World Electric Vehicle Journal

MDPI

Article

A Multidisciplinary Approach for the Sustainable Technical Design of a Connected, Automated, Shared and Electric Vehicle Fleet for Inner Cities

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Abstract: The increasing volume of personal motorized vehicles (PMVs) in cities has become a serious issue leading to congestion, noise, air pollution and high land consumption. To ensure the sustainability of urban transportation, it is imperative to transition the current transportation paradigm toward a more sustainable state. Transitions within socio-technical systems often arise from niche innovation. Therefore, this paper pursues the technical optimization of such a niche innovation by applying a technical sustainability perspective on an innovative mobility and logistics concept within a case study. This case study is based on a centrally managed connected, automated, shared and electric (CASE) vehicle fleet which might replace PMV use in urban city centers of the future. The key technical system components of the envisioned mobility and logistics concept are analyzed and optimized with regard to economic, ecological and social sustainability dimensions to maximize the overall sustainability of the ecosystem. Specifically, this paper identifies key challenges and proposes possible solutions across the vehicle components as well as the orchestration of the vehicles' operations within the envisioned mobility and logistics concept. Thereby, the case study gives an example of how different engineering disciplines can contribute to different sustainability dimensions, highlighting the interdependences. Finally, the discussion concludes that the early integration of sustainability considerations in the technical optimization efforts of innovative transportation systems can provide an important building block for the transition of the current transportation paradigm to a more sustainable state.

Keywords: multidisciplinary sustainability approach; system innovation; ride pooling; vehicle fleet; connected; automated; shared; electric; CASE vehicles; electric powertrain; longitudinal control; capacity traffic management system; operation center; vehicle human–machine interface (HMI)

Citation: Rieger, P.; Heckelmann, P.; Peichl, T.; Schwindt-Drews, S.; Theobald, N.; Crespo, A.; Oetting, A.; Rinderknecht, S.; Abendroth, B. A Multidisciplinary Approach for the Sustainable Technical Design of a Connected, Automated, Shared and Electric Vehicle Fleet for Inner Cities. *World Electr. Veh. J.* **2024**, *15*, 360. https://doi.org/10.3390/wevj15080360

Academic Editors: Yaoji Deng, Xinglong Zhang and Fen Lin

Received: 5 July 2024
Revised: 31 July 2024
Accepted: 2 August 2024
Published: 9 August 2024

1. Introduction

1.1. Motivation

The ongoing trend of urbanization, coupled with the rising prevalence of personal motorized vehicles (PMVs) operating at low occupancy rates, has emerged as a major concern for cities in terms of sustainability. High traffic volumes cause considerable congestion effects like noise and air pollution [1,2]. Another pressing sustainability challenge within the current transportation paradigm revolves around the undeniable and well-documented impact of its greenhouse gas (GHG) emissions on climate change [3]. Furthermore, due to the low occupancy rates of PMVs, they also consume a high amount of energy and utilize a significant amount of resources per capita, including road space and natural resources [4–6]. Since a significant proportion of PMVs are only used during peak hours, low effective utilization also increases land consumption due to the parking of PMVs [7].

The current main technological trends in the automotive industry are characterized by electrification, digitalization and automated driving [8]. These have the potential to partly reduce some of the aforementioned negative effects by decreasing GHG emissions or respectively increasing road capacity [9]. However, these trends represent a way of linear thinking, also characterized as incremental innovation, which means to merely think about technical improvements in the predominant system [10–12]. In contrast to incremental innovation, system innovation, also called regime transformation, industrial transformation, technological transition, socio-economic paradigm shift, or simply transition, takes a more holistic perspective on innovation [13]. Concretely, system innovation takes into account that a transportation system is a socio-technical system which consists of different elements, e.g., technology, regulations, user practices and markets, cultural meanings, infrastructure, maintenance networks and supply networks [12]. System innovation therefore questions the current transportation paradigm, allowing for a bigger search space for innovations and solutions for sustainability issues [13].

Empirically, the beginning of transitions of socio-technical systems can often be traced back to radical innovations which provide a new solution to existing problems but are not or not yet aligned with the demand of the market or other elements of the socio-technical system [12,14,15]. Since radical innovations often evolve and gain maturity in niches (e.g., market niches) which serve as "incubation rooms" they are also called niche innovations [14]. Such niche innovations might have the potential to move from the niche-level to the regime-level if they manage to integrate adequately into the existing regime [16,17].

This paper focuses on a niche innovation: connected, automated, shared and electric (CASE) vehicle fleets. As a concrete example for the proposed case study, this innovation is illustrated by an innovative mobility and logistics concept, the EDAG CityBot. It is designed to function as a ride-pooling system, a mode of freight transport, and mobile robots carrying out municipal service tasks, such as city cleaning. The innovative mobility and logistics concept stands as an adept case study to assess the ways in which innovation in different technical disciplines is able to contribute to reaching higher levels of sustainability in transportation.

Acknowledging the significant role of non-technical factors which are necessary to move from the niche-level to the regime-level, this paper deliberately excludes their detailed discussion within its scope. Examples of such important non-technical challenges within the presented case study are, e.g., potential socio-spatial inequalities [18,19] or psychological barriers [20,21].

As a baseline for the further content of this paper, the EDAG CityBot will be shortly presented in Section 1.2. Section 1.3 gives a short discussion of what makes a transportation system sustainable. A short overview of approaches for sustainable design is given in Section 1.4. After that, the aim and approach of this paper are explained in Section 1.5. As a technical baseline for the approach, the system components which will be analyzed more deeply in the main sections of this paper are introduced in Section 1.6. The introductory section closes with a short description of the structure of the remaining paper in Section 1.7.

1.2. An Innovative Mobility and Logistics Concept: The EDAG CityBot

The EDAG CityBot provides a visionary mobility and logistics concept based on a CASE vehicle fleet [22,23]. The CASE vehicles, CityBots, comprise a "tractor" module that can be combined with different types of so-called "trailer" and "backpack" modules for on-demand and flexible deployment [23]. In Figure 1, the CityBot is shown with a trailer module in its people mover configuration.

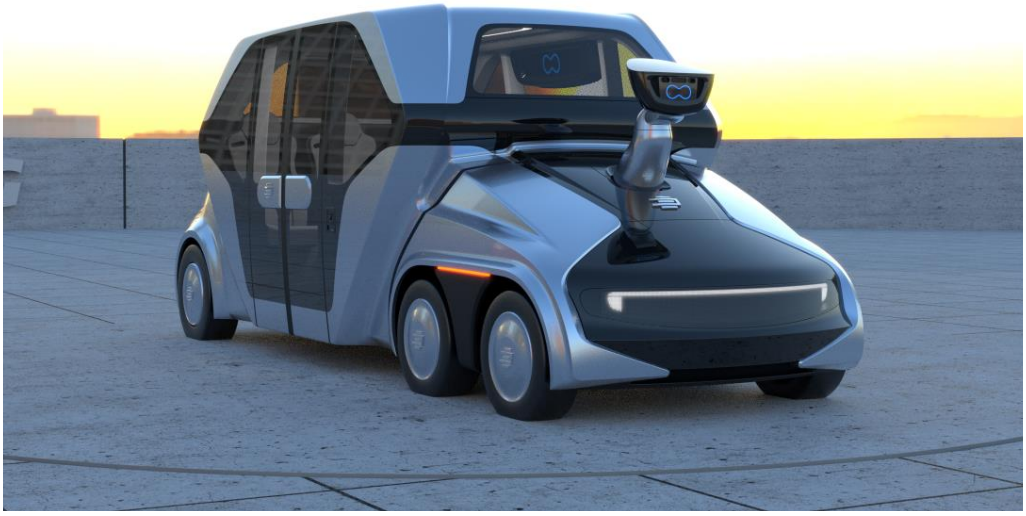

Figure 1. The EDAG CityBot connected, automated, shared and electric (CASE) vehicle equipped with a people mover trailer module. Copyright 2023 EDAG Group.

