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Review

A Review of the Transformation of Road Transport Systems: Are We Ready for the Next Step in Artificially Intelligent Sustainable Transport?

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Abstract: Mobility is experiencing a revolution, as advanced communications, computers with big data capacities, efficient networks of sensors, and signals, are developing value-added applications such as intelligent spaces and autonomous vehicles. Another new technology that is both promising and might even be pervasive for faster, safer and more environmentally-friendly public transport (PT) is the development of autonomous vehicles (AVs). This study aims to understand the state of the current research on the artificially intelligent transportation system (ITS) and AVs through a critical evaluation of peer-reviewed literature. This study's findings revealed that the majority of existing research (around 82% of studies) focused on AVs. Results show that AVs can potentially reduce more than 80% of pollutant emissions per mile if powered by alternate energy resources (e.g., natural gas, biofuel, electricity, hydrogen cells, etc.). Not only can private vehicle ownership be cut down by bringing in ridesharing but the average vehicle miles travelled (VMT) should also be reduced through improved PT. The main benefits of AV adoption were reported in the literature to be travel time, traffic congestion, cost and environmental factors. Findings revealed barriers such as technological uncertainties, lack of regulation, unawareness among stakeholders and privacy and security concerns, along with the fact that lack of simulation and empirical modelling data from pilot studies limit the application. AV–PT was also found to be the most sustainable strategy in dense urban areas to shift the heavy trip load from private vehicles.

Keywords: autonomous cars; urban mobility; rapid bus transport; greenhouse gas (GHG) emissions; energy conservation

1. Introduction

The buzz around autonomous mobility, intelligent transportation system and smart cities has propelled the ventures of personal and public transit into new domains. In its early purview, concept of autonomous vehicles was integrated with urban bus transit in the form of the United States Department of Transportation (US DoT)'s Vehicle Assist and Automation (VAA) programme (tested with 1 m spaced permanent magnetic markers over a 3-mile route in a maintenance yard), and California's PATH, a completely automated highway bus fleet in 2003. While the VAA tests on buses were performed in 2014 by operating an equipped bus for 6–8 h/day, completely autonomous bus transit operations have yet to be developed, as most current systems require drivers with the partially automated speed or lane controls [1]. At present, automated vehicles are categorised by the National Highway Traffic Safety Administration (NHTSA) [2–4] according to their automation functionality into five levels of increasing automation (ranging from zero automation to a completely unmanned autonomous vehicle).

For example, the VAA programme demonstrated a Level 2 in the US state of Oregon, that is, precision docking and lane adherence by the steering automation, while with the manned braking and throttling of on-transit bus. Figure 1, prepared after Liu [5], covers the state of research on the autonomous transportations systems in urban areas around the world based upon the vehicular size, capacity and operational features.

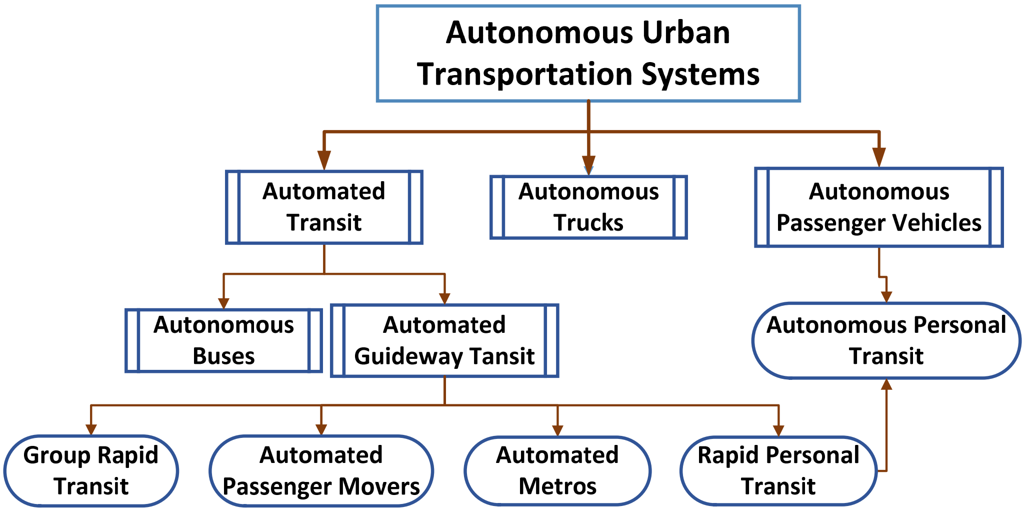

Figure 1. Mode classification of autonomous urban transportation (based on Liu [5]).

On the note of autonomous buses, CityMobil2 is an innovative PT project, tested at the University La Sapienza in Rome to investigate the feasibility of autonomous public transit by studying the shared and on-demand mobility on an automated guideway transit, road user interactions and bus user experiences, where a considerably positive outlook from the public (See Section 2.3) was observed. Automated guideway transit was defined by Liu [6] and Liu et al. [1] as a mode of urban transportation where dedicated tracks are used for the operation of completely autonomous vehicles. In the case of autonomous personal transportation, companies such as Volvo and Nissan have expressed interest in commercially marketing autonomous vehicles by the year 2020 [7,8]. While according to Google co-founder Sergey Brin, autonomous vehicles may be a reality on U.S roads within the next five years [9] or so. Researchers such as Wang [10] and Fagnant and Kockelman [11] proposed that the operation of autonomous personal cars may result in safer and less congested travel. As already evidenced by the increased fuel savings, roadway capacity, accident aversion and lower emissions are now due to the introduction of some level of automation (e.g., assisted parking and adaptive cruise control) in newer cars. Apart from fully automated cars such as Massachusetts Institute of Technology (MIT)'s fully autonomous Land Rover LR3 Talos [12], shared autonomous vehicles (SAVs) have also been researched as an extension of the emerging e-hail or car-sharing [13]. Fagnant and Kockelman [14] simulated the behaviour of these SAVs and observed that technological barriers of completely operational and affordable autonomous vehicles, as well as regulations regarding commercial automated taxi service licensing, are still to be drafted.

In the domain of on-demand mobility, Tang et al. [15] have respectively expressed the ability of an overall ITS in improving user behaviour, air quality, travel time, productivity and safety, propelled by revolutions in the fields of electronics, robotics, information technology and cybernetics. Due to logical and temporal constraints, accurate recognition and distinction between objects and humans on a roadway are most critical for autonomous vehicles on urban roads, followed by complex manoeuvre, blocked routes, congested traffic operations and obeying traffic rules [16], as well as the overall sustainability of commissioning AVs from public investments.

The purpose of the current paper is to perform a critical review of peer-reviewed research in the field of vehicular automation, so as to map the status of autonomous urban transportation, and specifically to ask the question of how driverless vehicles are changing the way we think of artificially intelligent transportation systems.

