

METHODS

Evaluation of sustainability of using autonomous vehicles for the last-mile delivery industry

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This study aims to determine if autonomous vehicles (AV) for last-mile deliveries are sustainable from three perspectives: social, environmental, and economic. Because of the relevance of AV applications for last-mile delivery, safety was only addressed for the sake of societal sustainability. According to this study, it is rather safe to deploy AVs for delivery since current society's speed restrictions and decent road conditions give the foundation for AVs to run safely for last-mile delivery in metropolitan areas. Furthermore, AV has a distinct advantage in the event of a pandemic. The biggest worry for environmental sustainability is the emission problem. It is established that AV has a substantial benefit in terms of emission reduction in terms of a series of emissions. This is mostly due to the differences in driving behavior between autonomous cars and human vehicles. Because of AV's commercial character, this research used a quantitative approach to highlight the economic sustainability of AV. The study demonstrates the economic benefit of AV for various carrying capacities.

Keywords: supply chain management, logistics, sustainability, autonomous vehicles

Introduction

The in the e-commerce market is US\$2,237,481 million in 2020 and this figure is anticipated to grow by 7.6% annually (1), a trend that results in a market value of US\$3,003,971 million in 2024. The e-commerce market's largest part is made up of fashion, which occupied US\$717,993 million in 2020. Moreover, e-commerce user penetration is estimated to increase from 56.1% in 2020 to 65.5% in 2024. The average revenue per user (ARPU) currently is US\$535.70 (2). The number of customers in the e-commerce market has risen gradually during the past few years, and this number was estimated to go up to 5,060.3 million by 2024.

Express delivery is a necessary support for online shopping, so the delivery market has boomed significantly with such a flourishing worldwide e-commerce market. The courier, express, and parcel (CEP) market volume in the world increased stably from 2009 to 2018 and reached 306.18 billion euros (3). In addition, the global CEP market is expected to grow by USD 90.63 billion during 2019–2023,

progressing at a compound annual growth rate of over 5% (4). There are three main companies—namely, DHL, FedEx Corp, and UPS—to share the couriers and local delivery services. For example, the three delivery giants accounted for more than 90% of the delivery service business in the world in 2018. Another research (5) shows that the world autonomous last-mile delivery market volume is estimated to reach \$11.13 billion by 2021, and is anticipated to increase to \$75.65 billion by 2030, progressing at a compound average growth rate of 23.7%. North America is expected to be the highest revenue contributor, which accounts for \$4.5 billion by 2021, and this number is projected to climb to \$35.67 billion by 2030, with a compound average growth rate of 25.9%. Europe and North America are predicted to collectively account for approximately 71.1% in 2021, with the former constituting roughly 40.6%. Europe and North America are estimated to witness considerable compound average growth rates of 25.9% and 24.5%, respectively, during the forecast period. The cumulative share of these two parts is expected to be 71.1% in 2021 and is projected to ascend to 79.1% by 2030.

Overall, the rapid growth of urbanization and the rise in the disposable income of consumers are boosting the e-commerce industry. An inclination toward online services because the rise in usage of smartphone devices has caused the growth of trade through online portals. This phenomenon, in turn, has been thriving in the worldwide express delivery industry. The rise in internet penetration has led to an increase in last-mile delivery services. Additionally, multinational e-commerce organizations—such as Amazon—are paying attention to the progress of their speed of delivery and reach. Therefore, these firms are investing remarkably in express delivery businesses. Last-mile delivery is the last step in the network of CEP. It is an entire ecosystem that brings various goods to customers' doors (or very close). According to a survey conducted by McKinsey (6), there are three insights in this industry: consumer expectations are high and these expectations are going up; automation potential is high; and competitive dynamics are changing (6).