In the following, the characteristic attributes of the CASE vehicles are shortly described. Vehicle-to-everything (V2X) technology allows the CityBots to *connect* digitally with each other as well as with infrastructure components [24]. The exchanged data can be used for optimized execution and the control of vehicle operations [25]. Through *automation*, the CityBot operates independently from human drivers. Therefore, time-flexible tasks, for example city cleaning, can be scheduled independently from main working hours and especially outside rush hours [24,25]. For passenger transportation, the CityBot functions in its people mover configuration as a *shared* ride-pooling on-demand service. The sharing approach might have the potential to replace individual transportation or at least to reduce the overall number of required vehicles [23,25]. Thus, the sharing approach decreases resource consumption as well as the congestion and space previously allocated to individual transportation [23,25]. Being an *electric* vehicle, the CityBot's energy efficiency is higher compared to conventionally powered vehicles [26].

Using the CityBot ecosystem as an exemplary case study, this paper illustrates how various technical disciplines can address sustainability when optimizing an innovative mobility and logistics concept like the EDAG CityBot. As a baseline for this, the term sustainability will be shortly discussed in Section 1.3 and a definition fitting the scope of this paper will be chosen.

1.3. Sustainable Transportation Systems

The concept of sustainability evolved with the concept of sustainable development during the second half of the 20th century [27–30]. Its classic definition was coined in the Brundtland report as "meeting the needs and aspirations of the present generation without compromising the ability of future generations to meet their needs" [27] (p. 292).

Based on the above-presented definition, Goodland further detailed sustainability as a multidisciplinary construct with three main dimensions: economic, ecological and social. These dimensions can be expressed by the economic, natural and social capital that needs to be sustained [28].

At the outset, achieving economic sustainability entails sustaining economic capital. Thus, a system needs to fulfill public and individual needs by limiting the consumption of its resources in such a way that it can continue to grow without increasing public debt or leaving irreparable economic damage for future generations [29,31].

Similarly, for ecological sustainability, a system's resource consumption needs to be limited in such a way that natural capital, which includes all natural resources and life forms existing on earth, can be sustained in the long term. Natural capital encompasses the entirety of Earth's resources and biodiversity, and its sustainable management requires a dual role: serving as a source of inputs and acting as a resilient "sink" for waste [28,31].

To reach social sustainability, a system must contribute to the maintenance of social capital. This can be achieved by designing a system that addresses social inequalities by promoting equal opportunities and access to resources and promotes health and well-being as well as social inclusion and participation for all [32].

For transportation systems, the Brundtland definition can directly be applied by defining the requirement to "satisfy the current transportation and mobility needs without compromising the ability of future generations to meet those needs" [33].

Additionally, a set of objectives for sustainable transportation can be defined or derived from the sustainability dimensions [34,35]. Furthermore, a detailed investigation of the three dimensions and the derivation of a set of indicators to measure each dimension in detail during the process of transportation evaluation and planning are given in [36].

In [37], Vreeker and Nijkamp build upon the three sustainability dimensions and further specify each of these in the context of land use patterns in transportation, recognizing the challenge of balancing these three objectives. Accordingly, overall sustainability, hereafter simply referred to as sustainability, is achieved through multi-objective optimization of the three sustainability dimensions. Therefore, the dimensions of economic, ecological and social sustainability have to be weighed against each other, leading to an optimized compromise with a solution space for sustainability along the Pareto front.

As an alternative definition to the three sustainability dimensions, a socio-technical perspective on sustainable transportation is given by [38] defining the sustainable mobility paradigm by suggesting four key elements: making the best use of technology; regulation and pricing in such a way that external costs are internalized; integrated land use development to support shorter travel times; and clearly targeted personal information to raise acceptance for sustainable forms of mobility.

The derived indicators and objectives given in [36] provide a detailed baseline for the evaluation of practical problems in transportation evaluation and planning. However, the scope of this paper considers the evaluation of technical optimization efforts for an innovative mobility and logistics concept which, until now, only exists in theory. Accordingly, the sustainability baseline of this paper is proposed to be on a higher abstraction level. Furthermore, that abstraction level should be applicable to the technical scope of this paper. Therefore, the concretizations of the three sustainability dimensions within [37] narrow down the sustainability objectives too much considering only impacts on land use. On the other hand, the socio-technical perspective from [38] exceeds the technical scope of this paper.

Therefore, the context-independent Goodland definition of sustainability [28] remains as a potential baseline for the technical optimization efforts and their further discussion in the main sections of this paper. Overall, most of the above-discussed previous work on sustainable transportation refers to the Goodland definition [28], which was derived from Brundtland's work [27]. Thus, Goodland's work provides a suitable framework both for the derivation of sustainability objectives and indicators as well as for the evaluation of any technical optimization efforts. Hereby, interdependences between the three dimensions need to be considered.

Regarding the current literature on sustainable transportation, most recommendations are of a normative nature, defining criteria for sustainable innovation. There currently exists a research gap on how to design the system components of an innovative transportation system in a sustainable way. To close this specific research gap, general approaches for sustainable system design might be applicable. Therefore, in the following, general approaches for sustainable design are shortly introduced.

1.4. Sustainable Design Approaches

Sustainable design approaches can generally be viewed from the perspective of the development process or from the life cycle perspective [39]. Their focus is mostly on economic or ecological sustainability requirements, but some extensions and further guidelines exist to include social sustainability requirements. These will be discussed as well in this subsection.

From the development process perspective, the methods and tools for sustainable design can be chosen according to the current development phase: planning, conceptual design, detailed design and prototyping. For each of the phases, adequate methods for the sustainable execution of the design steps are suggested in [39].

For the phase of early concept design, a development process is suggested in the VDI guideline 2221 [40]. An extension of the suggested process with regard to social sustainability was suggested in [41].

For the detailed design phase, the standards for life cycle assessment (LCA) are defined in DIN EN ISO 14040 [42] and DIN EN ISO 14044 [43]. For socially sustainable design, the development should follow the human-centered design process of DIN EN ISO 9241-210 [44] as well. The process engages in multiple iterative stages, starting with the analysis of the context of use and the derivation of user requirements. This allows for the particular needs of diverse individuals, for example, those with disabilities, to be addressed. Subsequently, prototypes are developed and assessed through an iterative process that incorporates input from both experts and end-users.

From the life cycle perspective, strategies, guidelines and options for ecodesign can be derived. The strategies are the minimization of material consumption, the minimization of energy consumption, the choice of resources with a low environmental impact, the optimization of product lifetime, the maximization of material lifetime, and disassembly support [39,45]. For social sustainability, to the knowledge of the authors, no comparable strategies exist. However, essential aspects for social sustainability contain trust, common meaning, diversity, a capacity for learning and a capacity for self-organization [46].

1.5. The Approach and Aim of This Paper

Considering the need of the current transportation paradigm to transition toward a more sustainable state, as introduced in Section 1.1, the CityBot ecosystem, as introduced in Section 1.2, presents notable technical opportunities for optimization on the technology level of the transportation system. This encompasses not just the vehicle components but also the orchestration of the vehicles' operations. Thus, in order to ensure the sustainability of the ecosystem, it is imperative to assess the technical optimization efforts for vehicle components and the vehicles' operations from the perspective of economic, ecological and social sustainability, as discussed Section 1.3. More specifically, within a case study framework, this paper strives to unveil the central challenges and offers potential technical solutions for optimizing the design of five central technical system components, namely, powertrain, longitudinal control, a capacity and traffic management system, vehicle fleet and malfunction management in the operation center, and the vehicle human–machine interface (HMI).

In essence, this paper aims to provide an example of the impact of integrating sustainability concerns into the optimization of innovative transportation technology by adopting a multidisciplinary approach for the sustainable technical design of a CASE vehicle fleet. By individually evaluating the sustainability potential of each system component using the task-specific sustainable design methods outlined in Section 1.4, a bottom-up approach is provided to identify opportunities for improving the overall sustainability of the system. This approach provides deeper insights into designing the components of an innovative transportation system in a sustainable manner.

1.6. Introduction of System Components to Be Optimized

In the following, each of the aforementioned system components is individually assessed to highlight both the necessity and the potential for optimization, all while maintaining a focus on the sustainability dimensions under consideration.