The question of the smart cities of the future and technological transformation of urban roadway systems is also closely linked with the triple-bottom-line sustainability approach: cost, environment and social interactions [17]. This current study is intended to serve as a platform for a pilot study on the exploration of artificially intelligent sustainable urban transport with the city of Abu Dhabi as a case study. Our keywords: autonomous cars, sustainable transport, smart cities, intelligent urban transportation and ITS, were entered, and the 22 primary and 79 supplementary studies returned from Google Scholar and ScienceDirect were analysed, and are described in the following sections.

2. Dimensions of Artificially Intelligent Transport Systems

This section discusses the primary dimensions of artificially intelligent transport systems (Figure 2) across the existing literature, as: on-demand mobility, shared autonomous vehicles, autonomous public bus transport, lane control and vehicular guidance systems. The benefits of smart technologies and artificially intelligent transport systems for travel time reduction and easing congestions, along with incident management, are also discussed in this section. A general finding was that the majority of existing studies on the performance evaluation of such systems largely focused on programming and technological aspects, public law and transport law and profit generation. Although demand management was also extensively studied in recent literature, little attention is paid to the long-term impact of implementing artificially intelligent transport systems and the resulting travel pattern variations, particularly in the context of sustainability performance evaluations.

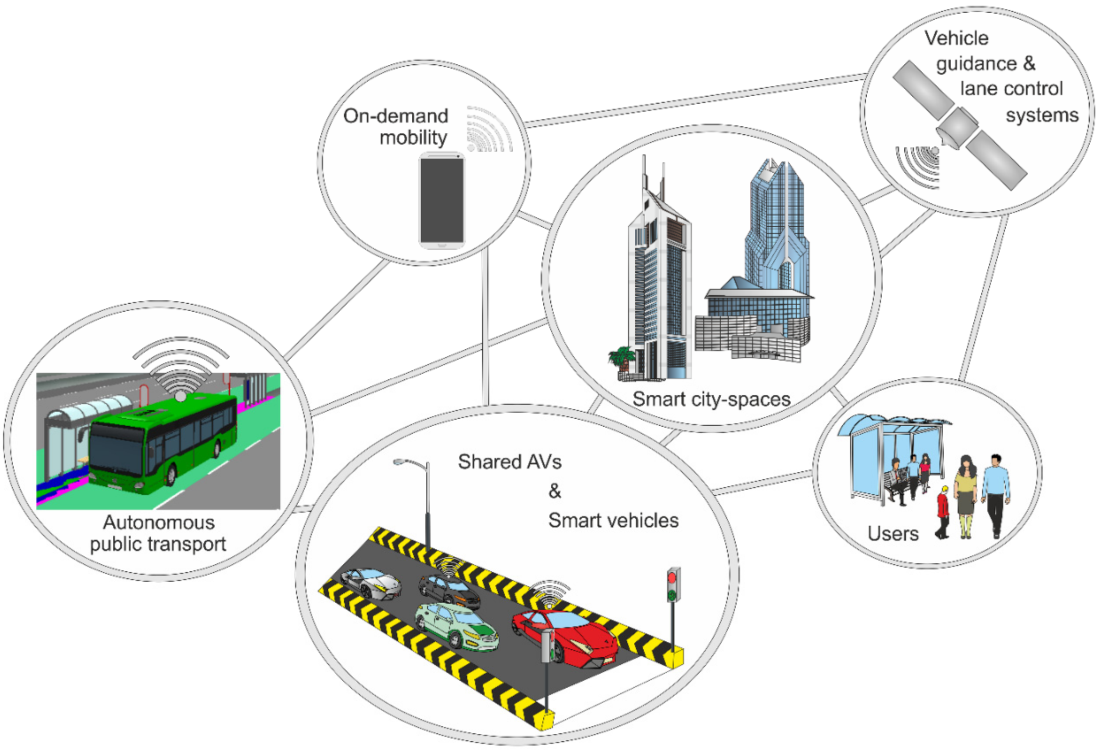

Figure 2. Dimensions of a connected artificially intelligent transport system: on-demand mobility, smart city-spaces, users, PT and vehicle guidance systems.

2.1. On-Demand Mobility Solutions

The advances in on-demand mobility have increased their popularity before the introduction of automation (e.g., Uber, Lyft, Hailo etc.). These programmes have been aimed at replacement of private automobile trips from vehicle ownership to a rental service that is run on-demand. Fagnant and Kockelman [14] have commented on the increasing popularity of these services, for example, the users in the United States double every year or two.

Greenblatt and Shaheen [13], in their study reviewing automated, on-demand mobility and the associated environmental impacts, found that around eighty percent or more greenhouse gas (GHG) emissions and energy use reduction may be observed with the use of autonomous vehicles. They also proposed that social benefits (lower VMTs and ownership reduction), environmental load suppression, land-use and mass transit benefits may be achievable through on-demand mobility. Adding AVs may result in further reduction as smaller and more efficient SAVs become a reality, as these vehicles may result in overcoming the ride-sharing obstacles of users travelling to a reserved spot to access rental cars.

2.2. Shared Autonomous Mobility Solutions

Preceded by existing, commercial, car-sharing rental services (e.g., ZipCar and Car2Go), probably one of the most widely researched applications of autonomous vehicles as a solution to urban transit problems is the SAV. The concept of shared car mobility came from the relatively low ratio between the number of private vehicles owned and the actual number of vehicles in use during a typical day. Santos et al. [2] suggested that approximately 10% of vehicles (models > 10 years) are on road on a representative day, which became slightly higher (17%) when newer vehicles (models ≤ 10 years) were considered. Buying more cars is not the mobility solution for the present trip demands in most areas, and a transitioning towards a subscribed or pay-as-you-go vehicle in suitable areas may have more economical and environmental viability as the vehicle kilometres travelled are reduced. Shaheen and Cohen [18] found that the ride-sharing users increased to be 890,000 in the U.S. by 2013 from 12,000 in 2002. A follow-up survey by Shaheen and Cohen [19] found that around 104,000 shared vehicles are currently serving 4.8 million users across 1531 cities globally, with the fleet distribution in Figure 3, and with Mexico and Italy accounting for the highest (131:1) and second highest (107:1) member-vehicle ratios, respectively.