The research aims to identify the sustainability of autonomous driving for last-mile delivery from three perspectives: social sustainability, environmental sustainability, and economic sustainability. Moreover, this research also aims to put forward suggestions for the use strategy of autonomous vehicles (AVs) for delivery. To analyze sustainability, the three pillars—social sustainability, environmental sustainability, and economic sustainability—were discussed step by step. This research first qualitatively analyzes social and environmental sustainability through identifying the current status of safety status and the emission of AVs. Even though social sustainability has four main components theoretically, safety was solely discussed because of the importance of AV application for last-mile delivery. The safety issue was divided into three contexts: safety, driving behavior safety, and technology safety. For environmental sustainability, the main topic in this part is the emission of AV because the emission is the most significant part of AV related to the environment. This research cites a large number of data points and research to show the emission status of AV. Then this research tries to quantitatively analyze the economic sustainability through building a quantitative model to calculate the average expenditure of AVs and conducting a comparison between the cost of self-piloting automobiles and the cost of manned vehicles, in order to analyze and discuss the cost advantage of the two types of vehicles for delivery. This research finally proposes some recommendations for the use of AVs based on the cost advantages of AVs.

This paper is mainly organized in terms of objectives. After a general introduction about the delivery industry's status, research aims, and objectives, a literature review is presented in the second stage, which includes the background of autonomous driving for last-mile delivery and the sustainability of this transportation. Sustainability is divided into three parts—namely, social sustainability,

environmental sustainability, and economic sustainability. The following three sections are the analysis and discussion of social, environmental, and economic sustainability. In addition, the findings of each sustainability are carried out at the end of each section. Finally, the main body of this research ends up with a conclusion, which is made up of a research overview, key findings, recommendations, limitations of the research, future research suggestions, and a conclusion. The reference list and the ethics certificate are placed at the end.

Literature review

The application of AVs in delivery

It is believed that the combination of intelligent ordering methods—such as telephone and internet—and up-to-date supply chain management techniques supports companies to serve their customers in innovative ways. In a commercial context dominated by the importance of cheap service and any meaningful connection with customers (7), these ways are convenient, of high quality, customized, and enjoyable experiences. In addition, Gramatikov et al. (8) stated that the number of online orders is increasing steadily; accordingly, it is necessary to deliver goods to the customer efficiently and environmentally friendly. The AVs are obviously becoming the next revolution in goods delivery, which should be the background.

Statista (9) argued in the research of fast-forwarding last-mile delivery that consumer expectations are high and rising, automation potential is high, and that competitive dynamics are changing. The three main insights in this research provided the fundamental needs of the autonomous drive for delivery; accordingly, it is necessary to conduct further research in terms of autonomous drive sustainability. However, Michael and Delila (10) pose some questions about this advanced technology in terms of safety concerns, environmental risks, and economic issues. They illustrated the problems in general circumstances but did not consider the details of a specific scenario. These potential problems could have decisive impacts on the implementation of AVs in the “last mile.” Moreover, if these problems can be probed, the corresponding conclusions can be used to illustrate the sustainability of autonomous delivery. This research is going to research the sustainability of the autonomous drive of last-mile delivery in terms of those risks mentioned earlier.

Sustainability

The definition ((11):3) provided by the World Commission on Environment and Development in 1987 argued that sustainability is an economic-development activity that meets the current requirements without impairing the ability of future generations to satisfy their requirements.



FIGURE 1 | Three pillars of sustainability.

However, Robert et al. (12) contend that sustainability means meeting basic human needs while protecting the earth's life support systems. Besides, Lim and Taihagh (13) suppose that sustainability is not an objective but a course of continuous advancement according to the needs and the context, which can change in space and time. Moreover, the organization's corporate finance institute (CFI) defines sustainability as the capability to provide for the needs of the current generation using available resources without adversely impacting future generations (14). It seems that they have a reasonable perspective on defining sustainability. The three opinions, however, cannot generalize sustainability separately. However, it is realistic to utilize them individually when facing a specific issue.