When introducing new vehicle classes like the CityBot, it is particularly important to consider GHG emissions [3]. Even if electric vehicles are advertised with a reduction in GHG emissions in comparison to internal combustion vehicles, it would be too short-sighted to describe electric vehicles as emission-free. Additionally, there is often a higher consumption of rare earths with electric vehicles, because batteries, power electronics and electric machines as the state of the art need a high amount of rare earths to reach acceptable efficiencies, e.g., lithium and cobalt [47]. To objectively evaluate and estimate electric vehicles' GHG emissions already during vehicle development, from a life cycle assessment (LCA) perspective, not only the emissions during use but also the emissions that occur during production and disposal must be considered. One central method to increase a vehicle's efficiency is the design of the *powertrain*, i.e., hardware design with the aim of reducing electric consumption. Moreover, the optimization of software in terms of the vehicle's driving strategy, i.e., the design of *longitudinal control*, also has the potential to increase ecological and economic sustainability. Adaptive cruise control is the state-of-the-art method for longitudinal control for automated driving and is suitable for simple traffic situations such as driving through a highway with a focus on maintaining safety [48]. However, in an urban context, this driving strategy is insufficient for an ecologically and economically efficient driving style and can be improved by taking advantage of the fact that vehicles are connected to each other and to infrastructure components.

In addition to optimizing each individual vehicle, an economically, ecologically and socially sustainable operation and interplay of the vehicle fleet has to be ensured by the design of a so-called *Capacity Traffic Management System (CTMS)*. The CTMS processes incoming transportation requests to generate a feasible and robust schedule for the envisioned transportation system. The CTMS is designed to tackle traffic flow optimization and traffic control at intersections and to adjust the schedule in case of unforeseen events. In the event of a malfunction due to technical failures or the system's limitations [49], according to the German legislation on automated driving [50], technical supervisors are required to monitor the CityBot fleet as well as to intervene and provide a point of contact for passengers in case of malfunction. Thus, the design of the workstations, workflows and tasks of supervisors in the *operation center* is of high importance to foster the system's economic and social sustainability.

To ensure the initial and long-term acceptance and seamless integration of CityBots as automated, i.e., driverless, vehicles into road traffic, an effective, efficient and satisfactory design of the interaction between vehicles and potential users is required [50]. Thus, to facilitate the implementation of a socially sustainable novel transportation system, the design of human–machine interaction, especially the design of the *vehicle HMI*, is a critical factor. The vehicle HMI serves as a communication medium between human users and automated robotic vehicles with the aim to increase user accessibility [51,52].

1.7. The Structure of This Paper

In the remainder of this paper, for each of the presented system components, the materials and methods used for their optimization and the expected results in terms of sustainability are presented in Sections 2 and 3, respectively. In Section 4, the effect of the presented results of system component optimization is discussed from the perspective of each of the three sustainability dimensions and briefly put in the wider context of system innovation. Section 5 gives the conclusion, highlighting the main findings of this paper.

2. Materials and Methods

In the following, the materials and methods for the approaches to optimizing each of the system components, as described in Section 1.6, with regard to maximization of the overall system's sustainability are presented.

2.1. Powertrain Design

Powertrain parts like electric machines and batteries of electric vehicles have a significant ecological impact over the complete life cycle, from production to the use phase until disposal at the end of life. Therefore, it is important to consider GHG emissions produced during the whole life cycle when developing battery electric vehicles. Consequently, in powertrain design, LCA is used as a tool in accordance with the standards DIN EN ISO 14040 [42] and DIN EN ISO 14044 [43].

The chosen approach for optimizing the powertrain design of vehicles using LCA includes two steps:

In current vehicle development, standardized driving cycles (e.g., WLTC) are utilized. However, the simulated consumption within these cycles may differ from real-world applications. To address this discrepancy, the initial step involves creating representative driving cycles based on actual driving data, which ensures a more realistic simulation of electric consumption during the usage phase. Gathering driving data is conducted in a real-world laboratory where the vehicles work in use cases similar to desired tasks in smart cities.

To ensure representative driving cycles, real driving data need to be logged without any bias. Hence, the vehicle must perform under normal operation. To prevent the impact of special events (e.g., emergency breaking) on the gathered data, a big data set is needed in order to account for stochastic reliability. The logged real driving data are compressed into representative driving cycles to ensure computing efficiency by using a hybrid cycle generation tool, as proposed in [53,54]. The hybrid cycle generation procedure is modeled by using a combination of Markov chains and the segmentation of reference driving states. The driving cycles can be generated specifically for one use case or for a whole data set containing different use cases.

In the second step, the representative driving cycles are then used to parametrize the powertrain components and to calculate and minimize the GHG impact of the vehicle for the whole life cycle.

The representative driving cycles are used in a backward simulation of the vehicle and the powertrain. The cycle's driving resistance forces are calculated and converted to the needed torque at the wheel. With simulation models of all powertrain components, the power drawn from the battery and therefore the consumption of the vehicle can be calculated from wheel torque. The models span from static efficiency maps through simulation code (e.g., in Mathworks Matlab R2021b) to finite element models (e.g., electric motors).

Around the above-mentioned simulation of the vehicle, an optimization loop is constructed. The optimization parametrizes the powertrain components and the simulation evaluates the consumption on the chosen driving cycle. Additionally, the GHG emissions of the vehicle during production and disposal are calculated in order to evaluate the overall life cycle GHG emissions of the vehicle in accordance with [53,55,56]. By choosing representative driving cycles accordingly, optimization can be performed to simulate the optimal powertrain for a specific use case, or to gather the optimal powertrain for a combined driving profile. This approach allows us to evaluate whether it is worth producing vehicles with one powertrain version or whether to design different powertrain versions for each use case.

2.2. Longitudinal Vehicle Control Design

In contrast to conventional vehicles, a connected vehicle fleet can collect and process more information about the traffic and its environment by using roadmap and V2X information, as illustrated by the example of the CityBot in Section 1.2. The collected information can be used to optimize the longitudinal vehicle control of the CASE vehicles with regard to energy consumption. Thereby, the longitudinal vehicle control decreases energy consumption during the use phase and thereby contributes to the life cycle perspective, as introduced in Section 1.4.

Because of the increased processing power, artificial intelligence (AI) has become a common tool to predict future events which cannot be obtained by rule-based models. Therefore, AI models have lately been used to predict future vehicle speeds, which are highly affected by the high complexity of traffic [57,58]. This AI-based speed prediction can be based on multiple input features such as already used sensor information, roadmap information or V2X information. Choosing the right set of features may increase the capability of predicting very complex situations significantly.

Concerning longitudinal control, speed predictions can use this surrounding information as a predictive element in addition to a traditional longitudinal control system. For connected and automated vehicles like the CityBots, another driving mode is added, which includes the predicted vehicle speed of the leading vehicle and the predicted speed of the vehicle equipped with the shown technology (ego vehicle) [59].

To obtain the benefit of such a system and also considering a V2X-supported surrounding, this longitudinal vehicle control approach is tested in a simulated environment. For this purpose, a co-simulation environment is created. This includes the vehicle model, which consists of data collection and preparation, the prediction model for vehicle speed predictions, the longitudinal controller and the powertrain model of the vehicle. Combined with a traffic simulation of the city center of Darmstadt (Germany), this forms the co-simulation environment, which is shown in Figure 2.

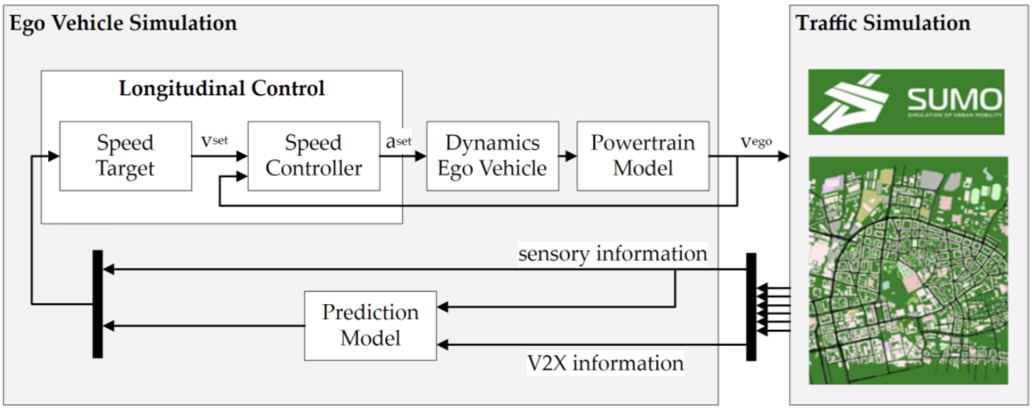

Figure 2. Co-simulation environment for simulated implementation of efficient longitudinal control for connected vehicles. Reprinted from Ref. [59].