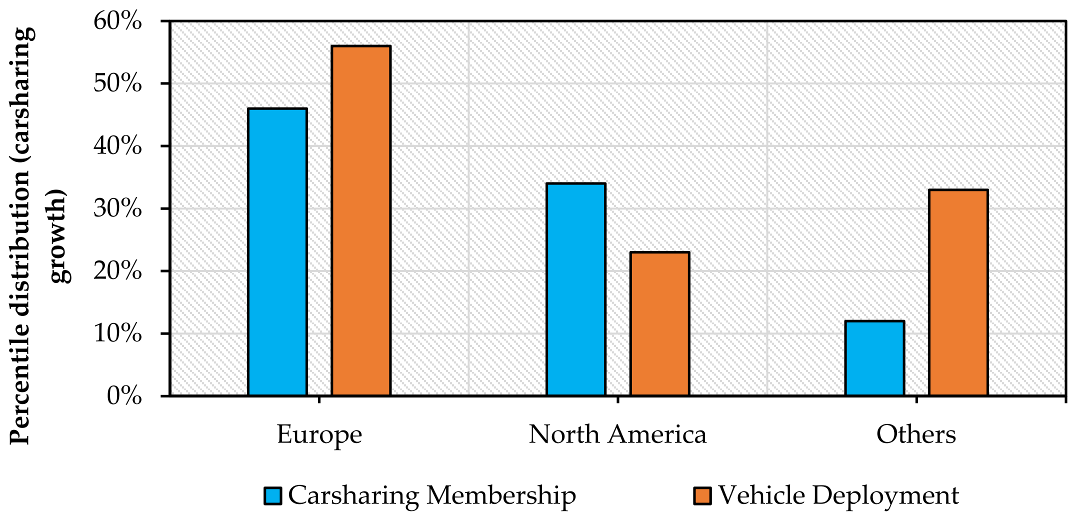

Figure 3. Percentile carsharing membership and vehicle deployment distribution of shared vehicle services.

To the end of on-demand, autonomous mobility or aTaxis, as dubbed by Kornhauser [20] complementing passenger transit in urban centres, a number of research works have been commissioned. For example, the replacement of private cars in metropolitan areas by SAV taxi services was analysed by Ford [21] and Kornhauser [20], where passengers were required to travel to taxi stations, similar to the Car2Go services. Rigole [22] in the metropolitan Stockholm region, focused on developing a framework to assist in dynamically allocating SAVs. This was achieved through the use of the present roadway network depiction, private commute-demand and multi-criteria evaluation (i.e., fleet size, travelling and waiting times), along with rerouting vacant vehicles based on varying values of these variables.

The life-cycle analysis was performed to evaluate the environmental burdens of both traditional (diesel and petrol) and electric cars. Their results showed that by only utilising under 10% parking spots and private vehicles, an on-demand personal SAV transportation system can provide highly efficient "door-to-door" services. However, the results of the study are exceedingly hampered by the decision of users to accept ride-sharing. On average around a 15% increase in passenger travel times and 10 min starting time window was expected along with lower traffic congestion and environmental impacts, which greatly increased as ride-sharing was replaced with vacant car drives between trips. Results are compatible with the market need for a shared vehicle which gave rise to projects such as ZipCar, for example, which aims for a "simple and responsible urban living" [23], and is supported through smart cards and Android/iPhone apps for identifying vehicle location. Affordability has been cited [1] as the primary driving force for the popularity of ZipCar with millennials, and especially in densely populated urban areas, with approximately 470 cities supported by 10,000 cars or so. Therefore, the potential application of SAVs on the mobility spectrum is promising.

Evaluation of the benefits of on-demand autonomous vehicles was conducted by Fagnant and Kockelman [11] and Fagnant and Kockelman [24]. Approximately 8.7% of the distances travelled by the 56,000 SAVs every day were found to be vacant, reduced to 4.5% by allowing for car-sharing. Three market penetration rates: 10%, 50% and 90%; with VMT per AV 10% higher at 90% and 20% higher at 10% market penetration were used, for representing the introduction of new technology and probably a more accepting public perception over the years. The study used the discount rate and dollar-value of passenger vehicle time based upon the cost data (17 USD/person-hr) and the 2020 traffic flow patterns, of Schrank et al. [25], as the baseline. Results illustrated benefits in the form of a reduced demand for parking, fuel savings and lowered congestion levels. Shladover et al. [26] proposed that congestion may fall in freeways by approximately 60% if market penetration is assumed at 90%. The study proposed that a careful evaluation of market penetration and public perception is the key to the efficient operation of SAVs.

2.3. Autonomous Public Bus Transport

Personalised rapid transport (PRT) is currently being researched as a sustainable transit solution with the use of electric autonomous single cabin vehicles in a pilot study by the Masdar Institute of Science and Technology, Abu Dhabi [27]. However, the future vision of PT in smart cities is expected to harness the potential promised by automation, as discussed earlier. The initial feedback received from the VAA field tests included lesser stress experienced by drivers and the ability of the steering system to aid the drivers in any complex manoeuvres through narrow rights-of-way. Stakeholder responses from the CityMobil2 project [28] have shown as being overwhelmingly predisposed towards autonomous vehicles, with the exception of Vantaa respondents, operating on dedicated lanes as illustrated in Figure 4 [28].

The potential for automated buses to change the fundamental nature of PT has been promising, but design sensibility and accounting for the social implications are considerably important for planners. Understanding that technological Darwinism has produced an overt emphasis over advanced mobility, projects such as Atkin's Venturer in Bristol for testing the sensors and communication networks of primarily AV buses, ARUP's UK Autodrive and the 8 million GBP government and consortium members has led the three years "Innovate UK" urban deliveries project in Greenwich. One of the most notable projects on driverless vehicles is the safer, cleaner and innovative transport being researched by the Transport Research Laboratory's GATEway (Greenwich Automated Transport Environment) project, which uses 8 to 10 passengers' capacity vehicles. In all phases of trials, public engagement and feedback were collected to further ascertain the perception of the public regarding autonomous vehicles, further discussed in the perception section of this study.

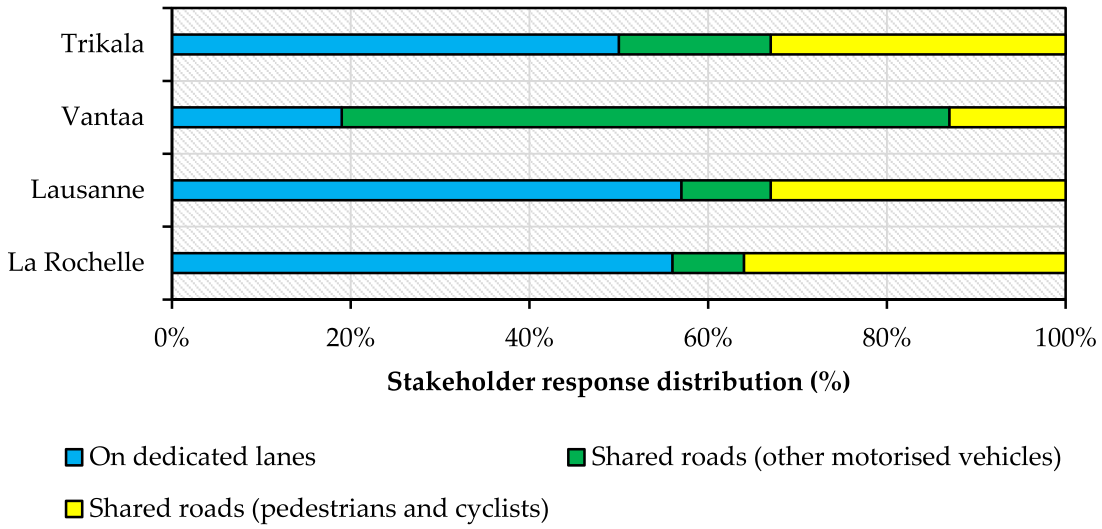

Figure 4. Stakeholder response distribution towards autonomous bus mode choices.

