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Review Article

Fully Autonomous Buses: A Literature Review and Future Research Directions

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Autonomous vehicles (AVs) represent a new, growing segment of transportation research. While there have been prior studies and deployments of AVs worldwide, full autonomy in bus transit has gained interest among researchers and practitioners within the last decade, which presents an opportunity to synthesize early trends. Therefore, the objective of this paper is to provide a review of the latest research on fully autonomous buses to summarize findings and identify gaps needing future research. Forty studies were reviewed in detail, and five main themes were identified, which are (1) technology deployment; (2) user acceptance; (3) safety; (4) social and economic aspects; and (5) regulations, policies, and legal issues. The results reveal that most prior studies have focused on technology development, and the area of regulation and policy would benefit from additional study. Noteworthy differences between research in Europe and the United States were also identified. In Europe, large funded projects involving real-world deployments have focused on user acceptance, security and safety, costs, and related legal issues, whereas in the United States, research has primarily concentrated on simulation modelling with limited real-world deployments. The results of this review are important for policy-makers and researchers as AV technology continues to evolve and become more widely available.

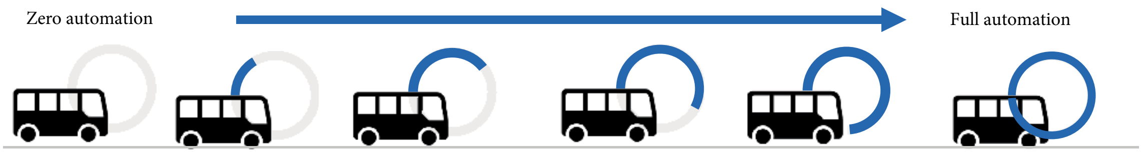
1. Introduction

Autonomous vehicle (AV) technology has grown and developed rapidly in recent decades. Accompanying this trend is increasing concern among professionals in related fields over how AVs will affect and shape the future transportation network. As a result, a growing amount of research has been conducted on this technology and its impacts on mobility, safety, the environment, and the economy. Within the broader topic of AVs, a small but growing amount of research has also been carried out specifically on bus transit and full autonomy. Therefore, this paper sets out to systematically review the published studies and reports conducted on autonomous buses. It will focus primarily on technological capabilities, safety, user acceptance, social and economic impacts, and policy implications. The findings will be synthesized, and the last section will discuss future research needs.

2. Background

An *autonomous vehicle* is defined as a vehicle that can drive without any human intervention by sensing the local environment, detecting objects, classifying them, and identifying navigation paths with information coming from different sensors while obeying transportation rules [1]. The US Department of Transportation classifies automated vehicles in a more specific manner using six levels of automation based on the Society of Automotive Engineers' (SAE's) definition [2, 3]. Level 0 represents no automation, Levels 1 to 3 are such that the driver has primary control over the vehicle and automation is partially used, and Levels 4 and 5 are met when the vehicle can be fully controlled autonomously (Figure 1).

Automation is not a new concept in public transportation. Since the late 1960s, automated guideway transit (AGT) systems with fully separated right-of-way have been deployed in numerous European countries, Japan, Canada, and the United



	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5
Driver's role	Performs all tasks	Controls vehicle	Engages in driving and monitoring the environment	Necessary to take control	May have the option to control	May have the option to control
Automation features	-	Driver assist features	Some automated functions	Some automation functions and monitoring the environment	Vehicle performs all driving functions under certain conditions	Vehicle performs all driving functions under all conditions

Figure 1: AV levels (adapted from SAE).

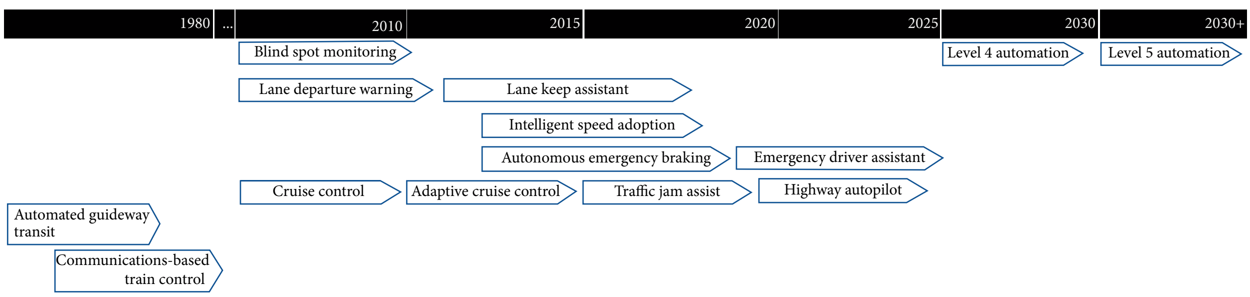


Figure 2: Transit autonomy timeline (*adapted from KMPG report).

States [4, 5]. Similarly, urban rail systems are increasingly using communications-based train control (CBTC), which typically utilizes continuous data communications instead of a driver to control vehicles [6]. More recently, automated technologies such as driver assistance, collision warning and avoidance, precision docking, and automatic lane-keeping and lane-changing are being utilized in the transit industry, particularly on buses [7, 8]. Figure 2 presents a general timeline of automation technologies related to public transportation.

Despite the growing use of automation in the transit industry, less interest has been given to research and development in this area compared to AV as personal automobiles [9]. In the last decade, the research in the literature focused almost exclusively on personal or shared vehicles even though autonomy of the other modes (e.g., buses) had begun to corner a fast-growing segment of transportation industry. Since 2010, many articles and reports have been published on this topic although the focus on personal vehicles is still disproportionate. To fill an emerging gap in the literature, this paper will focus specifically on *autonomous buses*, which can be defined as "a vehicle with rubber tires which–given its dimensions and its steering system—can be used in ordinary road traffic without geographical restriction, even if only in reduced power mode or at reduced speed" [10]. Last, it should be noted that the following review focuses on fully autonomous buses that can operate without a human driver.

