research. The design and optimization ferrite-less geometries in terms of power transfer capabilities and leakage flux control is ongoing. The use of reflection coils, also known as cancelation coils, are being employed in ferrite geometries like the DDP to form a ferrite-less double-D pad with reflective coil (FLDDwR) with controllable leakage flux [38]. Other geometries place an IC closer to the receiver pad to constrain the leakage flux lines in charging conditions with higher air gap values [27].

Besides the MC geometry, the pads disposition along the roadway and their feeding arrangement is also object of investigation. The simplest configuration uses a single high-frequency (HF) power supply to feed multiple Trms, either in series or parallel. Alternatively, lower HF power supplies can be employed to power each Trm individually. The configuration of **Figure 8a** extends the DC bus from the roadside cabinet to each individual converter and respective power pad. This configuration is simple to implement but arises safety concerns as it uses high-voltage and high-power rating DC lines. The configuration from

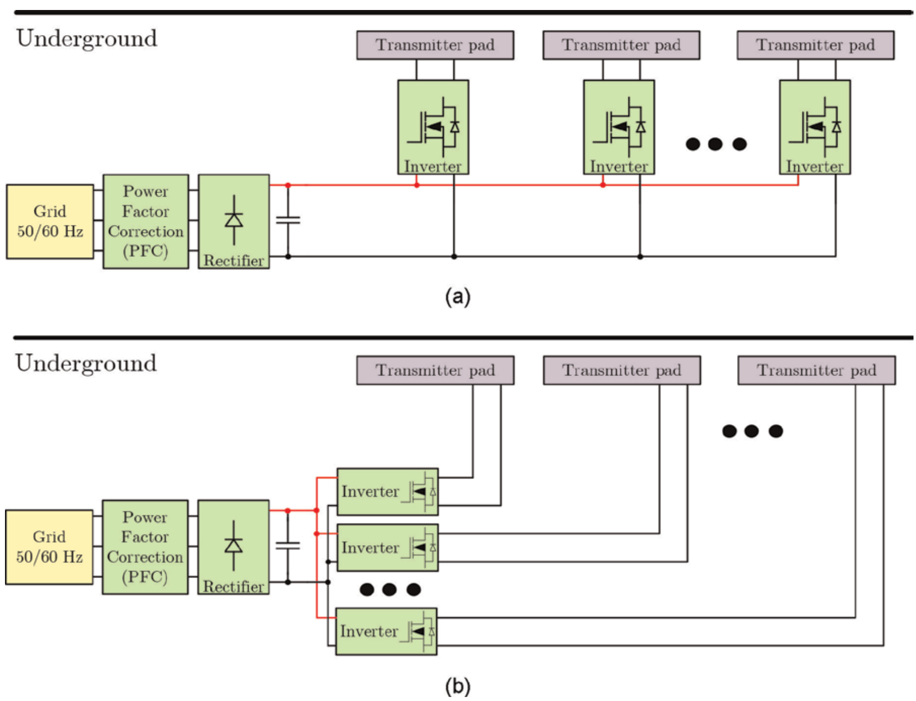

Figure 8.
Overview of different segmented pad configurations.

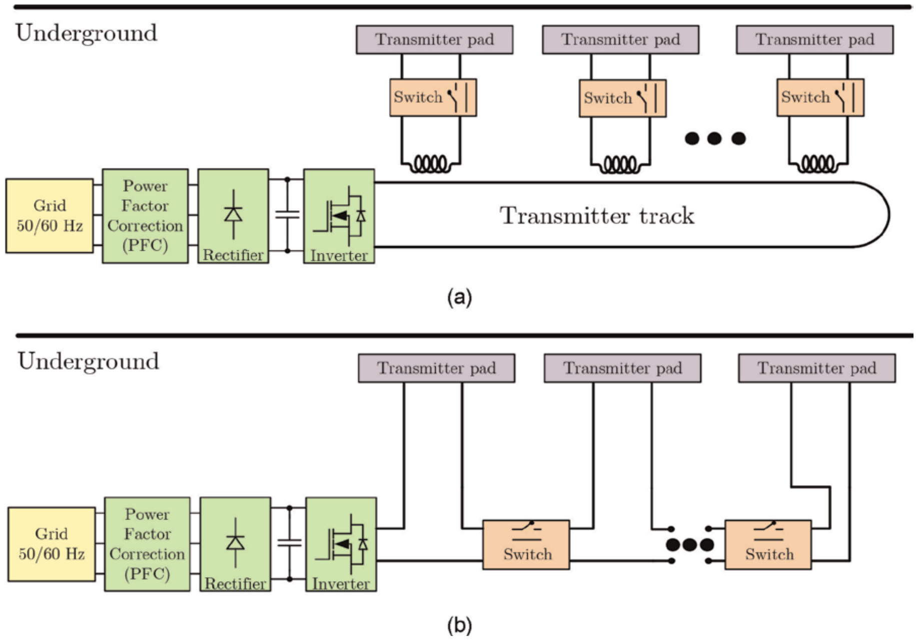

Figure 9.
Overview of different segmented pad configurations with switch breaks.

Figure 8b overcomes the limitations of **Figure 8a** and the maintenance of the power converters, since they are all concentrated in the roadside cabinet. Unfortunately, the installation costs increase exponentially with the number of segmented power pads.