The three-pillar (social, environmental, and economic) conception of sustainability, normally described by three intersecting circles with sustainability at the center, has become pervasive (15). Furthermore, Chokshi (16) supposes that economic, environmental, and social pillars are foremost in assessing sustainability, and if any one of the three pillars is weak, the overall system can become unsustainable. As a result, when the AV emerges, the three-pillar theory is an exacting standard to assess the sustainability of this innovative means of transportation. This research is going to analyze whether this transportation for delivery is sustainable by applying this theory. The following sections are divided into three parts to analyze social sustainability, environmental sustainability, and economic sustainability, respectively.

Social sustainability

There is little literature that pays attention to social sustainability, so a detailed interpretation of this concept is still lacking (17). However, a study by the OECD (18)

supports the idea that social sustainability is dealt with in connection with the social influences of environmental politics rather than regarded as an equal component of sustainable development. Moreover, Assefa and Frostell (19) believe that social sustainability is the outcome of development, while environmental and economic sustainability are both the objectives of sustainable development and tools for its realization.

Overall, even though the past definitions of social sustainability are few and unclear, it is easy to connect social sustainability with autonomous driving. For example, the potential social impact generated by AVs is correlated with social sustainability. For example, if an AV causes an accident and hurts people, it indisputably impacts society. Thus, this research chooses safety as one of the social issues as a topic to analyze the sustainability of AV for delivery.

Environmental sustainability

A simple and traditional explanation of environmental sustainability is meeting human needs without jeopardizing the health of ecosystems (20). Similarly, Moldan et al. (21) suppose that environmental sustainability is the preservation or improvement of the integrity of the earth's life operating systems. Environmental sustainability is the second pillar, which is one of the main concerns for the future of humanity. It indicates how we should study and preserve the ecosystems, air quality, and sustainability of our natural resources and focus on the components that hamper our environment (16). Overall, most of the definitions of environmental sustainability are focused on its biogeophysical aspects. When it comes to the environmental sustainability of autonomous driving for last-mile delivery, this research pays attention to the vehicle's emissions in the process of transportation.

Economic sustainability

Economic sustainability is the motivation of businesses and organizations that is aimed at observing and obeying sustainability guidelines beyond their normal legal requirements. It should also encourage the average person to participate in whatever capacity they can; an individual rarely achieves much, but a group can go much further (16). As shown in **Figure 1**, the three-pillar theory is a relatively comprehensive definition of sustainability.

Based on the discussion of sustainability, this research is going to apply the three-pillar model to analyze the autonomous drive delivery of last mile. For the economic aspect, this research is going to investigate the cost of autonomous driving and compare it with the traditional delivery of last mile. When it comes to social sustainability, this research focuses on the risks that could impact

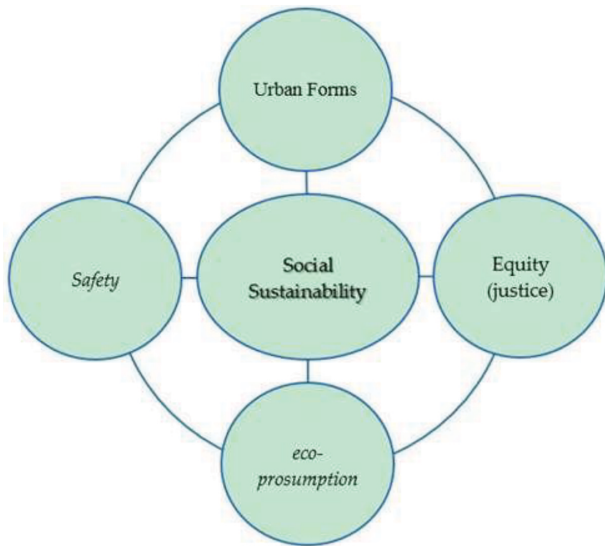


FIGURE 2 | Conceptual framework of social sustainability (23).

customers. The emission will be the theme in terms of the environmental part.