3. Method

This section describes the method used to compile and categorize the literature in this review. The types of publications considered for this review were primarily peer-reviewed journal articles and conference proceedings. We have also included reports from large ongoing federal and governmental autonomous bus projects from Europe and the United States, such as CityMobil2, Federal Transit Administration (FTA), National Cooperative Highway Research Program (NCHRP), and their references.

In order to systematically identify the relevant literature, the search process used the following keywords: "autonomous transit", "autonomous bus", "autonomous shuttle", "automated public transport", "driverless bus", "driverless shuttle", "automated road transport", "autonomous mobility services", "shared automated mobility", "autonomous transport system", or "future bus".

The search process, which was conducted in November of 2018, began with a general Internet search to quickly identify key references. Then, three electronic academic databases were used: Google Scholar, Transport Research International Documentation (TRID), and Web of Science. The primary search was Google Scholar, which resulted in approximately 1600 papers. Given the rapidly changing nature of the topic, only studies that were published after 2010 in the English language were then considered, which reduced the number of total articles to 600. TRID and Web of Science were secondary searches that resulted in 30 papers, some of which were already included in Google Scholar result. After an initial review of titles and then a subsequent review of abstracts, a total of 40 articles on autonomous buses were deemed relevant to this review.

Each of the 40 studies considered in this review was then divided into categories based on their content. This was first done by publication date and study location(s), and the results are shown in Figure 3. Then, the full manuscripts were

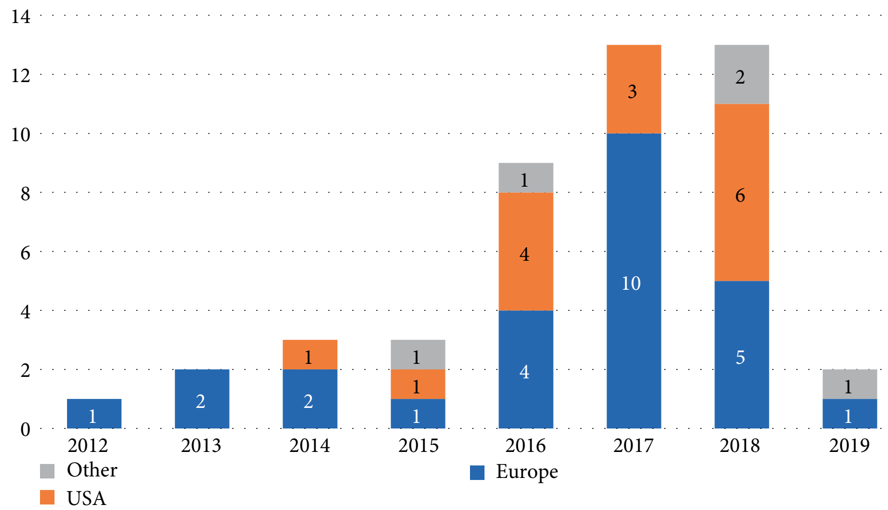


FIGURE 3: Number of reviewed studies per year and study location ($n = 40$; some studies counted multiple locations).

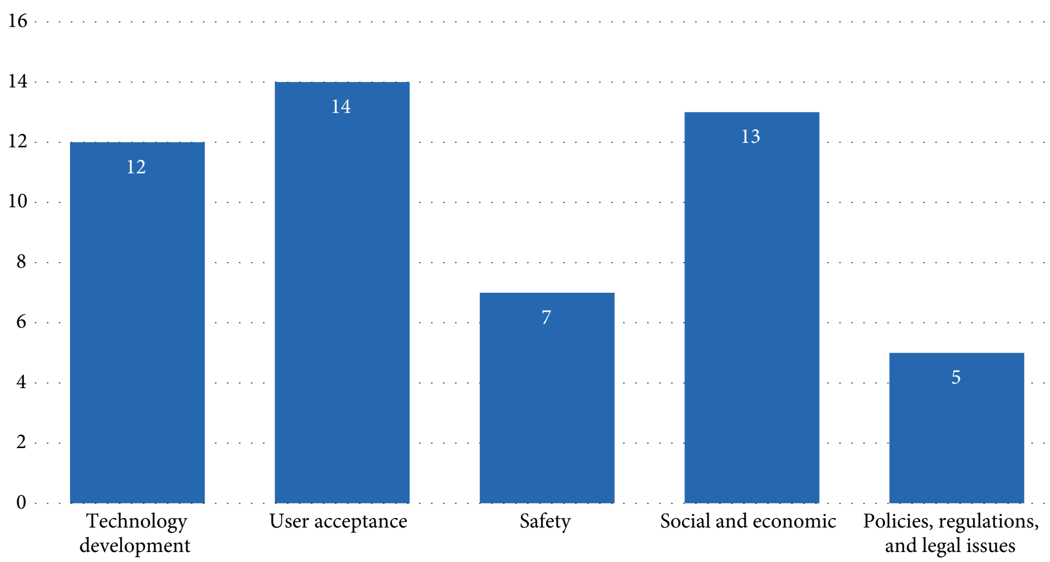


FIGURE 4: Number of reviewed studies in each theme ($n = 40$; some studies counted multiple times).

reviewed and categorized into five topical themes to create a framework for this paper; the results are shown in Figure 4. These themes were initially derived from CityMobil2 document that had four primary themes [11]; however, this framework was adapted to fit all of the topics considered in the 40 papers. These themes are briefly described below:

(1) *Technology development:* This includes studies of the level of automation in buses, conceptual designs, and technical demonstrations.

(2) *User acceptance*: This theme pertains to passengers' attitude towards autonomous buses—with and without previous experience of riding in autonomous buses—and the factors that influence their opinions.

(3) *Safety:* This considers traffic safety, personal security, and emergency management of autonomous buses, including passenger perceptions thereof.

(4) *Social and economic aspects:* This broadly considers employment/jobs, costs, accessible services such as paratransit, and environmental considerations.

(5) *Regulations, policies, and legal issues:* This theme includes current and proposed regulations and policies to address the impacts of autonomous buses.