It should be noted here that the large-scale application of AV buses has not been implemented for real-world mobility issues. Nonetheless, AV buses can be integrated with the already-used PT priority schemes [29] to tackle congestion issues. These integrated transport systems (i.e., AV buses equipped with transit prioritisation schemes) may have improved ride comfort and travel time over conventional buses, as also demonstrated in a microsimulation study by Nguyen et al. [30]. This may aid in a largescale acceptance of AV buses by the public due to time savings, low cost and high ride comfort [31].

2.4. Lane Control, Remote Sensing and Vehicular Guidance System: Vehicle to Infrastructure Communication

A common feature of paved roadways around the world is the presence of lane control features, such as painted boundaries, lane markers, road signs, etc. The application of ITS for modernising the roadways and improving lane control, dynamic message signs and remote radio-frequency identification (RFID)-type controllable sensors have been cited by researchers [32,33] as a critical feature of modern cities. Better communication between ITS roadway sensors and AVs may also be observed which can reduce average vehicle mileage, crashes and traffic congestions. The big data and machine learning revolution [34] is expected to result in intelligent control, traffic pattern recognition, embedded electronic markers (similar to barcodes), cognition of roadway users and adapting according to traffic behaviour. According to Wang [35], agent-based controlling of transportation management on an on-demand basis may be a more cost-effective and reliable alternative to traffic control while providing flexibility. Wang [10] commented that instead of traditional reliance on traffic lights, cooperative intelligent-space technology may be implemented at intersections over ad-hoc networks. Sustainable, ITS-controlled transportation systems may also account for the social and climatic variations [36,37] of automated transit gateways through a comprehensive agent-based model.

At present, there are many sensor-based, vehicular guidance systems available for partially automated assistance in navigation, parking assistance, crash aversion and warnings in lane departures, such as the adaptive cruise control (ACC). Shladover et al. [26] estimated that the effective capacities of roadway lanes may be increased by up to 80% (for a 90% market penetration of ACC), depending upon market shares. KPMG and the Center for Automotive Research [38] found that improvements in traffic congestion not only depend upon automated driving, but also efficient roadway sensors providing active in/out vehicle-environment sensing. For instance, vehicle to the roadway (e.g., traffic signals) and vehicle to vehicle communications to increase system performance and improve operational safety. Dey et al. [39] note that reliable, efficient and effective wireless communication between connected vehicles (i.e., vehicles using vehicular guidance system for Level 1–2 automation) or autonomous vehicles and the appropriate infrastructure, is essential for modern transportations systems. The authors [39] also highlighted the need for a safe, sustainable and secure wireless network for a large-scale operation to tackle mobility issues for real-world applications. Future research on vehicle guidance and vehicle-to-infrastructure communication for ITS application in transportation should acknowledge the safety-related issues as also noted by Ndashimye et al. [40]. Nonetheless, public investments should be directed accordingly at exploring all dimensions of the transport system's life-cycle, including social factors, environmental, mobility and safety features.

2.5. Traffic Congestion and Travel Time Reduction

So far, it has been discussed that the majority of travel time and environmental burdens to users on a roadway network come from the supported traffic [41], and a transit system may considerably reduce the emissions [42]. The cost of traveller time delays has been found by Rister and Graves [43] as a significant contributor to the total cost of the operation of a roadway. Gupta et al. [44] and Litman [45] have proposed that if the demand–management strategies are not carefully developed, the miles travelled by roadway users are expected to greatly increase. Traffic flow patterns are expected to fluctuate if effective vehicle–environment communication and autonomous vehicles are to become a reality on future smart cities. Research on connected automated vehicles (CAVs), has been proposed in the 2015 Automated Vehicles Symposium [46] to heavily rely on their impact on network routing, traffic control and bottleneck capacity recognition. Utilisation of adaptive cruise control and ITS-based monitoring of traffic flow have been reported by Atiyeh [47] to increase traffic speeds (8–13%) and fuel savings (23–39%).

Similar to the agent-based model for ITS roadway systems, described earlier, another study focusing on the design of an agent-based model for SAVs was conducted by Fagnant and Kockelman [14]. They studied the environmental benefits of SAVs comparative to the traditional privately-owned vehicles by mimicking trips based on real-time travelling profiles, departure and destination times and origin and destinations in a grid-based, urban setting. The case study model, run over 100 days, was equipped with the relocation of unused vehicles (which was observed for some vehicles when the model was run), varying fleet size, and service and trip generation distribution and congestion levels. Relocation of SAVs may result in 11% higher travelling as vacant vehicles move to towards the subsequent travel, showing dependence on user concentration, but may replace 10 times of privately owned vehicles. Nonetheless, the model predicted that the block-to-block relocation strategy resulted in more benefits compared to zonal relocation. It may be more suitable for reducing traffic congestion if a dynamic SAV relocation strategy is applied followed by the use of an alternate source of energy and newer vehicles in the network to reduce environmental loads.

2.6. Incident Management

The conversation on autonomous driving mostly ventures towards crash aversion and incident management, with a common argument given that autonomous vehicles are not expected to tailgate, speed or drive under the influence of drugs and alcohol. The National Highway Traffic Safety Administration [3] notes that approximately 90% of crashes are caused by an error on the part of drivers and also that fatigue, distraction and alcohol/drug-use is behind 40% of fatal accidents [11]. Additionally, improper incident management on busy roads and highways contributes to traffic congestions that can have adverse impacts on driving behaviours, ride quality and travel time [48]. Nonetheless, Cambridge Systematics [49] noted that the cost of congestion is actually half than that of crashes, which cost approximately 277 billion USD/year. However, as noted by researchers like Farhadi et al. [50] and Campbell et al. [51], it may be difficult for the currently developed autonomous vehicles to safely tackle all crash scenarios and distinguish between objects and roadways.

The immediate application of autonomous vehicles for incident management purposes can be in the form of ambulances and other emergency services, provided that public acceptance is achieved [52]. On the other hand, Tupper et al. [53] compared the benefits of the ITS incident management system (traffic cameras) against savings from sustainable construction strategies: warm-mix asphalt, pavement recycling [54,55], reduction of fossil fuel reliance and using regionally-sourced materials [56,57]. Schrank and Lomax [58] have commented that urban areas prone to traffic delays by incidents often utilise cameras as an ITS-based incident management strategy. Fries et al. [59] also used traffic cameras for incident management, which forms the basis of Tupper et al. [53]'s study. Paramics' traffic micro-simulator with traffic pattern, control and geometric information as inputs and EIO-LCA [60] were used to compare savings in fuel consumption and reduction in direct GHG emissions on a six-lane, 16.4 km interstate segment.

However, the disturbance of traffic flow patterns during construction was not modelled. Mobile6 was used to determine the emission rates which were later used as inputs for Paramics. The simulation was supported by incident modelling through a dedicated algorithm to randomly select incident detection time from 1–5 min historical distribution. In general, the results illustrated that over 3–4 years of operation of ITS incident management strategy, the benefits of this system surpassed those from the sustainable construction-phase strategies. The study also recommended that higher weightage should be assigned to ITS incident management in the Greenroads rating system.