The traffic simulation is created using the software tool "Simulation-of-Urban Mobility" (SUMO Version 1.19.0). This provides a microscopic, inter- and multimodal, space-continuous and time-discrete traffic simulation [60]. SUMO provides the possibility to include a speed controller in a specific vehicle as well as the required information to simulate a functional V2X infrastructure.

2.3. CTMS Design

Traffic Management Systems (TMS) were first developed within the context of the rail industry and typically encompass functions such as conflict detection, conflict resolution and real-time speed profile generation and implementation [61]. In the last few years, further development has been made [62–64] and the concept has evolved to include additional functionalities, particularly scheduling during the planning phase [65,66]. Such a next step in the development process is referred to as the CTMS.

Compared to rail transport, traffic management in road transportation has a greater and much more straightforward impact on both directly and indirectly involved stakeholders. Therefore, given the role of the CTMS as the central manager of the transportation system, it is particularly relevant to consider not only the stakeholder requirements but also the sustainability dimensions to systematically derive its functionalities. Since the early concept design of the CTMS is derived within the scope of this paper, the development process is based on VDI guideline 2221 [40]. To consider social sustainability requirements, the expansions from [41] are included as well. In the following, the requirements, methods and approach for the development of an appropriate CTMS architecture for road traffic are derived while especially taking sustainability requirements into account.

In order to specify the sustainability requirements of the system, it is helpful to differentiate according to stakeholders. These can be summarized as road users, operators and the general public [67]. The road users include the customers of the considered system as well as pedestrians, cyclists, etc.

By applying the ecodesign strategies as introduced in Section 1.4, as well as the perspectives and needs of each stakeholder and each sustainability dimension, the requirements for the envisioned CTMS are derived. The requirements obtained from the analysis are depicted in Appendix A. It is important to bear in mind that conflicting requirements can arise. For example, a solution with the shortest travel time for a transportation request may have a negative impact on traffic quality measures, such as traffic density. As a meta-requirement, it is therefore necessary to find a suitable mechanism for balancing the various requirements with each other, for example by the definition of a suitable objective function.

In addition to the requirements derived for the CTMS, the overall system architecture must include all relevant functions, which result from transferring the CTMS concept from rail to road. Additionally, ride pooling must be supported since it is a central aspect of the shared transportation concept. The relevant functions thus include scheduling, conflict detection and resolution during operation at the intersection level, the adjustment of speed profiles during operation and the assignment of orders to individual vehicles.

The CTMS system architecture is to be derived such that all deduced CTMS requirements and functions are supported. Methodologically, the development of a system architecture is a creative and iterative process in which several approaches can generally lead to a meaningful result. The basic approaches can be divided into top-down and bottom-up design methods [68]. In the derivation of the system architecture, a hybrid approach, simultaneously combining both the top-down and the bottom-up approach, is used for optimal utilization of the findings. The minimum functions to be included, as derived above, represent the first basic elements in the bottom-up approach. Based on the general requirements for the system, the functions and modules that are still missing are completed as part of the top-down approach.

2.4. Operation Center Design

To ensure reliable and safe operation of the automated vehicle fleet and the necessary malfunction management processes through technical supervisors in the operation center, it is necessary to develop efficient and satisfactory workstations, processes and tasks. Therefore, the operation center concept for the vehicle fleet should be optimally adapted to the needs of technical supervisors and passengers and accordingly designed in a socially sustainable approach. For instance, the design of the operation center should allow for processes to be adjusted in a way that prioritizes physically impaired passengers or provides communication options for those who cannot read. Thus, the development follows the human-centered design process of DIN EN ISO 9241-210 [44] (cf. Section 1.4).

The absence of operation centers for automated vehicle fleets such as those examined in this study makes it impossible to analyze actual systems and interview actual users. Therefore, the primary source for analyzing and describing the context of use in future operation centers for automated vehicles is a systematic literature search, which includes research reports for vehicle fleets and for control centers in rail and air transport. The search is focused on both task analysis and the design of human–machine interaction. The first step is to identify the tasks required to comply with German legislation on automated driving [50] and to provide support for vulnerable passengers in using automatic vehicles in an inclusive manner. Additionally, design options for the interaction concept are researched to address the identified tasks.

To supplement the findings of the literature search, an expert workshop with developers of automated vehicles and specialists in human–machine interaction within the transportation sector is conducted. Utilizing the results of the context of use analysis, workflows that enable efficient and financially viable handling of the assigned tasks are established. Utilizing the data collected, the role definitions and distribution of employees of the operation center are determined. Furthermore, the location requirements for the control center, the size of the vehicle fleet and the human–machine interaction concept are identified.

Subsequently, initial design solutions are created and assessed (cf. Section 1.4). Following the human-centered design process, HMI design solutions for technical supervisors are developed and implemented iteratively. These solutions will be assessed in terms of their error robustness, safety, effectiveness and efficiency during subject tests performed in laboratories. Additionally, subject tests will determine to what extent technical supervisors can enhance safety, satisfaction and trust among passengers and pedestrians.

2.5. Vehicle HMI Design

Given that HMI design primarily functions as the conduit for human–machine interaction, the HMIs employed in automated vehicles such as the CityBots must be meticulously developed according to the human-centered design process outlined in DIN EN ISO 9241-210 [44]. This approach places a strong emphasis on prioritizing human needs and placing them at the core of the development process.

In the first step of the human-centered design process, similar to the procedure previously reported for the operation center, a context of use analysis is conducted in an expert workshop consisting of specialists in human–machine interaction within the transportation sector as well as with computer science and automotive industry engineers. Thereby, the relevant use cases and user groups of the vehicles, the user tasks and equipment, and the physical and social environments in which the vehicles will be used are identified and characterized. Moreover, the interaction processes and steps between users and vehicles are described. Interaction steps that occur in multiple use cases are grouped thematically to ensure the consistent development of vehicle HMIs for the essentially same or similar vehicle usage, handling and interaction across different use cases. Nevertheless, use case or user-group-specific requirements necessitate specific design or modification of the interaction processes, which are also taken into account.

In the second step, based on the context of use analysis as well as the literature search, requirements of the user groups regarding the vehicle HMI design are derived.

In the third step, with the user requirements previously identified, the modalities and transmitted content in each interaction step are defined, and the design solutions for the external and internal HMIs are developed.

In the fourth step, the concept variants are visualized in the form of prototypes, which are later inter-evaluated with potential users in virtual reality studies and online surveys. These evaluation findings are used to adjust the design concepts in an iterative manner. In the main evaluation, users assess the preliminary final design solutions for the HMIs under real conditions of the vehicle's use and interaction in a real laboratory. In the context of HMI evaluations, on the one hand, pragmatic quality criteria such as effectiveness, i.e., the user's goal achievement in interacting with the vehicles, and efficiency, i.e., the ratio of resources (e.g., time or perceived cognitive load) used in interacting with the vehicles [44], are considered. On the other hand, hedonic qualities such as cooperation, well-being, comfort and emotion, which have been less intensively considered in HMI evaluation to date, are also captured to ensure a satisfying interaction with the vehicles [69]. The ergonomic target variables of an effective, efficient and satisfactory interaction and use are captured using both objective measures such as eye movement, motion, behavior and observation data as well as subjective measures such as survey data via (semi-structured) interviews and (standardized) questionnaires [69].

3. Results

In the following, the technical optimization efforts of the five examined technical system components of the CityBots are described. Moreover, their potential qualitative contribution to the sustainability of the envisioned mobility and logistics concept is elaborated.

3.1. Powertrain Design

With the presented procedure of using representative driving cycles and optimizing powertrain components, it is possible to objectively evaluate the overall life cycle GHG emissions of an electric vehicle and optimize the powertrain components to achieve minimal GHG emissions for the real use situation of the vehicle. The procedure has already been used to compare different vehicle classes and shows that for different applications, different vehicle classes and parametrizations can be optimal in terms of overall GHG emissions [53].