4. Results

This section presents the results of the literature review on fully autonomous buses, and it has been divided to summarize findings for each of the five key themes (technology development, user acceptance, safety, social and economic aspects, and regulations, policies and legal issues). For each theme, a summary table was created to synthesize five dimensions for each study pertaining to that theme: (1) authors; (2) type of publication;

(3) study location; (4) method(s); and (5) key findings. The *types of publications* included four sources: journals, conference proceedings, reports, and book chapters. *Study locations* were classified as the United States, Europe, and others. The *methods* included surveys, case studies, cost analyses, definition/concepts, position papers, simulation modelling, design, interviews, risk analysis, expert opinions, and expert workshops. *Key findings* were also identified for each study, and these were used to summarize results across studies and identify future research needs, which are discussed in the following sections beginning with technology development.

4.1. Theme #1: Technology Development. A summary of the most relevant studies that pertain to the theme of technology development is provided in Table 1. As shown in Table 1, twelve studies were reviewed, which included four journal articles, six conference proceedings, one report, and one white paper. Six publications were from Europe [9, 10, 12–15], and the other half were conducted in the United States [16–20], and one study was conducted in Australia [21]. Numerous types of methods were used in these studies, with the most common being simulation modelling (four studies), design proposals (two papers) and concept papers (two papers).

The key findings of these technology-related papers are briefly summarized here. First, two concept papers proposed a definition for autonomous buses—including technology and transportation system characteristics—and compared this to fully automated train systems [10, 14]. Other papers focused on specific technologies that can be used for partial (e.g., Level 2 and Level 3) and eventually for full automation, such as collision avoidance technology [18, 19], autonomous control systems [12, 15], cooperative adaptive cruise control (CACC), and platooning [13, 16, 19]. Similarly, new concepts were proposed pertaining to technology and vehicle design, such as slim semiautonomous bus rapid transit (SSaBRTransit) [17]. Last, a study by Pessaro [9] summarized five real-world autonomous bus technology demonstration projects, including CityMobil2, WEpods, and CarPostal in Europe, and Contra Costa Transportation Authority (CCTA) and the Minnesota Valley Transit Authority (MVTA) projects in the United States. Of these five technology demonstrations, CityMobil2 is the largest and most well-documented; papers and reports pertaining to this project, in which low speed (~10 km/hr) autonomous shuttle buses have been deployed in numerous cities, will be cited in each of the subsequent sections.

There are numerous areas for future research pertaining to technology development that emerged from this review. First, many of the prior studies focused on specific technologies, but there is room for significantly more research on the combinations of technologies that could be used in higher levels of bus automation, particularly Level 5. Additionally, only one study focused on larger vehicles; evaluation of autonomous bus technologies in larger vehicles such as articulated vehicles commonly found in bus rapid transit (BRT) systems should be done. It is important to do more real-world technology demonstrations beyond CityMobil2, which was primarily in Europe.

By removing the driver scheduling and related costs, the overall operating performance of an autonomous transit system is expected to change. These changes correspond to different parameters of routes, costs, and travel time. System measures such as reliability, waiting time, and frequency can be enhanced by optimizing the components of an autonomous transit system such as schedule-free dispatch, autonomous intersection management, or transit signal priority [21]. However, there is a strong need for developing a framework and methods that enable operators, agencies, and researchers to evaluate and optimize the overall performance of autonomous buses by exploiting the new tools and technologies in the transit system.

4.2. Theme #2: User Acceptance. In this section, studies pertaining to user attitudes toward autonomous buses and the factors that influence user (or rider) acceptance are reviewed and summarized in Table 2. In total, fourteen studies were reviewed. Half of the studies (7 of 14) can be found in journals and the other half (7) were published in conference proceedings. Almost all of these studies (12 of 14) were from Europe [22, 24–28, 30–35]. Only one study focused on the United States [23], and another considered both the United States and India [29]. Notably, more than half of the studies were conducted as part of the CityMobil2 Project in Europe. In terms of methods, twelve of the fourteen studies used survey-based methods and two conducted interviews of autonomous bus users or potential users.

A brief summary of the key findings pertaining to user acceptance is presented here. Most studies concluded that users (who have experienced riding on an autonomous bus) and potential users (such as those who currently ride conventional buses but have not yet ridden in a driverless bus) generally have positive attitudes toward autonomous buses [22–28, 30–32]. Notably, the experience of actually riding in an autonomous bus or living in a city where autonomous buses operate generally improved user acceptance and perceptions of this new technology [28, 33, 34].

Additionally, numerous studies explored specific factors that could affect acceptance of autonomous buses, including demographic and socioeconomic characteristics of riders (e.g., age, gender, nationality), service and operational characteristics (e.g., speed, having an onboard staff member), as well as other broader constructs (e.g., user enjoyment, perceived usefulness). The results of the studies considering demographic and socioeconomic characteristics occasionally yielded heterogeneous results [22, 27, 33], but one common finding was that younger people tend to have more positive perceptions of autonomous buses [23–25]. In terms of service and operational characteristics, one common concern was security of autonomous buses; however, having an onboard attendant generally improved responses [23, 26]. Finally, the perceived usefulness of autonomous buses was cited in numerous studies as an important factor influencing acceptance [32, 35].

Although user acceptance was found to be a relatively common theme in this literature review, there are numerous additional areas for research. First, more studies are needed in locations outside of Europe, particularly with other populations that have experience riding autonomous buses (rather than through stated preference surveys). Second, some studies found that having onboard transit staff may help improve

Table 1: Key studies on technology aspects of autonomous buses.