2.7. Tackling Problem of Parking

Maintaining equilibrium between the demand and supply of parking spots within urban regions has been critical for many transportation agencies around the city, as parking control forms an integral part of trip flow management. So far, the design of ITS-supported parking management systems has been researched, primarily focused on the close integration of entire roadway systems and parking facilities, thereby discarding the older approach of a secluded evaluation of parking-reserved areas in urban regions. A feasibility study on the use of telematics resources for the data management and logic architecture development of parking systems in the Rio de Janeiro metropolitan area of Niteroi was performed by Vianna et al. [61]. The study found that utilisation of telematics may potentially increase transport system coordination, the efficiency of control routine implementation and existing parking spots' management, which can then reduce pollution and traffic congestion. The primary outcome of the study was that the seemingly technological transportation systems are faced by problems that may not be entirely technical. The main obstacles in implementing ITS parking are the defragmentation of planning agencies, lack of policies, social and political issues, control and inspection, administration of various parking types (on-, off- and commercial) and a lack of will from parking operating agencies. Moreover, the parking systems should be planned together with the transportation systems, and cities should focus on a rational assignment of PT systems, the highest-burden of trip distribution load. Another solution to the parking problem, specifically user time wasted in the so-called "cruising for parking" may be avoided by AVs [62,63]. One of the studies, cited earlier [24], has indicated that approximately 10 user-owned vehicles may be replaced by a single SAV. Moreover, SAVs may also decrease the parking cost. Currently parking in general urban regions may cost 1400–3700 USD/spot and 3300–5600 USD/spot in central business districts, as Litman [64] has reported. Shladover et al. [26] commented potentially 250 USD/AV may be saved in parking costs, depending upon sharing rates.

3. Long-Term Implications: The Question of Urban Development and Sustainability

3.1. Urbanism and Urban Sprawl

A question that is not usually addressed in the AV-based research for transport systems is what automation in urban mobility will mean for urban development. Urban sprawl and the relocation of residents to cheaper neighbourhoods is a direct result of car-dependence, a behaviour that may witness further increases if AV private vehicles are readily available in the consumer market [65]. A preliminary study on the potential impact of AVs by Carrese et al. [66] was conducted in the city of Rome. The authors found that more than 70% of survey respondents showed interest in relocation to suburban areas based upon the market penetration rate of private AVs. The authors also projected through choice modelling and traffic simulation that by the year 2050, around a 50% penetration rate of private AVs is expected to result in excessive urban sprawl, which in turn will result in heavy traffic congestions in the suburban road network. On the other hand, PT usage may see a rapid decline after AV introduction in the private vehicle market [67] if adequate long-term planning measures are not implemented.

Transit-oriented development (TOD) can be adopted to reduce the overburden on personalised vehicle transit, and encourage PT uptake if mixed-use, high-density, residential developments are clustered around efficient, fast and reliable PT [68,69]. Lu et al. [70] performed a choice modelling study for the residents of Atlanta, GA, USA. They found that the integration of SAVs with TOD can result in extending the PT service radius of TOD to 3.22 km.

This study by Lu et al. [70] assumed that SAVs are expected to serve the first and last-mile need of local residents, and the survey results showed around 39.3% of the residents supported AV integration with TOD. However, Lu et al. [70] also recommended that future research should use real-word traffic flow data to develop traffic simulation models and investigate the application of AV-based PT system towards solving mobility issues. The AV-based intelligent transport study, currently being performed by the authors of this paper, is aimed towards addressing this recommendation.

3.2. Cost Implications

Further application of strategies such as intelligent transportation spaces, automated transit gateways and AVs may result in higher savings. For example, 4000 USD/year/AV from social benefits of parking, fuel efficiency, travel time and crash aversion as Fagnant and Kockelman [11] reported. Stephens et al. [71] found that the per-passenger mile cost of AVs is approximately $0.2 in the United States, provided that large-scale ride-sharing can be implemented. These results were considerably lower than the Netherlands-based findings of around $0.1 by Hazan et al. [72] for ride-sharing services using AV passenger cars. However, their study relied on average values and less detailed vehicle data, disregarding some stages of the vehicle life-cycle as well as the overhead cost.

Bösch et al. [73] conducted a detailed study on the cost implications of the vehicle fleet automation for the Swedish traffic. They found that the life-cycle costs of electric-powered AVs for the different vehicle types (shared/taxi vehicles, bus and rails) were lower than the respective types of conventional vehicles (CVs). This was mainly due to the high purchase costs being offset by cost savings in the low fuel, maintenance and insurance costs. In general, these operational level costs (per passenger-kilometre) showed that the AV-based bus, rail and shared taxi cars were 54.7%, 6.4% and 82% lower than their CV-based counterparts, respectively. The only exception was the passenger car where the AV-based car was slightly (4%) more expensive than the conventional cars due to the significantly higher share of the initial purchase cost in the vehicle life-cycle cost. However, the study did not account for the cost externalities, such as costs of growing a PT fleet, mode choice variation, user time costs and vehicle occupancy, as well as the per-unit cost of the environmental emissions.

3.3. Environmental Implications

Cities around the world are constantly pursuing energy conservation and climate preservation (i.e., to reduce adverse environmental emissions). Luers et al. [74] projected that in order to avoid the drastic climatic changes, GHG emissions must be considerably reduced. While Shaheen and Lipman [75] found the transportation sector to be the primary source of emissions (14%) around the world, and as such, the sustainability problems in roadway projects should be addressed. Although, there have been various programmes, e.g., Green Highway Partnership and Greenroads [76–78], for promoting partnership and innovation in sustainable transportation planning. Recycling of pavement materials [79,80], e.g., ~99% in Japan [81], and the introduction of newer materials such as warm-mix asphalt [82] have increasingly become popular. However, as Clyne [83] commented, the impacts on the performance of pavements are still uncertain.

The triple-bottom-line sustainability approach has also been researched, yet, the implementation of ITS as a tool for increasing sustainability of urban roadways is also uncertain. A life-cycle assessment study of Tupper et al. [53] on the urban South Carolina interstate found that an ITS strategy can reduce CO_2 emissions (992 tons over 2 years) more than five times than any of the Greenroads-recommended sustainable construction stage strategies, explained earlier. The study emphasised over the importance of ITS as a sustainability tool, especially since the fuel consumption reductions from ITS were 30 times higher than all four strategies combined over eight years of repaving. They further iterated that despite the emphasis of transportation agencies on strategies such as warm-mix asphalt (WMA) [84,85], ITS can potentially provide higher savings. It should be noteworthy that the study did not account for the cost parameter of sustainability; nonetheless, these environmental savings were noted for the implementation of only one ITS strategy.