The procedure is applied to the CityBot as an automated electric vehicle with wheel hub motors. Within this vehicle class, different powertrain technologies are compared with each other in terms of GHG emissions. Starting with the battery, various cell chemistries are evaluated (e.g., lithium iron phosphate, lithium nickel cobalt aluminum oxide etc.). All chemistries show different charging and discharging behaviors and especially influence the usable motor power for traction and recuperation [70]. Concerning wheel hub motors, different types of electric machines (e.g., permanent synchronous machines, asynchronous machines, axial flux motors, etc.) are simulated via the finite element method and used with static efficiency maps for the powertrain model. Additionally, simulations are conducted with different sizes (scalable maximum power) and quantities (two or four) of motors. Furthermore, the use of a planetary gearbox will be evaluated. As shown in [71], gearboxes have the potential to significantly reduce the energy consumption of electric vehicles while driving in inner cities.

Taking all of this together, the procedure is capable of calculating and optimizing the GHG emissions over the whole life cycle of electric wheel-hub-driven vehicles. This is already performed during the development phase of the vehicles and not only reduces the energy consumption during use but prevents the superfluous use of resources and electric energy during the production and disposal phases. Therefore, the procedure contributes to the economic and ecological sustainability of the transportation system. This ensures that only the economic and natural capital is preserved. In particular, electric vehicles can have a high impact on those two dimensions because rare earths are used for components like batteries, power electronics and electric motors. Parameter optimization of the components can therefore make a great contribution to a sustainable transportation system.

3.2. Longitudinal Vehicle Control Design

With the displayed method, it was possible to set up the co-simulation environment with a validated simulation of the city center of Darmstadt. The AI-based speed prediction model was trained with a Long Short-Term Memory (LSTM) encoder–decoder architecture supervised learning approach with different feature sets. The training process is executed as shown in [72]. The feature sets contain V2X information along with sensory-data, which can be obtained with conventional technology. The results of the evaluation of the impact of the feature sets on longitudinal vehicle behavior are shown in [39].

Additionally, as a result of the prediction model's performance on the longitudinal control, the energy consumption and mean speed of an electric vehicle are evaluated in [59]. These results are a first indication toward the importance of longitudinal control for a battery electric vehicle like the CityBot. It is shown that in comparison to traditional longitudinal control, the energy consumption has the possibility to be reduced by around 7% for the routes examined, along with only a slight increase in travel time. This is an important combination of results, because it can therefore be concluded that the reduction in energy consumption actually results from improved longitudinal control and is not just based on a lower mean speed during the drives considered.

Additionally, user acceptance is a major factor for taking a ride in a driverless vehicle; therefore, a drive as comfortable as possible should be provided. To also consider this aspect, the jerk during the drive is investigated. A reduction in the jerk of up to 28% can also be achieved, as seen in [59]. This is perceived as a more comfortable drive with the shown system for optimized longitudinal control.

These results show the impact of optimized longitudinal vehicle control on ecological and economic sustainability. The software-based solution for this control approach does not require a specific hardware change. The sensors and communication set already included in connected and automated vehicles are sufficient for the operation of the shown system. This means that it is possible to add this system to already existing vehicles without adding any resource-extensive supporting hardware. This results in a limited ecological impact for the installation of the system but causes a reduction in energy consumption during operation. For the exemplary energy composition in Germany in 2023, with 40–60% of electrical energy originating from non-renewable sources, optimized longitudinal control leads to a decrease in the ecological impact of the automated battery electric system's operation [73]. Moreover, current statistics show a steady increase in cost for electric energy in Germany since 2000, with a tendency to further follow these trends in the upcoming years. Therefore, a decrease in energy consumption for a given vehicle route gains importance as it results in less costs for a given trip [74]. This results in an increase in economic sustainability.

3.3. CTMS Design

In the following, the CTMS system architecture for the shared transportation concept is derived by using a hybrid approach combining a bottom-up with a top-down approach. Hereby, the input for the bottom-up part of the approach is derived from the CTMS literature for rail transportation, whereas the input for the top-down part is given by the general CTMS sustainability requirements derived previously. The system architecture derived in that way is depicted in Figure 3.

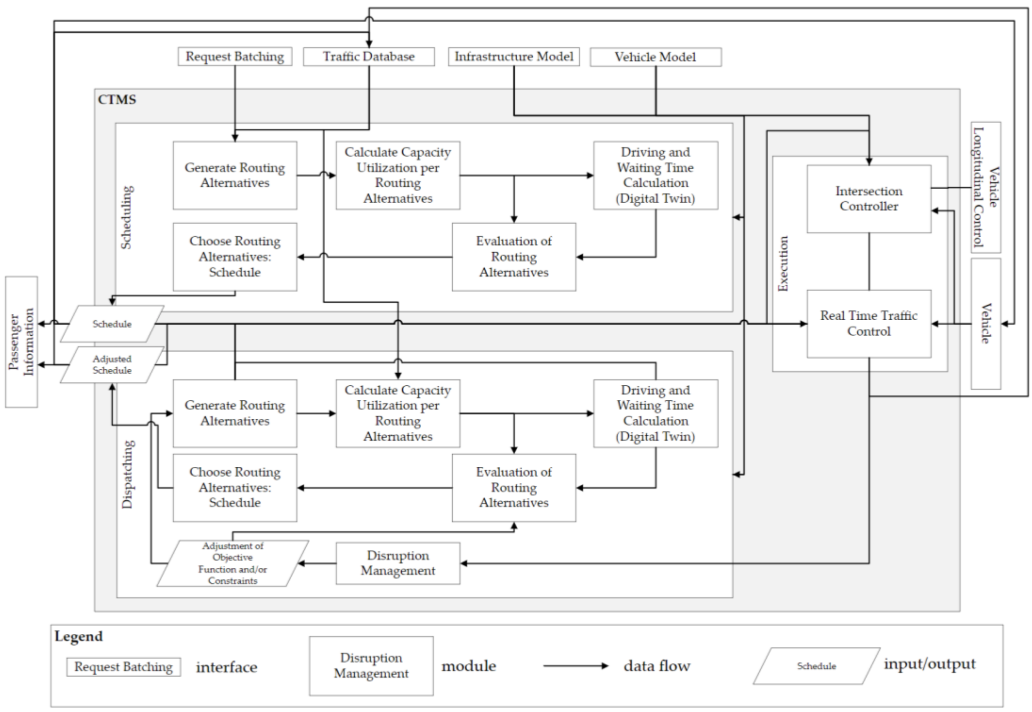

Figure 3. The system architecture of the capacity traffic management system (CTMS) for an on-demand ride-pooling transportation system.

A separate subsystem is formed for *Scheduling*, which includes the module for generating routing alternatives as a basic element. Taking also the requirements from the top-down part of the approach into account, the requirement *Weigh-Up Quality Measures for all Road Users* is of particular relevance for the operational evaluation of a solution. Here, the resulting travel and waiting times as well as the capacity utilization of infrastructure for different routing alternatives must be weighed against each other in an objective function to be defined. At the same time, the optimization performed by the CTMS needs to fulfill the requirements from the ecological and economic sustainability dimensions. This can be achieved by restricting the solution space of the route search by constraints or by further adjustment of the objective function. Since vehicle routing and the assignment of requests to individual vehicles are closely linked, these two tasks must be solved simultaneously [75]. As a basis for the evaluation of routing alternatives, the additional modules *Capacity Utilization Calculation* and *Driving and Waiting Time Calculation* as well as an interface to the *Traffic Database* as a data source for calculations based on information about the predicted traffic volumes are required.

The other basic elements for conflict detection and conflict resolution in operation at the level of intersections and adjustment of speed profiles during operation are located at the level of operation execution in the *Execution* subsystem. Here, conflicts at intersections are resolved by the *Intersection Controller* module. Consideration of all derived sustainability requirements when defining a suitable objective function for this optimization module during the development of this module's algorithms is a key challenge. For the resulting solutions, the target trajectories are transmitted via a vehicle interface in a similar way to rail transport. The resulting waiting times are transmitted to the *Real Time Traffic Control* module, which uses location and timetable data to determine the timetable deviations and disruption information that are relevant for dispatching interventions of the system within the *Dispatching* subsystem.