Author(s) (year)	Type	Location	Methods	Key findings
Villagra et al. (2012)	Journal	Europe	Simulation and testing (vehicle on a test track)	(i) A planning algorithm was proposed and resulted in smooth driving in terms of comfort and efficiency (ii) This was compared to manual driving on a test track and the results were reasonable
Lam & Katupitiya (2013)	Conference proceeding	Europe	Simulation (using a nonlinear dynamic model and a path-following and car-following model for platooning)	(i) The proposed model of platooning is well-behaved with acceptable error interaction in a complex vehicle-road system
Lutin & Kornhauser (2014)	Conference proceeding (TRB)	United States	Case study (cost and benefit analysis and capacity analysis for one transit agency)	(i) The implementation of collision avoidance technology on buses can be cost effective (ii) Cooperative adaptive cruise control (CACC) can increase the capacity of an exclusive bus lane (iii) Collision avoidance and CACC are promising technologies
Lam et al. (2016)	Journal	Australia	Simulation (employing AV in public transportation network)	(i) A reliable representation of the real system utilizing autonomous buses and covering various technologies such as schedule-free dispatch or autonomous intersection management illustrates the performance of the transit network
Lutin et al. (2016)	Conference proceeding (TRB)	United States	Safety analysis and export opinion with road map	(i) Safety analysis showed the number of bus-related injuries, casualties, and liability expenses is currently increasing (ii) The proposed road map calls for partnerships between stakeholders (iii) The authors call for more research on technologies such as autonomous collision avoidance and autonomous emergency braking
Polzin (2016)	White paper	United States	Position paper/expert opinion	(i) Autonomous buses could enable increased performance in terms of vehicle speed and passenger volumes (like bus rapid transit) (ii) Automation technology could significantly change travel time and monetary costs
Pessaro (2016)	Report	United States and Europe*	Case studies (five demonstration projects)	(i) Three of five case studies are European, and they are at the forefront of testing autonomous buses in real-world situations (ii) Two of five case studies are in the United States but are still in the planning stages (pre-deployment) (iii) Europeans are leaders (compared to Americans) in manufacturing and deploying autonomous bus technology
Sinner & Weidmann (2017)	Conference proceeding	Europe	Definition/concept paper (comparison of automated bus and train system)	(i) When considering automation in the future, the line capacities of bus and train systems are similar (ii) Future train systems likely have greater station capacity due to longer vehicle lengths, but they require higher infrastructure cost
Sinner et al. (2017)	Conference proceeding (TRB)	Europe	Definition/concept paper (definitions of bus and train in age of automation)	(i) With automation, transit vehicles are not steered by humans any more (ii) The key element defining future buses is compatibility with ordinary road traffic (mixed traffic) without needing mechanical guidance

Table 1: Continued.

Author(s) (year)	Type	Location	Methods	Key findings
Ginn et al. (2017)	Journal	United States	Design/prototype (slim semiautonomous bus rapid transit concept)	(i) The advantages of the proposed bus rapid transit system are decreased operational costs due to narrower bus body sizes and modularity of the vehicles (ii) The disadvantage of the proposed system is that the implementation cost could be high
Montes et al. (2017)	Journal	Europe	Design/experiment (of automatic control for articulated buses)	(i) The experimental testing of three separate control systems (velocity, steering, and safety) yielded good results
Gao et al. (2018)	Conference proceeding (TRB)	United States	Simulation (data-driven CACC algorithm)	(i) The proposed algorithm has the capability to increase transit vehicle throughput (ii) The method has better performance in theory and practice than previous control methods

*Discusses CityMobil2 Project.

Table 2: Key studies on user acceptance aspects of autonomous buses.

Author(s) (year)	Type	Location	Methods	Key findings
Alessandrini et al. (2014)	Conference proceeding	Europe*	Stated preference survey (survey conducted in 12 cities)	(i) User preference is higher for automated public transport compared to traditional buses across the cities (ii) The impact of socioeconomic variables on users' preferences is heterogeneous across cities
Alessandrini et al. (2016)	Journal	Europe*	Stated preference survey (same survey as Alessandrini et al. (2014))	(i) User preferences for automation are higher in cities where automated buses have been implemented (ii) Users with no experience of autonomous buses tend not to trust autonomous buses (iii) The socioeconomic factors' that influence users' attitudes are heterogeneous across cities
Piao et al. (2016)	Conference proceeding	Europe*	Survey (N = 425, La Rochelle, France)	(i) Approximately two thirds of respondents would consider riding an autonomous bus if both autonomous and conventional buses are available (ii) Respondents were concerned with passenger security, particularly in the evening and at night
Madigan et al. (2016)	Conference proceeding	Europe*	Survey (N = 349, La Rochelle, France and Lausanne, Switzerland)	(i) Performance expectancy, effort expectancy, and social influence impact users' preferences for autonomous buses (ii) Performance expectancy has the strongest impact on intentions to use autonomous buses
Madigan et al. (2017)	Journal	Europe*	Survey (N = 315, Trikala, Greece)	(i) User enjoyment strongly impacts intentions to use autonomous buses (ii) Performance expectancy, social influence, and facilitating conditions are other factors that have significant effects (iii) Gender is not highly correlated with user acceptance
Nordhoff et al. (2017)	Conference proceeding	Europe	Survey (N = 326, Berlin Schoeneberg, Germany)	(i) Perceived usefulness, ease of use, and social influence are the primary factors that impact acceptance of driverless shuttles
Portouli et al. (2017)	Conference proceeding	Europe*	Survey (N = 519, Trikala, Greece)	(i) Younger people are more willing to accept and use autonomous minibuses
Dong et al. (2017)	Journal	United States	Stated preference survey (N = 891, Philadelphia)	(i) Approximately two–thirds of respondents (current transit riders) were more willing to ride driverless buses when there is an onboard transit employee (ii) Males and younger people have more willingness to ride driverless buses than females and older respondents
Moták et al. (2017)	Journal	Europe	Stated preference surveys ($N1$ = 370, first-year psychology students, $N2$ = 162, potential and actual users in France)	(i) Researchers applied the technology acceptance model and theory of planned behaviour frameworks to study acceptance of autonomous shuttles (ii) Intentions to use autonomous shuttles depends on factors such as the aspects that are linked to its perceived usefulness and positive affective attitude

Table 2: Continued.