Sustainability analysis

Social sustainability (safety)

The social influence of business is easy to identify but difficult to assess. However, understanding the effects of business on society and the environment is important to achieve sustainability (22). Eizenberg and Jabareen (23) proposed a general conceptual framework (Figure 2) of social sustainability. The framework comprises four associated concepts of socially oriented practices, where each concept has a particular function in the framework and incorporates primary social aspects. The concept of safety in this framework is the ontological foundation of sustainability in general and social sustainability in particular. The concept refers to the right to not only be safe but also to take all methods of security and adaptation to prevent future casualties and physical injury. This framework and the corresponding definition provide evidence that it is essential to analyze the safety issues of the autonomous drive for delivery before implementation. Hence, safety issues related to autonomous driving are discussed and analyzed in the following paragraphs.

Context safety

The last-mile delivery is usually the final part of the entire delivery, and the environment is probably complicated and of high risk, especially in the crowded urban area, which has a large number of pedestrians, trucks, cyclists, buses, cars,

and different barriers. Those subjects have different moving directions at different times. This circumstance makes the context of last-mile delivery suffer huge safety risks. However, the driving speed limit in cities is normally low. For example, the UK national speed limit is 30 miles per hour in built-up areas (24), a limit applied to all kinds of automobiles such as cars, vans, motorcycles, coaches, buses, and goods vehicles. If the AVs are designed with a relatively low speed as well, the vehicles would have sufficient time to judge, respond, and control themselves. Therefore, it can be expected that the safety risk from a speed perspective is relatively low. Second, most areas that need last-mile delivery are located in urban areas, which have relatively good road conditions. AV could be safer when running on those roads compared to bad road conditions. For example, AV is not likely to cause an overturned accident while running on flat roads.

Driving behavior safety

It is true that misoperations while driving can hardly be prevented, such as drink-driving, seatbelt use, and fatigue-driving. Most countries have established a set of very strict regulations and legislation to prevent improper and lawless driving. For example, according to UK drink-driving penalties rules (24), those who drive or attempt to drive while above the legal limit through drink may get: 6 months of imprisonment, an unlimited fine, and a driving ban for at least 1 year (3 years if convicted twice in 10 years).

Despite such rigorous legislation, approximately 1.2 million people die and millions more are harmed or disabled as a result of road accidents all over the world each year (25). Besides, another study (26) shows that an anticipated 20–28% (25% average) of all road casualties in Europe correlate with alcohol use. Furthermore, fatigue-driving contributes to 10–20% of road crashes worldwide (27), and 4% of fatal crashes in Britain are caused by tiredness (28). These data show that manned driving has significant disadvantages when compared to manual driving. Also, Araz and Lim (29) stated that more than 90% of road tragedies are projected to be the consequence of human fault; consequently, choosing AVs can potentially reduce or eliminate the largest cause of traffic accidents and also outperform human drivers in execution, perception, and decision-making.

A study by McKinsey & Company (30) expects that in a future where all cars are AVs, people could witness an accident rate that is reduced by up to 90%. The important reason for this reduction is that AV can eliminate the occurrence of human faults: from loss of attention to delay of reaction and failure to conform to the regulations of the road because AV does not get tired, angry, frustrated, or drunk (31). Notably, delivery drivers for manned vehicles—who work long hours with few rests—could be more vulnerable to these faults. Another possible reason why AV is safer is that the AV drive system probably performs driving better than

humans. For example, humans have a visual blind point when driving, while AV can avoid this through programming.

Technology safety

The implementation of AV for delivery is unrealistic without enough support from unmanned drive technology. Litman (32) stated the impacts on self-driving as well as their implications for various planning issues. It investigated the speed of self-driving, costs and benefits, and how they are likely to influence travel needs. Although this analysis is not focusing on the autonomous drive for delivery, the estimated implication in the future suggests that the viability of the autonomous drive is fulfilled in terms of the technology aspect.