The *Dispatching* subsystem is essentially a mirror image of the *Scheduling* subsystem, whereby the schedules generated and communicated to the customers are taken as the basis for optimization, redefining the objective function. The subsystem is supplemented by the *Disruption Management* module, which generates another adjustment of the objective function and/or boundary conditions of the optimization in case of a major disruption and thus an adjustment of the operational strategy, depending on the disruption situation. In accordance with the requirements, this aims as far as possible to achieve sufficient transportation capacity while continuing to minimize travel and waiting times in the disrupted overall system.

3.4. Operation Center Design

Based on the literature review and workshops, the tasks of technical supervisors of the automated vehicle fleet can be divided into seven categories: monitoring, enabling and disabling, indirect control, direct control, coordination, communication, and other tasks [76]. Monitoring entails the observation of vehicle data in terms of error messages [77]. If the automated vehicle is incapable of handling a situation, the technical supervisors have the task of checking and enabling or disabling the driving maneuvers proposed by the vehicle or putting the vehicle in a state of minimal risk [50]. In the latter case, the technical supervisors must initiate an alternative maneuver through indirect control, where they do not have direct control over the vehicle's actuators but specify driving maneuvers that the vehicle then executes independently [78,79]. An alternative is direct control, in which they have control over the vehicle's actuators and thus not only plan but also execute the maneuvers [78,79]. Coordination includes the organization of the fleet operation [79–82]. To ensure the social sustainability of the system, the technical supervisors should have the opportunity to restructure the deployment plan [81], for example to give priority to users with disabilities. In contrast to operation centers found in aviation or rail transport, operation centers for automated vehicles will lack the presence of trained and responsible personnel on board of the vehicle [50]. Therefore, the operator also must be able to communicate with passengers, which may involve addressing passengers' inquiries or informing them of incidents, and thus maintain users' feeling of safety and trust [78]. Additional responsibilities of the technical supervisors include recording and analyzing operational incidents or initiating safety measures in the event of a malfunction [50].

To achieve an economically sustainable design of the workflow, it is suggested to divide the technical supervision into the roles of dispatcher and teleoperator [76]. The dispatcher monitors, coordinates and communicates, while the teleoperator is responsible for enabling and disabling indirect and direct control. Moreover, the teleoperator must also be able to communicate with passengers or pedestrians. For this purpose, the dispatcher's workstation functions as a standard control room workstation, while the teleoperator's workstation requires specialized input devices for vehicle control (see Figure 4).

(**a**) (**b**)

Figure 4. The operation center consists of a workstation for the (**a**) dispatcher and the (**b**) teleoperator.

Additionally, it is advisable to position the dispatcher in close physical proximity to the automated vehicle fleet, while the teleoperator requires only a stable connection to the vehicles that could be used for several vehicle fleets at the same time. This approach optimizes the number of workstations needed based on task frequency and creates workstations in an economically sustainable manner. Furthermore, dividing tasks by required skills ensures employees have a satisfying workload that avoids either overloading or underloading, thus contributing to employee well-being.

3.5. Vehicle HMI Design

To promote the implementation of a sustainable, novel transportation system from a social perspective, the automated vehicles' internal and external HMIs building the bridge between users and vehicles are optimized. Addressing the social dimension of sustainability, the development of HMIs for automated vehicles aims to ensure participation and equal opportunities in interacting with the novel transportation system and thus its societal acceptance [32]. Following the human-centered design process, an effective, efficient and satisfactory interaction with the vehicles is ensured by iterative, multi-step HMI development starting from the users' needs.

Thereby, in addition to the obvious intended users, incidental users must also be considered [83]. The context of use analysis has shown a wide range of possible vehicle uses, both for passenger transportation and for supporting or taking over various working activities. Passengers using the vehicles as a means of transportation as well as working persons integrating the vehicles into their work are relevant user groups. Besides those user groups, both characterized by an intended vehicle use, incidental users such as pedestrians, who do not necessarily want to interact but have to when encountering the vehicles in the shared traffic space, should also be considered [83].

Furthermore, the analysis of user requirements shows that a multimodal HMI design approach seems the most appropriate [52,84]. Multimodality means the combined use of visual, auditory and gesture-based input methods by the human and output methods by the machine [52]. Because vehicles as a means of transportation can increase mobility for people who cannot drive themselves due to mobility and sensory impairments, such as the elderly and blind, HMIs that address multiple human modalities meet the requirements for an inclusive approach [52]. Although in the vehicles' primary context of use—road traffic—communication is primarily non-verbal and the visual modality is paramount [85], in close interaction with working persons, the audiovisual modality might be preferred due to the combination of verbal as well as non-verbal information exchange. Inside the vehicle, the combined use of visual and auditory modalities also ensures that passengers do not miss relevant information while they are engaged in other activities, such as looking at their smartphone or listening to music [84,86].

In addition, to provide an intuitive, easily understandable interaction concept that builds upon existing and known concepts and is not cognitively demanding, the automated vehicle uses a unique anthropomorphic interaction concept—the avatar—serving as the central point of contact for all user groups [87]. As an external HMI, the avatar head on the vehicle's hood is equipped with a display featuring abstract robotic eyes (see Figure 5a) and can not only mimic driver behavior in terms of eye contact and head gestures, but also make or receive voice announcements and sound signals via speakers and microphones [24,88]. The avatar can negotiate with incidental users such as pedestrians about the right of way in street crossing situations, can be used by passengers to check into the vehicle and can take instructions from working persons. In addition, in the area of the grille, the vehicle is equipped with an LED matrix display (see Figure 5a) as another external HMI that displays the vehicle's maneuver, automation and job status via text and symbols. Thus, the automated vehicle's external HMIs combine anthropomorphic and textual features, which has been rated as the best approach from the perspective of pedestrians as vulnerable road users in large crowdsourcing surveys on a variety of external HMIs presented by the automotive industry [89]. Through the interplay of information conveyed by the avatar head and LED matrix display, the vehicle communicates its perception and intention, which is considered particularly relevant by pedestrians [90].

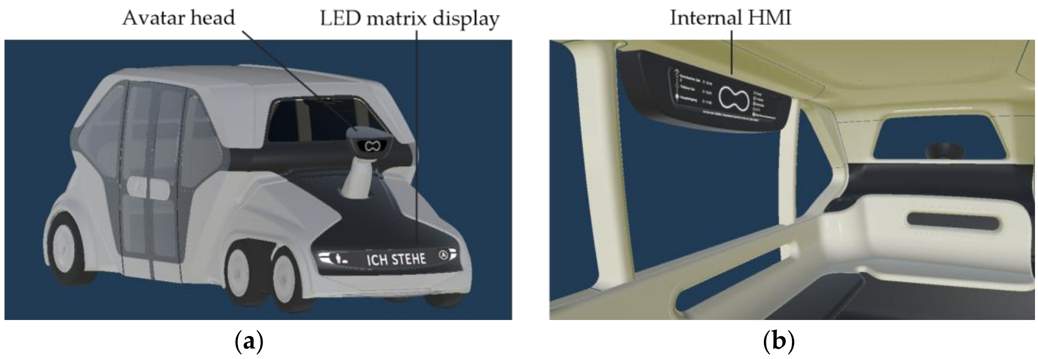

Figure 5. The CityBot human–machine interface (HMI) components consist of (**a**) external HMIs such as an avatar head with a display, speakers, microphones and an LED matrix display, and (**b**) an internal HMI with a display, speakers and microphones.

Moreover, to prevent passengers from feeling disconnected from the driving task and suffering a loss of control in the automated vehicle, the avatar eyes that people come to know outside the vehicle as a representative of the AI driver are also integrated into the display as part of the internal HMI (see Figure 5b) [91]. In addition, as part of the shared transportation concept, travel-related information is presented visually and communicated verbally via speakers in line with current interface concepts in public transportation [92,93]. Furthermore, the internal HMI is equipped with microphones, which mainly serve as the communication interface between passengers and the operation center.

4. Discussion

A short overview of the applied approaches for the sustainable design of the examined system components is given in Section 4.1. After that, the qualitative impact of the suggested technical optimization efforts of the considered system components from the perspective of the different sustainability dimensions, as defined by Goodland [28], is given in Section 4.2. The baseline for that discussion is to highlight the contribution of the technical optimization efforts to the overall sustainability of the innovative mobility and logistics concept. Within this context, an outlook on further research on the interdependences between the sustainability dimensions is given. Furthermore, the methodological framework of this paper is briefly discussed and framed within the existing sustainability discourse in Section 4.3. Finally, the contributions are briefly contextualized within system innovation by assessing their potential impact on the further development of the predominant transportation regime in Section 4.4.