Author(s) (year)	Type	Location	Methods	Key findings
Eden et al. (2017)	Conference proceeding	Europe	Interviews of before and after experience ($N = 17$, Sion, Switzerland)	(i) Although there were some safety concerns before riding the autonomous shuttles, passengers had fewer safety concerns after riding (ii) Overall there was a positive opinion about comfort and convenience of autonomous shuttles
Nordhoff et al. (2018)	Journal	Europe	Survey ($N = 384$, Berlin Schoeneberg, Germany)	(i) Survey respondents generally had positive attitudes toward autonomous shuttles (ii) Passengers were less satisfied about autonomous shuttles than their existing travel modes (iii) Older respondents had more intention to use autonomous shuttles (iv) No correlation between gender and user acceptance was found (v) Autonomous shuttles need improvements in terms of efficiency and speed
Wintersberger et al. (2018)	Conference proceeding	Europe	Interview ($N = 12$, Germany)	(i) After riding in an autonomous bus, acceptance and positive attitudes increased
Salonen (2018)	Journal	Europe*	Survey ($N = 197$, Vantaa, Finland)	(i) Males and younger people were more willing to ride driverless buses than females and older respondents
Anania et al. (2018)	Journal	United States and India	Two surveys ($N1 = 50$, $N2 = 600$)	(i) Parents are less willing for their children to ride autonomous buses to school in comparison with riding school buses with a human driver (ii) American females are less willing to let their children rides in driverless school buses than Indian females

*CityMobil2 Project.

Table 3: Key studies on safety aspects of autonomous buses.

Author(s) (year)	Type	Location	Methods	Key findings
Lutin & Kornhauser (2014)	Conference proceeding (TRB)	United States	Case study (cost and benefit analysis and capacity analysis for one transit agency)	(i) The implementation of collision avoidance technology on buses can be cost effective (ii) CACC (Cooperative Adaptive Cruise Control) can increase the capacity of an exclusive bus lane (iii) Collision avoidance and CACC are promising technologies
Sessa et al. (2015)	Report	Europe, US, and Asia*	Stated preference survey and workshop with experts ($N = 89$, from academia, automotive industry, city and local authorities)	(i) Two extreme scenarios ("automated private car ownership vs. automated car-fleet sharing") and four different urban typologies ("urban sprawl, city network, small compact city, and rural/tourist areas") were considered in this online survey of experts (ii) Safety impacts are expected to be positive; for example, there could be a 90% reduction in accidents by employing different circulation rules
Lutin et al. (2016)	Conference proceeding (TRB)	United States	Safety analysis and export opinion with road map	(i) Safety analysis showed the number of bus-related injuries, casualties, and liability expenses is currently increasing (ii) The proposed road map calls for partnerships between stakeholders by educating the industry, creating new programs, and identifying funding sources
Piao et al. (2016)	Conference proceeding	Europe*	Survey ($N = 425$, La Rochelle, France)	(i) Survey respondents were concerned with passenger security, particularly in the evening and at night (ii) Onboard security is a major concern (iii) Onboard employees could reduce safety concerns and increase willingness to use autonomous buses
Montes et al. (2017)	Journal	Europe	Design/experiment (of automatic control for articulated buses)	(i) The experimental testing of three separate control systems (velocity, steering, and safety) yielded good results (ii) The proposed safety system properly stops the bus or reduces the velocity based on the distance between a bus and an obstacle
Portouli et al. (2017)	Conference proceeding	Europe*	Survey ($N = 519$, Trikala, Greece)	(i) Survey respondents perceive autonomous minibuses to be somewhat safer than conventional buses in terms of crashes with other vehicles or pedestrians (ii) Survey respondents perceive autonomous minibuses to be as secure as conventional buses in terms of attacks
Salonen (2018)	Journal	Europe*	Survey ($N = 197$ in Vantaa, Finland)	(i) Survey respondents perceive traffic safety to be better in driverless shuttle buses than conventional buses (ii) 64 percent of respondents felt that driverless shuttle buses were worse than conventional buses in terms of in-vehicle security (probably due to a lack of driver)

*CityMobil2 Project.

Table 4: Key studies on the social and economic aspects of autonomous buses.

Author(s) (year)	Type	Location	Methods	Key findings
Sessa et al. (2015)	Report	Europe, United States, and Asia*	Stated preference survey and expert workshop (N = 89, from academia, automotive industry, city and local authorities)	(i) Two extreme scenarios ("automated private car ownership vs. automated car-fleet sharing") and four different urban typologies ("urban sprawl, city network, small compact city, and rural/tourist areas") were considered in this online survey of experts (ii) Economic impacts (e.g., personal trip costs, fines, insurance) are expected to be mostly positive except for possible employment impacts (iii) Environmental impacts (e.g., energy and emissions, urban requalification, land saving) are expected to improve (iv) Transportation impacts in terms of road capacity and comfort and convenience are mostly positive
Lam et al. (2016)	Journal	Australia	Simulation (employing AV in public transportation network)	(i) Journey time significantly affects the waiting time, cost, and reliability of the system
Piao et al. (2016)	Conference proceeding	Europe*	Survey (N = 425, La Rochelle, France)	(i) Survey results show the largest benefit from the passenger perspective is lower bus fares due to reduced driver costs
Polzin (2016)	White paper	United States	Position paper/expert opinion	(i) Autonomous buses can lead to restructuring of public transport systems by providing services based on riders' needs (e.g., paratransit service) (ii) Technology related factors such as flexibility, safety, and reliability might affect travel decisions
Executive Office of the President, The White House (2016)	Report	United States	Macroeconomic and labour analysis	(i) Up to 100% replacement of bus driving jobs due to automation is likely to happen
Bösch et al. (2017b)	Conference proceeding (TRB)	Europe	Simulation (policy combinations in an AV based transport system)	(i) Different AV based scenarios are likely to increase VMT and decrease accessibility (ii) Lower fares for autonomous buses could lead to higher accessibility, fewer cars, and lower VMT (iii) One of preferred policy scenarios was free autonomous bus and autonomous motorized individual transport, which increased average accessibility by 0.5% and reduced total system VMT by 1%
Bösch et al. (2017a)	Journal	Europe	Cost analysis	(i) The current form of public transportation will remain competitive only if demand is sufficient, e.g., in dense urban areas (ii) Autonomous buses could be competitive in dense urban areas where the price of public transportation is lower than autonomous taxis
Cedar et al. (2018)	Conference proceeding (TRB)	Europe and New Zealand	Simulation model (time and cost models for Paris Charles de Gaulle Airport, France, and the Auckland Airport, New Zealand)	(i) Costs can be reduced by 20–64% if future systems are comprised of 75–100% autonomous public transport vehicles

Table 4: Continued.