Apart from the long-term implication of ITS in terms of environmental impacts, the life-cycle environmental performance of AVs in the transport system has also been investigated in the literature to a certain degree. A recent traffic simulation study by Patella et al. [86] in the city of Rome (assuming 100% battery-electric AV private vehicle penetration rate and 15-year vehicle service life) projected that the GHG emissions in the 100% AV scenario can be 60% (~744 tonne CO_2eq.) lower than the non-AV scenario over the 15 years period. Noise emissions are also a critical concern in modern societies with an increase in traffic levels. Patella et al. [87] investigated the acoustic environment of future cities in a hypothetical scenario (100% electric AV passenger cars in Rome) using traffic simulation. They found due to the differences in propulsion noises between conventional and AV passenger cars a better utilisation of road capacity by AVs (i.e., platooning) and improved traffic flow in the AV scenario. It should be noted here that these studies only focused on the automation of private vehicles and disregarded mix-type traffic flow situations. Similarly, the mode choice patterns of passengers, ride-sharing and population growth, etc., were not considered. Future work on estimating the environmental impact of AVs can build upon the preliminary results of these studies to develop traffic simulation models utilising the real-world traffic flow data for the mix-type traffic containing origin–destination, occupancy, mode choice and speed–time–volume profiles of all vehicle types. This way the impact of AV on modern cities can be accurately estimated towards aiding long-term policy development by the relevant municipal agencies.

4. Limitations of Past Research and Implementation Barriers

The current research identifies that multi-disciplinary problems are associated with making ITS and AVs an everyday reality. Intelligent transportation systems in general, and AVs in particular, have been viewed as a potential driver of the safer, cleaner and more efficient futuristic system. As the field is ever-changing, heavily dependence on the investment decisions of policy-makers, and its benefits and shortcomings deeply embedded in the question of on-demand mobility, uncertainty remains in its overall impact on the life-cycle of the urban roadway system. Hence, based on the agendas identified, Table 1 provided below, covers a comparative review of the studies covered in this paper to identify the important findings and limitations of existing research that can be further investigated in future research work.

In general, a review of the above 22 studies shows that if energy-efficient, urban transport systems have to be implemented, factors such as the value of commuting time, knock-ons to economic productivity, stress and time implications on travellers (whilst complex to evaluate), require consideration in the planning of modern ITS and AV-based transportation. Approximately, 18% of the studies focused on ITS, while more than 82% of studies focused on AV application. Current transport literature has largely analysed AV technology for ride-sharing (32% studies), public transportation (28% studies) and personal/on-demand transport (9% studies). The benefits of ITS and AV technology in transportation systems were mainly identified in terms of travel time and congestion (46%), emissions and energy use (36%), cost factors (28%) and road capacity (9%). The major concerns and barriers were stakeholder acceptance (23% studies), and policy and technological shortcomings (18%). The limitations of existing studies that can be investigated in future research are discussed in the next section (Section 5).

Table 1. A critical comparison of the methodologies, findings and limitations of 22 primary research studies covered in this paper.

Researchers	Methodology	Findings	Limitations (for Future Works)
Liu et al. [1]	Analytical	- AV and ride-sharing interaction needed for AV-PRTs. - AV-buses need dedicated roads.	- Prioritisation SAVs. - Policy and regulations. - Lane-keeping and docking.
Fagnant and Kockelman [11]	Analytical	- Vehicle fatality rates may reduce. - Vehicle gap reduction. - High penetration rate is needed - Data privacy, hacking, security, cost and regulatory concerns exist.	- Mode-choices effects. - Ride-sharing - Increase in traffic due to AV use as a private vehicle.
Greenblatt and Shaheen [13]	Analytical	- Ride-sharing will increase. - Lower GHG and energy use. - Traffic congestion will decrease. - VMT will change.	- Mode shift effects. - Electric power grid source. - Growth in car traffic. - Occupancy level. - Mixed-use traffic.
Fagnant and Kockelman [14]	Agent-based model	- Ride-sharing had positive results. - Single SAV can replace 11 CVs. - SAV adds 10% in travel distance. - Most travellers waited for $\leq$ 5 min. - SAV sedans decreased energy used by 12% (144 GJ) compared to light-duty vehicles. - GHG emissions decreased by 5.6%. - SO_2, PM and NO_x reduced by 19%, 6.5% and 18%, respectively, due to SAVs.	- Dynamic ride-share (DRS). - Life-cycle impacts. - Simulation of actual data. - Different types of vehicles. - Real traffic speed changes. - SAV relocation for parking. - Modelling of longer trips. - SAV occupancy levels. - SAV replacement rate. - Alternate SAV fuel. - Emission regulations. - Mode choice, destination and time-of-day models.
Rigole [22]	Simulation modelling	- SAVs used < 10% of CV parking - SAVs provide high service level. - SAVs increased travel time by $\leq$ 30%. - Benefits of SAVs are dependent on user's willingness to accept ride-sharing.	- AV technology aspects. - Socio-economics. - Transport system analysis. - Stakeholder engagement. - Dynamic simulation - Urbanism impacts. - Safety and legal aspects.
Fagnant and Kockelman [24]	Simulation modelling	- DRS of SAVs reduces travel cost. - Private operators can earn 19% annual return on investment. - DRS critical in limiting VMTs. - DRS reduce waiting by 4.5 min. - Service time reduced by 0.3 min.	- Traffic emissions. - Life-cycle costs.
Shladover et al. [26]	Microscopic simulation	- ACC had minimal change on lane capacity. - Cooperative ACC can increase lane capacity (almost double) with high market penetration rate (around 100%).	- Dynamic response of ACC systems. - Response to a strong traffic disturbance. - Emergency stopping conditions.
Alessandrini and Mercier-Handisyde [28]	Analytical	- Restricted AV-bus use showed user acceptance. - AV-buses have less likelihood of speed-limit violations. - AV-bus showed reduced fuel consumption and emissions.	- Restricted trials. - Regulations. - Mode-shift and mode choices - Sustainable development. - Infrastructure design. - System-wide integration.