4.1. Overview of Applied Approaches for Sustainable Design

An overview of the applied approaches for the sustainable design of each system component according to their specific tasks is given in Table 1.

Table 1. Applied approaches for sustainable technical optimization efforts.

System Components	Development Phase	Design Approach
Powertrain Design	Detailed Design	LCA according to DIN EN ISO 14040 [42] and DIN EN ISO 14044 [43]
Longitudinal Control Design		
CTMS Design	Early Concept Design	Adjusted VDI guideline 2221 [41] considering ecodesign strategies
Operation Center Design	Detailed Design	Human-centered design process of DIN EN ISO 9241-210 [44]
Vehicle HMI Design		

The powertrain and longitudinal control design is optimized during the detailed design phase by applying the LCA approach according to DIN EN ISO 14040 [42] and DIN EN ISO 14044 [43].

The CTMS design is developed in the early concept design phase by applying the adjusted VDI guideline 2221 [41] and incorporating ecodesign strategies.

The operation center and vehicle HMI design are optimized during the detailed design phase by applying the human-centered design process outlined in DIN EN ISO 9241-210 [44].

4.2. A Discussion of the Achieved Impact on Sustainability of the Technical Optimization Efforts

An overview of the contribution of the five examined system components to the three sustainability dimensions is presented in Table 2.

Table 2. Contribution of system components to sustainability dimensions.

System Components	Sustainability Dimensions		
	Economic	Ecological	Social
Powertrain Design	✓	✓	
Longitudinal Control Design	✓	✓	
CTMS Design	✓	✓	✓
Operation Center Design	✓		✓
Vehicle HMI Design			✓

In the dimension of *economic sustainability*, the optimized vehicle powertrain design reduces the use of rare earths and electric energy, which is further decreased during operations by the optimized longitudinal control design. This creates the possibility to reduce costs for operating the system, making it more affordable for users. Also, with the help of the CTMS design, indirect economic costs, resulting from waiting times of users, congestion effects and operating costs are weighed up and minimized during operations. Furthermore, the design of the operation center is optimized with regard to the number of workstations needed based on task frequency in order to create workstations in an economically sustainable manner.

In the dimension of *ecological sustainability*, the reduced resource consumption of the optimized powertrain and longitudinal control design has a positive impact. While designing the powertrain, the LCA is considered to reduce the vehicle's overall GHG emissions from production and use to the disposal phase. Focusing on the vehicle's use phase, the improved longitudinal control design further decreases electric consumption and thus prevents the use of natural capital. Additionally, by increasing occupancy rates in the CTMS design via the ride-pooling approach, the need for vehicles and associated raw material consumption is decreased.

In the dimension of *social sustainability*, the wide range of social functions that can take place in the different kinds of public road space are considered by controlling road utilization in such a way that the needs of all stakeholders are accounted for. Most importantly, the CTMS design provides sufficient transportation capacity and thereby ensures accessibility to transportation. The operation center design further increases social sustainability by offering the opportunity to give special consideration to disabled users and providing a contact point for passengers to contribute to their feelings of security. Moreover, to ensure participation from the interaction perspective as well as equal opportunities in interaction with the novel transportation system, for the vehicle HMI, a universal, intuitive and inclusive design approach in the form of a multimodal, anthropomorphic HMI interaction concept is pursued.

This work focuses on the direct effects of system components on the three dimensions of sustainability in order to delimit the various dimensions of sustainability, enhance their comprehensibility and clarify the contribution of the different research fields. However, a closer look at the economic, ecological and social sustainability dimensions reveals interdependences between them, as discussed in [37].

In terms of the interdependence between economic and ecological sustainability, conserving natural capital through reduced resource use and lower electricity consumption also leads to higher economic sustainability, as costs and thus economic capital can be saved (e.g., reduced use of rare earths). The interdependence of ecological and social sustainability can be best shown by the reduction in the required amount of rare earths per vehicle. This reduction improves ecological and social sustainability by decreasing the ecological and social conflicts emerging from mining activities in the global south. However, it may be mentioned here that a reduction in material use can only be one building block to decrease the ecological and social impact. Given the growing global demand for rare earths, further solutions are needed which exceed the scope of technical optimization [46]. Similarly, the source of electrical energy impacts the system's sustainability but also exceeds the scope of technical optimization within the considered system. The interdependence between economic and social sustainability is best exemplified by the user costs of a transportation system. The low cost of using the system makes individual mobility affordable for more people, especially lower-income groups, thus increasing social sustainability by enabling participation by all. Despite the low costs for users, the profit for the system provider must also be considered to assess overall economic sustainability. These examples show that there can be positive and negative correlations between sustainability dimensions. This means that sustainability cannot be maximized in an absolute manner and that the sustainability dimensions must be balanced against each other. Different combinations of the three sustainability dimensions can therefore lead to the same level of overall sustainability.

The aforementioned examples depict the interdependence of the sustainability dimensions in different technical disciplines, offering a foundation for further comprehensive analysis in future work.

4.3. A Discussion of the Methodological Framework

Taking a glance at the methodological framework of this paper, previous studies have contributed to defining what makes transportation sustainable by deriving measures or objectives for sustainable transportation from the three sustainability dimensions in a top-down manner [34–36,38]. Previous studies have shown how sustainability considerations can be considered in the conceptual design of innovative mobility and logistics solutions [41]. In contrast to these, this paper took a bottom-up perspective by examining different possibilities of how some technical optimization efforts can contribute to sustainability in the framework of a case study approach. Hereby, early technical optimization efforts of different technical system components for an innovative mobility and logistics concept were presented. The results may be a first step toward framing the further development of the discussed technical system components within existing sustainability discourses. Sustainability considerations during the early stages of technical system components' development may contribute to the ability of the resulting system to transition toward or potentially reach sustainability.

As discussed in Section 1.3, previous research on sustainable transportation primarily focuses on either designing sustainable mobility and logistics concepts or implementing these solutions in specific settings. However, it is also crucial to design system components sustainably between these steps. The proposed case study addresses this gap by evaluating the potential impact of sustainable component design on overall system sustainability and the interdependences among disciplines. Together, these three steps—concept design, component design and implementation—are vital for achieving system innovation and advancing transportation sustainability. The three suggested steps are then followed by the ongoing incremental change in system components causing incremental innovation, as widely seen in the current PMV-dominated transportation paradigm [13]. The suggested overall development process for sustainable mobility and logistics solutions is shown in Figure 6.

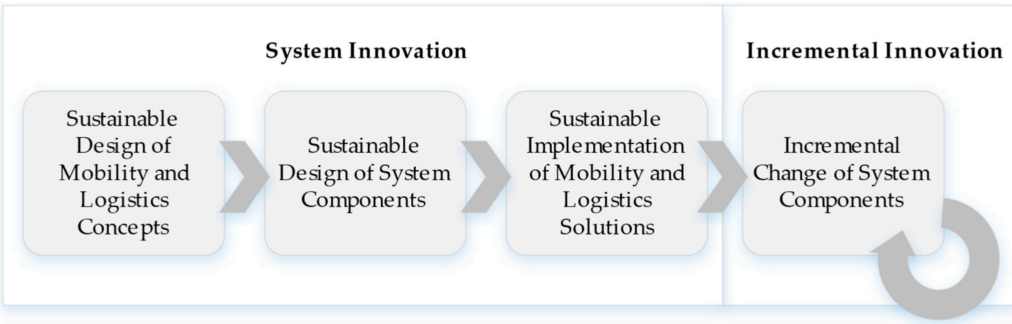

Figure 6. Suggested development process for sustainable mobility and logistics solutions.

4.4. A Discussion of the Results in the Context of System Innovation Requirements

Putting the results of this paper in the context of system innovation, it is worth mentioning that the discussed mobility and logistics concept, as introduced in Section 1.2, may currently fail to meet the non-technical requirements (see Section 1.1) to completely replace the current PMV-dominated transportation paradigm. On the one hand, sharing approaches represent a niche which faces growing acceptance [94,95]. But on the other hand, too many elements of the discussed mobility and logistics concept are not or not yet sufficiently aligned with the existing regime. This still prevents the discussed concept from facing significant competition with the existing regime. The reasons for this are, e.g., potential socio-spatial inequalities [16,17], psychological barriers [18,19], or simply the emotional ties people have with their own PMVs [9,93,94].