Author(s) (year)	Type	Location	Methods	Key findings
Cuellar et al. (2018)	Conference proceeding (TRB)	United States	Interviews, Case studies, and Expert workshop	(i) Different categories of disabilities were considered, such as the visually impaired and those with hearing impairments (ii) Several services and technologies were considered that can support system functions, such as speech to text (iii) Use cases were developed with three parts: requesting an autonomous shuttle, boarding the autonomous shuttle, and navigating the shuttle
Lutin (2018)	Journal	United States	Position paper	(i) Autonomy can benefit the transit industry if they concentrate resources in areas where additional automobile traffic and parking would be costly. However, it might not benefit the transit industry in areas where transit load factors are too low (ii) Autonomous buses can improve paratransit service and reduce operating costs, which is almost 10 times more than the operating cost per transit trip on fixed route services ($34.43 compared to $3.68, data from 2014)
Quarles et al. (2018)	Conference proceeding (TRB)	United States	Life-cycle cost analysis	(i) Electric and fully autonomous buses would be life-cycle cost-competitive with diesel-powered buses at a faster rate than electric buses due to reductions in driver costs
Sinner et al. (2018)	Conference proceeding (TRB)	Europe	Cost model (Zug, Switzerland)	(i) Automation can affect transit network design parameters (such as accessibility, direct connections, and frequency), which would result in cost savings for the operator and the public sector (ii) Automation can result in a savings of 50–60% of system-wide bus operating costs
Zhang et al. (2019)	Journal	Europe and Australia	Cost model (values from Australia Transport Council)	(i) The authors developed a cost model for waiting, riding, operating, and capital costs for three types of bus services (conventional, semi-autonomous, and fully autonomous) (ii) Fully autonomous buses could reduce operations and waiting costs, even though they may have additional capital costs (iii) Fully autonomous bus speeds need to be closer to conventional buses (higher)

*CityMobil2 Project.

Table 5: Key studies on regulation, policies, and legal issues of autonomous buses.

Author(s) (year)	Type	Location	Methods	Key findings
Parent et al. (2013)	Report	Europe*	Risk analysis	(i) A four-step procedure for risk analysis in autonomous bus systems is recommended (ii) The steps are as follows: (1) risk reduction analysis; (2) determining application of safety regulations; (3) implementing the system; and (4) certification and validating the system
Csepinszky et al. (2014)	Report	Europe*	Legal review and interviews	(i) Liability (three types: contractual, product, and tort) is a clear issue (ii) Lack of a legal framework is an important issue (iii) Eight recommendations to address legal and liability issues were made (e.g., disseminating necessary information to vehicle users while they are using the system)
Executive Office of the President, The White House (2016)	Government report	United States	Macro-economic and labor analysis	(i) Possible policy strategies based on potential impacts of AI include the following: (1) "Invest in and develop AI for many benefits" (2) "Educate and train Americans for jobs of the future" (3) "Aid workers in the transition and empower workers to ensure broadly shared growth"
Transportation Research Board, National Academies of Sciences, Engineering, and Medicine (2017)	Report	United States	Expert workshop, review	(i) AV transit technology can shape both long-range transit planning and regional planning and coordination (ii) Some of the government laws that would have major impacts on AV transit technology are as follows: (1) Employee protection (2) Workplace safety (3) ADA regulation (4) Buy America (5) National Highway Traffic Safety (6) Administration (NHTSA) reports
Lazarus et al. (2018)	Book chapter	United States	Expert workshop	(i) Experts identified seven main policy areas for public transport and shared automated mobility: "safety, efficiency, affordability, equity, user experience, ecology, and public-private integration" (ii) Transit operators should strategically use automation for shared ride vehicles in areas where transit ridership is low (iii) Quality of the public transportation system will be improved at the intersection of autonomous vehicles, electrification, and shared mobility

*CityMobil2 Project.

perceptions of security and increase user acceptance of autonomous buses; in the short term, more research should evaluate the costs and benefits of having staff on vehicles until riders become accustomed to driverless buses. In the long term, the public may grow more familiar with automation, and therefore, perceptions should be evaluated over time to understand future changes. Last, future studies could consider additional factors affecting the choice to ride an autonomous bus compared to other modes of travel, such as trip characteristics.

4.3. Theme #3: Safety. In this section, studies on safety and security pertaining to autonomous buses are reviewed and summarized in Table 3. Seven publications were found (four conference proceedings, two journal articles, and one report). Four of these publications were conducted in Europe [15, 24–26], two were conducted in the United States [18, 19], and one had multiple locations including Europe, the United States and Asia [11]. In terms of methodologies, most of the articles used survey-based methods [11, 24–26].