Figure 9a depicts a segmented pad configuration that allows an independent operation of each segmented pad. This feature is accomplished by using a magnetic coupler connected to a bidirectional AC switch that turns "on" or "off" the power pad. A benefit of such configuration is individual maintenance of each segmented pad without affecting the normal operation of the remaining system. The configuration illustrated in **Figure 9b** uses two turn Trm track configuration in which the current direction in one of the turns can be changed using the switch boxes to turn "on" or "off" the magnetic fields in a specific segmented pad. Since all switch boxes are connected in series, all components have to be rated for the nominal current of the Trm pad. Other feeding arrangements include a second coupler or the Trms are connected in series in a push-pull array configuration. All existing configurations have merits and limitations, but additional research is required to assess the preferable configuration in a large-scale application.

Among the future research in DIPT, different research topics are being aim of research. These include the adaptation of road infrastructure to wireless technology and the use of magnetizable concrete to boost the effective coupling factor. Furthermore, a communication system, between the off-board and on-board sides, is required that synchronizes power converters and exchange batteries information. Additionally, precise EV detection systems are needed to activate and deactivate the transmitter pads, thus avoiding unnecessary no-load operation. These systems can use optical or magnetic sensors to detect the position of the vehicle or estimation algorithms that use off-board electrical quantities together with mapping methodologies and artificial intelligence solutions. Finally, the continuous optimization of shielding solutions with resource to cancelation coils or optimized MC geometries.

3.2 In-wheel

One milestone of IPT technology is its applicability into heavy duty vehicles like trucks or off-road vehicles. Unfortunately, these vehicles have typical ground clearances between 350 and 550 mm. This limitation requires high driving current on the off-board side to transfer significant amounts of power. However, the high leakage magnetic fields pose significant concern to the human body. New MC geometries with leakage flux control are under investigation, as stated the previous section. One way to maintain the air gap between the Trm and Rec pads of the MC to a minimum and independent of the vehicle type is to use the wheels as an intermediary stage between the off-board and on-board sides of the vehicle. An early mention of In-wheel IPT (inWIPT) system was made in 2017, and the authors envisioned the placement of several coils in the inner rubber surface of the tire [40]. Each coil is connected in series with a capacitor and a H-bridge rectifier to form a DC bus. The drawback in the proposed configuration is the use of slip rings to transfer the DC bus from the wheel to the on-board side. The low reliability and high maintenance of carbon brushes make it an undesired solution. Alternatively, the receiver pad can be placed in the inner side of the rim to reduce the air gap between the transmitter and receiver pads [41]. This approach, however, requires the use of carbon fiber-reinforced plastic rims, a costlier solution to traditional aluminum rims. The research group from University of Coimbra proposed in 2021 a double coupling in-WIPT system, illustrated in **Figure 10** [30]. The energy transfer from the off-board side to the on-board side occurs via two consecutive MCs without any physical contacts. The proposed solution avoids the use of slip rings to transfer the energy between the wheel and the on-board side. In addition, the aluminum rim shields the leakage flux lines above the receiver coils and avoids the use of additional shielding materials.

In-wheel IPT systems just follow the tendency of moving the powertrain and batteries charger from the vehicle into the wheels, leaving only the batteries itself within the vehicle [42]. The development of new airless tire designs with sustainable and nonmagnetic materials (glass fiber and resins), like the Uptis model from Michelin, strengthen the viability of inWIPT systems. These new airless tire designs also eliminate the risk of pressure increase in the tire caused by the Joule losses of the coils placed within the tire. This solution, however, presents new challenges, among them the sizing of both

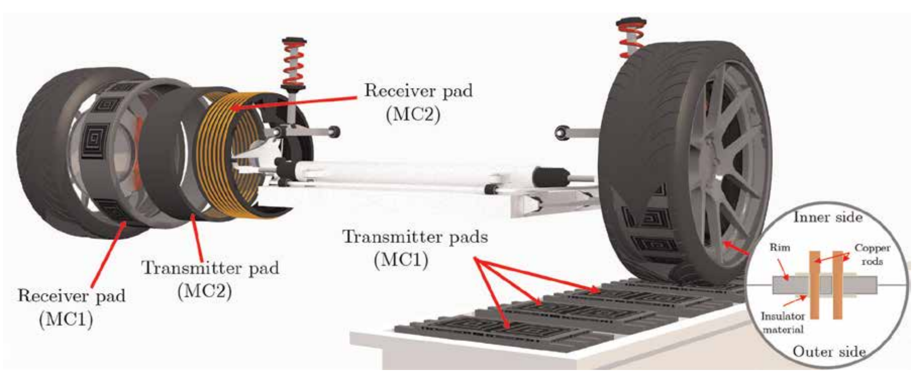

Figure 10.
Double coupling inWIPT.

MCs, since traditional IPT approaches do not take into account the curvature of the coils. Moreover, the rotational effect requires additional research regarding coils support, temperature dissipation, and power flow regulation in both static and dynamic modes.

4. Conclusions

EV technology has proven to be a propulsion technology of the future but urgently needs to address challenges such as lower-priced, reasonably sized EV for higher market penetration, higher life cycle efficiency, and increased power density. Nonetheless, this will not be enough if the issue related to reluctance to EV adoption due to the lack of charging stations, despite number increase, or especially limited range is not solved. Therefore, range extension, particularly in urban scenarios, is critical. IPT technology solves these limitations and offers additional recharging comfort when compared with traditional combustion vehicles.

Over the last decade, a great number of IPT solutions reached the market for static charging of small EVs and busses. These already available solutions offer high-power transfer capabilities with efficiency values comparable to plug-in chargers. Despite these advancements, there are still many challenges that need to be addressed, especially in dynamic IPT applications. Therefore, this chapter revises the past, active, and future research areas. During this transition, review of the resonant compensations and chronological evolution of MC geometry is presented. Then, future research areas namely DIPT and inWIPT systems are presented along with their main challenges not yet addressed.

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