In conclusion, all elements of the socio-technical system of transportation need to be thoroughly considered to allow the current regime to transition to a more sustainable state. Hereby, sustainability considerations for the technical design of niche innovations during early technical development stages may be a valuable contribution.

5. Conclusions

Taking the example of the CityBot ecosystem and motivated by the idea of system innovation, a multidisciplinary approach for the sustainable technical design of a CASE vehicle fleet was presented. For the given innovative mobility and logistics concept, technical optimization efforts aimed at increasing economic, ecological and social sustainability were presented and qualitatively evaluated. The technical optimization efforts applied to the CityBot ecosystem cover several vehicle components as well as the orchestration of vehicle operations. Specifically, key challenges and possible solutions for the design of the powertrain, longitudinal control, the CTMS, the operation center and the vehicle HMI were presented. Hereby, the focus was placed on maximizing the sustainability of the system components in the economic, ecological and social dimensions.

Previous work on sustainability in mobility and logistics focuses either on the sustainable design of mobility and logistics concepts or on the evaluation of implementing alternatives of concrete solutions. This paper closes a research gap by suggesting a third step in the development process for mobility and logistics solutions. The additional step is explored by a case study giving insights into the potential for sustainability enhancements by technical optimization efforts of given system components. The suggested technical optimization efforts provide an example of how different engineering disciplines can contribute to the different interdependent sustainability dimensions. Methodologically, the consideration and evaluation of sustainability within a given technical case study represents a bottom-up perspective, which is new compared to previous theoretic work on sustainability within the transportation sector.

The discussion highlights the significance of sustainability considerations within technical optimization efforts by putting the results into the context of the existing sustainability discourse and system innovation. Overall, the results of this paper show that detailed consideration of all dimensions of sustainability in the development of technical system components is required to maximize and ensure the sustainability of innovative transportation systems. These considerations can be one important building block contributing to a more sustainable transition of the overall transportation system, which might become relevant in the next few decades.

For further research on the issue of social sustainability, general strategies for social design still need to be developed analogously to the ecodesign strategies mentioned in [39,45]. To derive these, essential aspects for social sustainability like trust, common meaning, diversity, a capacity for learning and a capacity for self-organization need to be taken into account [46]. A comparison of the outcome of such strategies with the outcome of the application task-specific guidelines could open up further research gaps for the sustainable design of system components.

Furthermore, it would be valuable to investigate in detail how the three suggested steps for developing mobility and logistics solutions interact from a system innovation perspective and what recommendations can be made for industrial and political decision-makers. Additionally, given the pressing need for system innovation in transportation, interdisciplinary research is required to identify key factors, potential measures and implications for innovative mobility and transportation concepts, as well as for the design of their system components, to remain competitive with the prevailing transportation paradigm. Thereby, all three suggested steps for the development of mobility and logistics solutions should be taken into account to derive a comprehensive framework for sustainable system innovation in transportation.

Author Contributions: Conceptualization, P.R., P.H., T.P., S.S.-D. and N.T.; methodology, P.R., P.H., T.P., S.S.-D. and N.T.; resources, P.R., P.H., T.P., S.S.-D. and N.T.; investigation, P.R., P.H., T.P., S.S.-D. and N.T.; validation, P.R., P.H., T.P., S.S.-D., N.T. and A.C.; writing—original draft preparation, P.R., P.H., T.P., S.S.-D. and N.T.; visualization, P.R., P.H., T.P., S.S.-D. and N.T.; writing—review and editing, P.R., P.H., T.P., S.S.-D., N.T., A.C., A.O., S.R. and B.A.; project administration, P.R., P.H., T.P., S.S.-D. and N.T.; supervision, A.O., S.R. and B.A.; funding acquisition, P.R., P.H., T.P., S.S.-D., N.T., A.C., A.O., S.R. and B.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the German Federal Ministry for Digital and Transport (BMDV), grant number 45KI15I091.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors would like to thank the Campus FreeCity project consortium (https://www.campusfreecity.de/, accessed on 1 July 2024) for the valuable collaboration and support.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

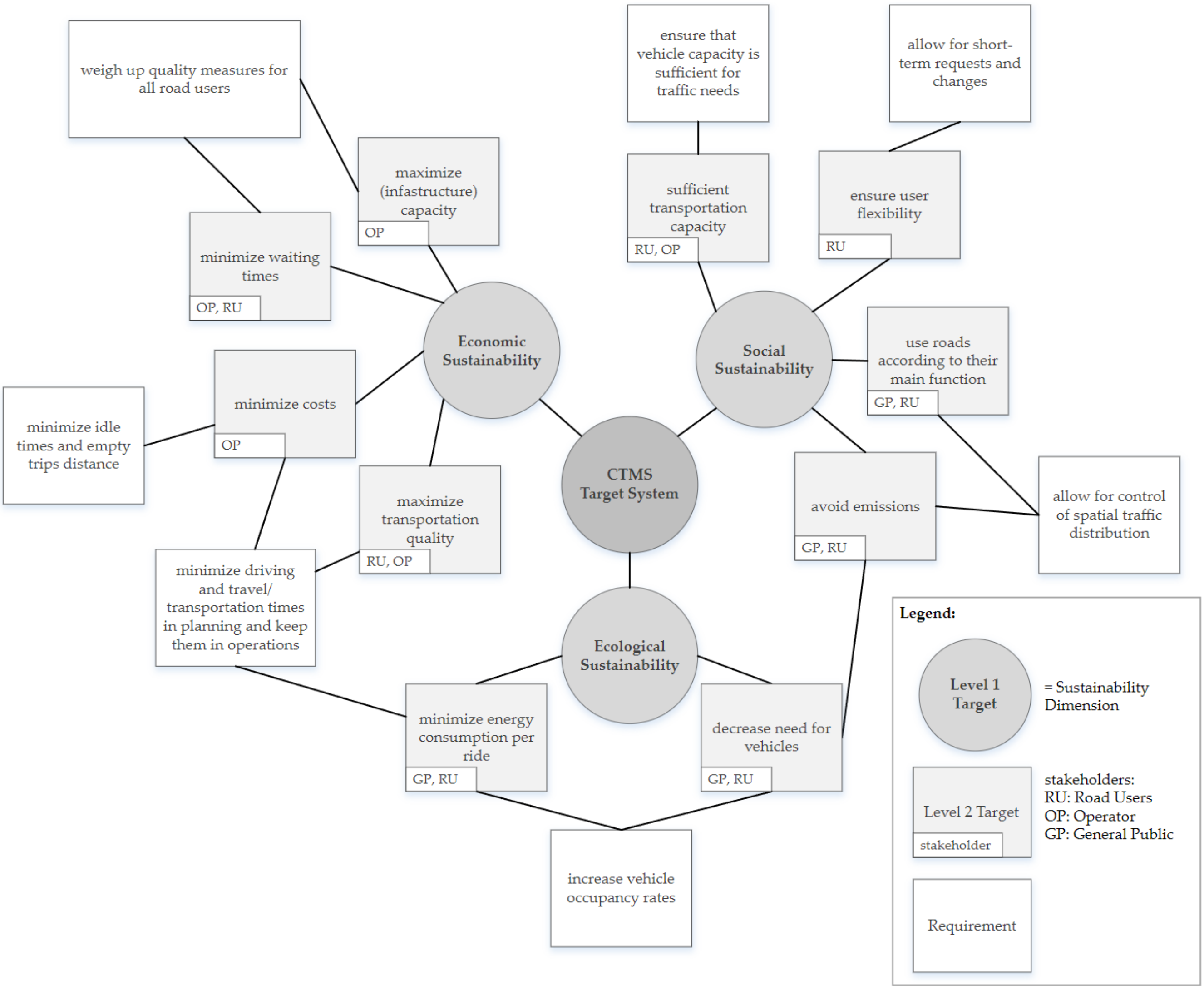

Figure A1. Derivation of capacity traffic management system (CTMS) requirements based on sustainability dimensions.

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