Key findings of these safety- and security-related papers are briefly summarized here. In public transport, "safety" generally refers to the likelihood of being involved in a crash, vehicular, or otherwise, whereas "security" involves crime [36]. For autonomous buses, safety and security were a commonly mentioned theme [23, 25, 26, 34]; however, some of the studies found few safety and security concerns among riders or potential riders. For example, in one study that surveyed experts, the perception of safety of autonomous buses was generally positive due to a reduction in distracted driving and bad driving behaviour [11]. In a second study that surveyed autonomous mini bus passengers, respondents generally agreed that there was less risk of an accident for autonomous buses compared to conventional buses [24]. In a third study of actual driverless shuttle passengers, survey respondents felt a greater sense of

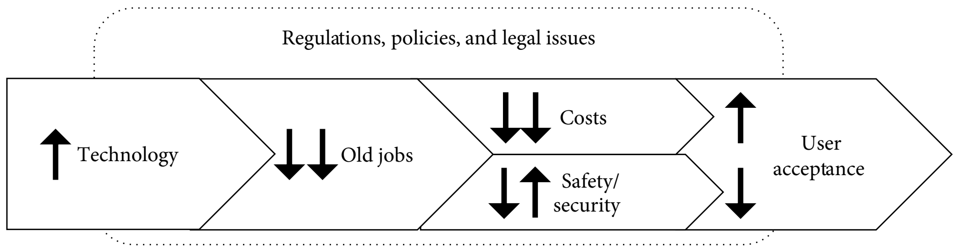


Figure 5: Relationships between the themes.

traffic safety in driverless shuttle buses compared to conventional buses; however, many (64%) of the respondents felt that driverless shuttle buses were worse in terms of in-vehicle security, probably due to the lack of a driver [25]. Beyond these survey-based studies, a few other safety-related studies have investigated or evaluated the impacts of new technologies on safety, such as collision avoidance technology [18, 19].

Numerous areas for future research pertaining to safety and security emerged from this review. First, to address potential security concerns, more research should be done comparing onboard drivers/attendants to virtual assistants, such as through a screen inside the vehicle. Second, in terms of traffic safety, more research should be done to evaluate actual traffic incidents in real-world deployments. For example, how often do vehicles stop to avoid collisions? Were there any actual collisions and if so, what caused the collisions? Are there incident logs that could be evaluated to shed more light on this topic? Last, data collection tools and performance measures should be developed to continuously monitor safety in autonomous bus systems.

4.4. Theme #4: Social and Economic Aspects. This theme broadly encompasses studies on social and economic aspects of autonomous buses, and the results are presented in Table 4. In total, thirteen studies were reviewed. These studies were published in various forums, including six conference proceedings, four journal articles, two reports, and one white paper. Four of the studies were conducted in Europe [26, 37–39], five in the United States [20, 40–43], one in Australia [21], and the remaining three studies had multiple locations [11, 44, 45]. The methods of these studies varied greatly depending on the specific topic of the paper; for example, two studies used survey methods, three used simulation, and three included cost models.

In this section, a brief summary of the key findings of these twelve studies is presented. This theme arguably had the broadest range of topics, which included studies on employment/job impacts [40], costs of autonomous buses [37, 39, 41, 43], accessible transit/paratransit [41, 42], and environmental considerations [11, 43]. In terms of employment, one of the main impacts of automation is the potential reduction in jobs for bus drivers; one study estimated that 60–100% of transit and intercity bus driving jobs in the United States would likely be eliminated by AV technology [40]. However, there is the possibility of new job opportunities in engineering (such as vehicle design and manufacturing), management (such as data analysis), and vehicle maintenance [11]. Because of potential decreases in drivers, numerous studies have analysed the costs associated with autonomous buses and identified reductions in operations costs as an important potential benefit, and reductions could range upwards of 50–60% of operating costs [26, 37, 39, 41, 43, 44]. Additional cost savings could be realized if autonomous shuttle buses are also used for demand-responsive transportation (DRT), particularly to serve paratransit trips such as for riders with disabilities [41]. Journey time in an autonomous transit network can affect the waiting time, total cost, and reliability of the system [21]. These changes should be integrated into regional transit master planning of transit network [46]. Finally, there was some limited discussion of environmental impacts of autonomous buses in the literature reviewed, including one study arguing that collective autonomous mobility could positively influence emissions and energy consumption, especially when compared to private AVs [11]. It was also found that electric and fully autonomous buses would be life-cycle cost-competitive with diesel-powered buses at a faster rate than just electric buses due to the reduction in operating costs [43].

Many areas for future research have emerged. First, network design, re-sizing vehicles, and re-routing conventional fixed-route transit and paratransit services are an important area for future research if driver costs—which are a large share of operations costs–are reduced. Second, one critical employment/job issue that has seen limited if any treatment in the literature is possible pushback from labour unions that will be impacted by fully autonomous buses. Last, there has been limited treatment of potential environmental and energy impacts of autonomous buses in the literature; future research is recommended in the area of autonomy in combination with electrification of buses.

4.5. Theme #5: Policies, Regulation, and Legal Issues. A summary of the most relevant studies on policies, regulations, and legal issues is provided in Table 5. Despite the importance of policy and regulatory topics, there is relatively little literature in this area. Five studies were reviewed, which included four reports and one book chapter. Two of the publications were from Europe [47, 48], and the other three were conducted in the United States [39, 46, 49].

Key findings obtained from the related studies are briefly summarized here. The two studies from Europe generally focused on risk and legal issues. One study presented a method for risk analysis in autonomous bus systems [47, 48]; the other argued that liability and the lack of a legal framework are critical issues and developed a framework with eight recommendations to address liability issues [47, 48]. The three American studies focused on policy-related topics. One study discussed the effects of artificial Intelligence (AI) on the American economy and possible policy strategies to address this, including for autonomous buses [40]. The two other studies summarized key policy areas for public transportation and shared mobility in an era of automation, such as equity, safety, and public–private integration [46, 49].

Given the small number of studies in this theme, additional research in this area is essential. For example, liability was considered in European studies [47, 48], but similar research is needed in the context of other countries, including the United States. Similarly, the United States government conducted a general analysis of the impact of automation on the economy; however, more analyses are needed focusing specifically on the economic impacts of autonomous buses in the United States and beyond.