Table 1. *Cont.*

Researchers	Methodology	Findings	Limitations (for Future Works)
Nguyen et al. [30]	Microscopic simulation	- AV PT bus platooning is feasible. - AV-buses had 60 s wait times and 44 s travel times.	- Delay impacts of AV PT. - Multiple traffic demand. - Vehicle-road surface interactions.
López-Lambas and Alonso [31]	Analytical	- Psychological barriers for AVs. - AV buses can reduce personal costs, congestions, waiting times and emissions. - Vehicle costs, infrastructure costs and safety risks exist for AV bus.	- Interpretability of results among countries. - Technology awareness of respondents. - Stakeholder engagement. - Actual performance results.
Dey et al. [39]	Field experiment	- ITS can be applied for traffic data collection and collision warning. - ITS reduce network interruption.	- Technology dependent. - Data security. - Changes in data network.
Dadashzadeh and Ergun [48]	Microscopic simulation modelling	- ITS ramp metering and speed limits improve travel time by 9%. - Bus delays reduced by 81.5%. - Traffic delays reduced by 29.1%. - Average speed increase by 12.7%. - ITS reduce bottlenecks by 2.8%. - Fuel use reduced by 78.2%. - Emissions reduced by 17.3%.	- Impact of different traffic management scenarios. - Open-source simulation software. - Performance testing using several merging points. - Automatic model optimisation.
Zarkeshev and Csiszár [52]	Analytical	- Respondents expressed negative feelings for AV ambulances. - Respondents from Kazakhstan less trusting than Hungarian respondents. - Readiness to ride is not influenced by gender.	- Level of awareness. - Exposure of people to AV ambulance service. - Representative population surveys needed. - Sensitivity to emergency level and severity.
Tupper et al. [53]	Economic input-output LCA and microsimulation modelling	- ITS traffic camera-generated higher fuel savings than sustainable road construction. - ITS strategy should be weighed more for sustainable roads.	- Traffic impacts of construction. - Ramp metering. - Automation of transport. - Social factors.
Meyer et al. [65]	Transport modelling	- AVs favour urban sprawl. - AVs may replace PT in low-density urban areas.	- AV impact on PT travel time and services. - Intra-zonal demand. - Only average traffic data were modelled. - Road capacity. - Cost factors.
Carrese et al. [66]	Analytical (surveys) and traffic simulation	- AVs may result in urban sprawl. - AVs increase travel time (suburb to city centre) by 12%, due to urban relocation. - SAVs reduce travel time by 19%.	- Travel time costs and fares. - Small sample size (~200) considered (i.e., population representation needed). - Mode choice impacts.
Lu et al. [70]	Analytical	- AVs may result in urban sprawl. - AVs and TOD integration. - Heterogeneity in preferences for TOD and AVs. - Results were dependent on time savings and productivity opportunities from AV use.	- Ownership of AVs. - SAV integration with AV PT and transport system. - Real traffic data for simulation modelling. - Cost and policy initiatives.

Table 1. *Cont.*

Researchers	Methodology	Findings	Limitations (for Future Works)
Bösch et al. [73]	Analytical	- Demand-bundling is necessary to maintain the competitiveness of PT against SAVs and private AV cars in dense urban areas. - High purchase and cleaning cost of SAVs is still a deterrence. - AVs may remain in private use due to low variable costs.	- AV impact on parking. - Mode choice impacts. - Government policies. - Personnel costs. - Market price fluctuations. - Alternate fuel use and costs. - Emissions results.
Patella et al. [86]	Traffic simulation modelling	- AVs decrease travel time and increase average vehicle speeds. - AVs increase VMT on long roads. - AVs increase GHG impacts on construction and procurement level - AVs decrease environmental impacts at mobility level by 60%.	- More likely internal combustion hybrid electric AVs must be modelled. - AV-specific modelling software should be used. - Mode-shift, ride-sharing & population growth impacts
Patella et al. [87]	Traffic simulation modelling	- Central city area benefits from lower noise emissions due to the high penetration rate of AVs.	- Modelling of different types of vehicles and mixed traffic in actual traffic fleet.
Srinivasan et al. [88]	Analytical	- Technological, policy and user acceptance are barriers.	- Pilot projects to analyse the transport impacts of AVs.
Loeb and Kockelman [89]	Simulation	- Gasoline hybrid SAVs had better cost and travel time performance than electric SAVs. - Cost benefit of gasoline hybrid SAVs depends on electric SAV price and gasoline cost. - Electric SAV capable of zero-carbon transport if coupled with a renewable power grid.	- Carbon taxes. - Vehicle occupancy levels. - Trip combinations. - Trip load reduction. - Comparison with PT services and automation. - Emissions and energy use.

4.1. Public Acceptance

Manufacturers like Google currently plan to release AVs by the year 2020 [13], which may result in the safer and more efficient use of roadways. The goal of mobility innovation and automation is to transform the travel choices of people, and as such, its implications on urban PT. Automation carries many social prospects in addition to the legal precepts of licensing and security. Future travellers may have the choice of using smartphones, consuming meals and engaging in recreational activities during their private or shared transit. Even though Google has logged over 1.1 million kilometres [90] through AVs on public roads in California, high costs limit the spread of autonomous cars on the consumer market [38,91], a challenge that may best be addressed through autonomous PT if the perception of the public is duly considered, and initiatives to promote a general understanding of autonomous PT (e.g., buses)-mainly safety features are conveyed to the users. Adoption of closely travelling autonomous buses on dedicated lanes may increase the capacity of lanes [92], which may in return mean fuel savings, as less brake-accelerate manoeuvre will be needed. Preliminary data from the CityMobil2 automated bus project has revealed that there is currently a positive attitude from the general public, as Figure 5 [28] illustrates.

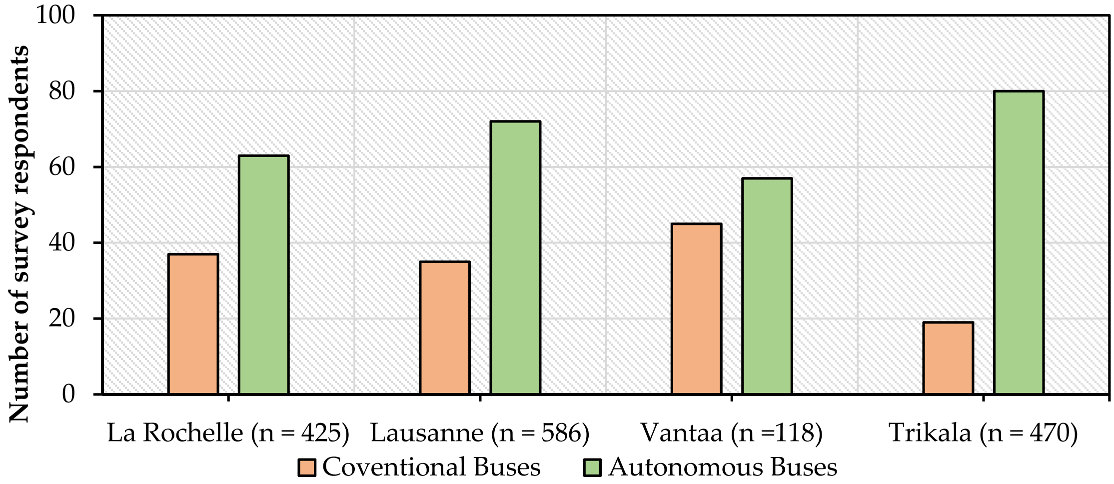

Figure 5. Public responses on mode choices: conventional vs. autonomous buses under the same route parameters

4.2. Policy and Technological Shortcomings

Routine infrastructure planning set aside, it is often expected of the government agencies to provide a platform, encourage discussion and dialogue between stakeholders, and commission research projects promoting equity, safety and technological integration and development policies as the machine-brawn artificial intelligence revolution engulfs transportation industry. Algorithms able to crunch big data and slicker transportation promised by autonomous vehicles opens a new window, yet due to the substantial uncertainties associated with their long-term deployment impacts, partial information makes policies difficult to draft. Srinivasan et al. [88], through a metropolitan case study from the Netherlands, found that despite the uncertainties associated with AV implementation, there is a need for encouraging systematic, approach-based pilot projects to study the long-term impacts. Researchers such as Liu et al. [1] asserted the need for developing a consensus on the transformation of the traditional transport systems through the emergence of vehicle automation technologies. Future research on the autonomous vehicle, and particularly autonomous PT as a mobility solution, should address how these alternate vehicle technologies can be adopted to reduce overburden on personalised vehicle transit and achieve city-wide sustainability goals of municipal authorities in congested and heavy traffic density cities around the world.