5. Conclusions and Future Research

This study systematically reviewed the existing literature on fully autonomous buses. The location of each study, and the results, which are shown in Figure 3, revealed that autonomous bus research varies by geography. In the United States, there are some newly funded research projects [50–52] and a small number of real-world demonstration projects, such as those in Minnesota and Las Vegas. However, autonomous bus demonstrations and accompanying research projects appear to be growing at a faster rate in Europe. European manufacturers have partnered in a large project (CityMobil2) co-funded by the European Union's Seventh Framework Programme and operated shuttles in demonstrations in different countries such as France, Greece, and Switzerland [9]. Approximately 60% of studies on autonomous buses have been conducted in Europe with almost half of them being based on the CityMobil2 Project (see Figure 3). The European studies considered a broader range of topics, such as user acceptance, security, safety, system technology, costs and legal issues [15, 26, 38]. Last, it is important to note that this study did not review works conducted in languages other than English; this is likely to exclude studies conducted in Asia, which could be another area for important future research if language barriers can be overcome.

Five main themes emerged from reviewing 40 studies conducted in the last decade: technology development, user acceptance, safety, social and economic aspects, and policies, regulations, and legal issues. As presented in Figure 4, "User acceptance" was considered in most studies (14 studies). This was followed by "Social and economic aspects" (13 studies) and "Technology" (12 studies). Surprisingly, "Policies, regulations, and legal issues" were considered least in the publications (only 5 studies), despite the wide range and importance of this topic.

Another important conclusion is that the main themes found in the literature are interrelated (see Figure 5). Technology development is associated with potential increases in safety and reductions in operating costs due to removing a driver from buses. However, user acceptance and perceived safety/security studies generally found that passengers prefer to have staff on board autonomous buses, which could negate operational cost savings. Planners and operators of autonomous bus systems should therefore strive to find the best combination of operational policies that achieve the potential benefits (e.g., operational cost savings) while addressing concerns about security.

Last, several important gaps were apparent in the literature and were identified in this review. For example, policymakers and experts have not developed a systematic framework for legal issues and liability of autonomous buses, particularly for locations outside of Europe. Similarly, the impacts of autonomous bus technology on labour unions have not been comprehensively studied, despite the fact that this could be a potential barrier to implementation [52]. Furthermore, there is limited literature pertaining to larger sized autonomous vehicles, such as articulated buses used in bus rapid transit (BRT) or other possibilities such as vehicle resize, network redesign, shared-ride vehicles, and alternative fuels. In summary, as automation technology continues to evolve, there are likely to be many valuable areas for future research pertaining to autonomous buses.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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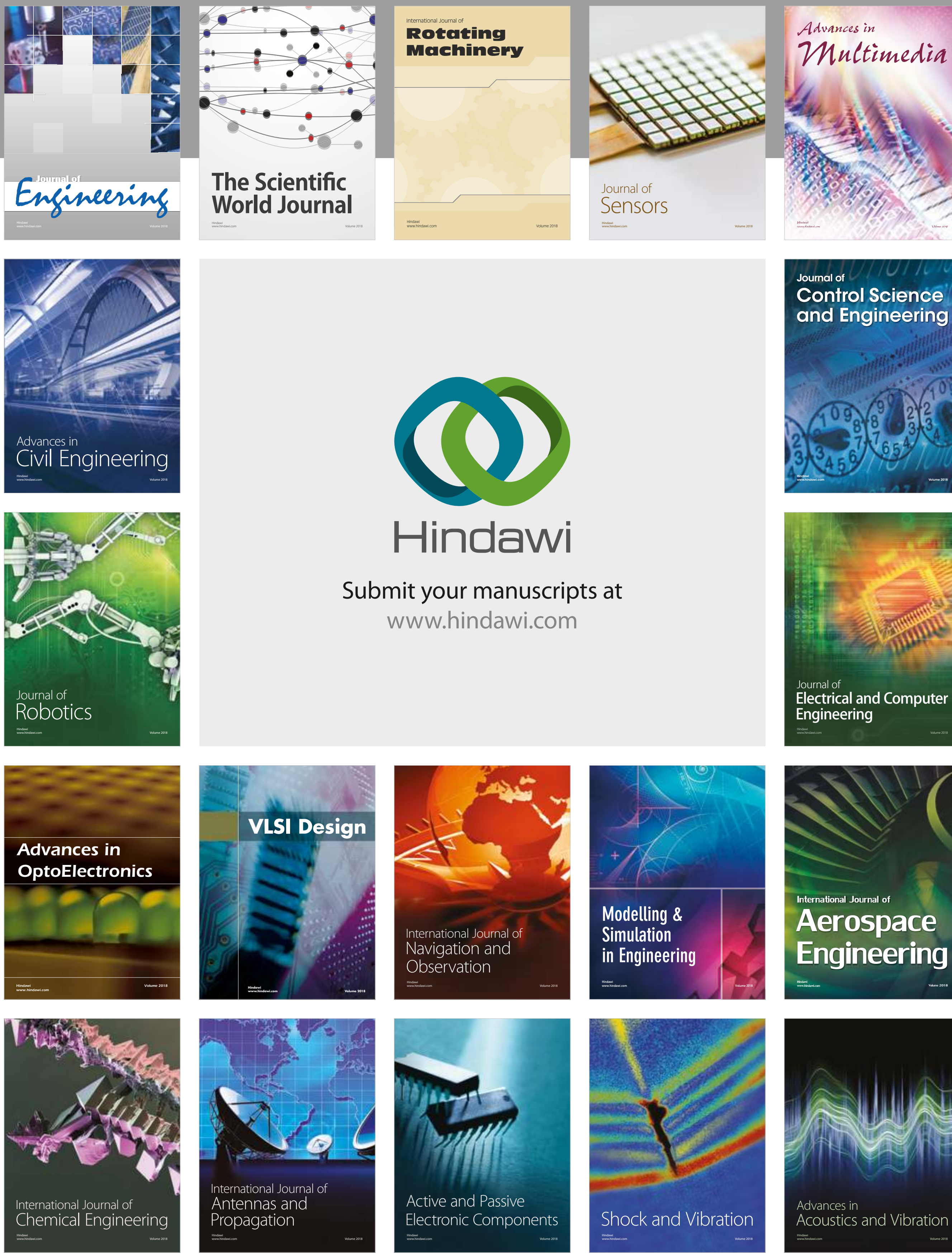
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