5. Future Research Directions

Although, information sharing initiatives such as Sustainability Mobility and Accessibility Research and Transformation (SMART) [93], have been aimed at carefully analysing the trade-offs between investment decisions, sustainability and innovative urban mobility. This is primarily because infrastructure investments are high budgeted and may become locked-in once the decisions have been made, and cities may be stuck with irreversible bad decisions, which predicament platforms such as SMART aim to avoid. Other programmes such as the global mobility start-up database Mobi [1] and smartphone app-powered commercial door-to-door shuttle service of Transdev also aim to provide an alternate and multi-modal solution to the urban transportation problem. Nevertheless, at present most government agencies around the world have yet to catch up to the technology of automated transit. For example, as Liu et al. [1] report, the vagueness in the Federal Transit Administration and ITS Joint Program Office-led, on-demand mobility programme's description of newer multi-modal mobility concepts and the absence of autonomous mobility from the U.S. Department of Transport strategic plan [94]. Due to the decreasing reliance of millennial travellers on single-occupancy vehicles and the divergence of trip load towards PT, researchers such as Liu et al. [1], Alessandrini et al. [27], Lesh [95] and Polzin [96] have commented that transportation agencies should also focus on long-term autonomous transit, SAVs, connected AVs and exclusive rights-of-way for AVs. Moreover, building upon the success of projects like the Morgan Town People mover [97], ideas like automated rapid bus transit, an automated vehicle serving > 15 travellers on dedicated lanes [5,98], may become the new mode choice for mass transit.

Although at present the procurement and purchase costs of private and public AVs may be a concern [31] for practical implications, the research covered in Table 1 above shows that these high initial costs may be offset by life-cycle ownership costs, specifically fuel cost savings. Environmental impacts notwithstanding, the travel time and ride comfort factors may be the primary drivers of AV adoption for public transport and ride-sharing transit systems, and as such, should be focused in future research. It is also uncertain how the mode choice of travellers shall be affected by the introduction of ITS and AV-based transportation systems. Similarly, the detailed impact of AV–PT, private AV cars and SAVs on the daily operation of traffic fleet as well as life-cycle implications need to be empirically calculated. Scenario analyses of various AV adoption rates, AV adoption methods and fuel sources should be performed with the simultaneous engagement of stakeholders (government, users and private sectors). Additionally, the following research directions are critical for the real-world application of artificially intelligent and sustainable transport systems in line with the literature studies covered in Table 1.

- SAV prioritization, vehicle occupancy and sharing technique (dynamic vs. serial ride-sharing).
- Mode-shift and mode choices.
- Variation of traffic density due to AV use in traffic fleet.
- Renewable electric power grid and alternate fuel sources.
- Long-term traffic and population growth.
- Use of actual traffic count data and growth models for simulations and empirical calculations.
- High-resolution (per vehicle level) calculation of cost, energy use and pollutant emissions.
- The penetration rate of vehicles following new emission regulations (e.g., distribution percentages of Euro 1–6 emission standards).
- System-wide analysis and modelling of the transportation network.
- Dynamic vehicle simulation and dynamic choice-modelling.
- Urbanism, urban relocation and zonal developments (TODs) integration with AVs and ITS.
- Impacts of AV traffic on the construction, maintenance and operation of road infrastructures.
- Impact of market fluctuations in AV prices, fuel prices and government taxes on AV adoption.
- Diversion of trip load towards AV-based public transport.
- Increasing the engagement level of public and government agencies in the decision-making process of transport systems to explore the benefits of automation and artificial intelligence.

Benefits of autonomous vehicles may result in a greater contribution to the life-cycle sustainability of transportation infrastructures. As stated by Hameed and Hancock [99], unused parking spaces and sustainable transportation initiatives may reduce the GHG emissions and energy consumption needs of urban mobility. Researchers [100,101] have highlighted that the sustainability triple-bottom-line approach should be the primary concern of decision-makers. Even with the uncertainties associated with the deployment and operation of autonomous public transport, it might be apt for the decision- and policy-makers to consider AVs as part of the sustainability investigations of urban public transportation solutions.

6. Conclusions

The goal of a future smart city is to have mass and goods mobility primarily supported by an entirely autonomous vehicle system. The goal behind this paper was to critically analyse the state-of-the-art of the research on AVs and ITS transport systems, specifically focused on establishing the research methodologies, main findings and limitations that can be researched in future works.

A total of 22 primary and 79 supplementary researches on the topic were reviewed from peer-reviewed transport literature. The results show that it is expected that in the next thirty years or so, autonomous vehicles may become a reality on public roads. Research has shown that the benefits of AVs and ITS in terms of insurance, congestion and parking costs are in the range of $2960–3900 per year per vehicle. The research on private autonomous cars concluded with a positive outlook on the SAV mobility if electric/hybrid electric autonomous cars were to be the driving force behind the system.

The situation of future transport systems is further complicated by the social, environmental, political, and more so, budgetary, constraints of transportation agencies, making sustainability the primary concern. Results of this review paper showed that automated urban mass transit may also be a promising alternative to personalised travel, where users can either subscribe or operate on a pay-as-you-go basis without the need for a driver or attendant for the service operation. The expected benefits of AV–PT are the reduction of land-use, cessation of traffic congestion, low user costs, fewer time delays and environmental burdens, mobility solutions to elderly and disabled people in the form of efficient and safe transport. The integration of shared mobility solutions with automated gateways and autonomous PT systems has also been investigated in the literature to certain degrees. Traffic simulation, analytical reviews and stated-preference surveys and limited filed data have been used to perform scenario analysis of various AV-based PT and ITS strategies in the existing transport literature. However, the review also found that the majority of literature lacked in concise integration of stakeholder engagement, real-world traffic data, cost and emission models and detailed traffic simulation modelling for life-cycle implications of ITS and AV transport.

Results also show that barriers regarding the technical, technological and policy-making exist for the practical, large-scale implementation of automated transit. Fragmentation of the government agencies involved, the distance between the research and stakeholder spectrums and divided public opinion further complicates the situation. The sustainability triple-bottom-line approach may be used for determining the long-term impacts of autonomous transit. As such, this study, which acts as a platform for describing the current state and need for a life-cycle analysis method for evaluating the application of autonomous rapid PT, identifies that there may be a potential for autonomous bus rapid transit (BRT) services to increase the productivity, energy and fuel savings capacity, as well as safety, of the urban transportation systems.

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