However, Lim and Taihigh (13) argue that despite the removal of driver mistakes, risks may be generated by a myriad of elements, such as system mistakes, cyber-attacks on safety systems, and incautious behavior from passengers and pedestrians. Furthermore, it is believed that vehicles have become increasingly heavy in recent years to meet stricter crash test standards, and that no AV will be released for use unless those strict test standards are met.

Response to COVID-19

Since the discovery of the first corona virus (COVID-19) in Wuhan, China, on December 31, 2019, there were 3,271,892 confirmed cases (Figure 3) worldwide on April 30, 2020 (33).

During such a pandemic, AVs have a significant advantage when running on the road because they create no infected risk while servicing people. Thus, it could be utilized for service delivery, healthy material transportation, and any transportation task related to fighting COVID-19. For example, AVs move through COVID-19 tests in Florida (34).

Environmental sustainability

Environmental protection is becoming more and more important in modern society. Any kind of transportation for last-mile delivery should consume less environmentally friendly energy. The emissions caused by transportation are becoming more and more notable. For instance, a carbon dioxide emission figure (35) shows that America's trucks, automobiles, and aircraft emit more carbon dioxide than its power plants do since February 2016. Accordingly, it is necessary to find out whether autonomous driving harms the environment to assess the sustainability of AV last-mile delivery. In the last-mile delivery scenarios, the first environmental issue that comes to mind is the emission problems. Therefore, an emission analysis of AV

in the process of last-mile delivery is conducted in the following sections.

Greenblatt and Saxena (36) found that small, shared, electric-driven AVs in combination with a future low-carbon electricity grid could lessen per mile (km) greenhouse gas emissions by 90% compared to current automobiles. Besides, Igliński and Babiak (37) conclude that precise anticipation of the possibility of AV in the decrease of greenhouse gas emissions is very difficult because of a set of variable factors that condition the operation of the future transport system. It may, however, be estimated that the total decrease will be roughly 40–60%. Moreover, they found that the drop in emissions will only happen after AV becomes more prevalent, and this requires their creators to reach the 5th level of autonomy, at which people will be freed from controlling cars.

Research (39) shows that adopting more efficient driving patterns is a method to decrease emissions from AVs. Reducing human interaction with driving would decrease repetitive acceleration and braking and even permit cars to run closer together, which is known to enhance aerodynamics. Thereafter, a quantitative analysis aimed at anticipating the emission impacts of AV, carried out by Liu et al. (40), concludes that AV runs smoother than manned vehicles because AV is projected to be faster and more accurate than human drivers in terms of reaction times and driving skills. They believe that human drivers are likely to undergo drastic and continual speed fluctuations (i.e., hard brakes and fast accelerations) and have a long reaction time (e.g., 1.5 s), while AV technologies may rarely be influenced by such fluctuations, allowing for smoother driving. Therefore, they contend that hard braking and rapid acceleration actions correlate with increased emissions, so, by smoothing human vehicles' existing driving cycles, this work expects to achieve the emission advantages of AVs. Furthermore, Liu et al. (40) found that the results from their modeling and calculations show that, normally, if human vehicles are substituted by AVs, greater emission benefits (up to a 14% emission decrease) are estimated in driving conditions where there are many hard acceleration and braking events, and for drivers with bad driving styles. The outcomes of the Austin cycle indicate the average emission drops are 10.89% for volatile organic compounds (VOC), 19.09% for fine particulate matter (PM_{2.5}), 13.23% for carbon monoxide (CO), 15.51% for nitrogen oxides (NO_x), and 6.55% for sulfur dioxide (SO₂) and carbon dioxide (CO₂). They also found that road with higher mean speeds have greater emission decreases in all emission items. This quantitative analysis presents the specific values of each emission that AV can reduce when compared to manned vehicles. It justified the advantage of AV in terms of emission reduction.

However, it is still hard to say that the emissions will drop if the manned vehicle is replaced by an AV. The



FIGURE 3 | COVID-19 confirmed cases statistic (33).

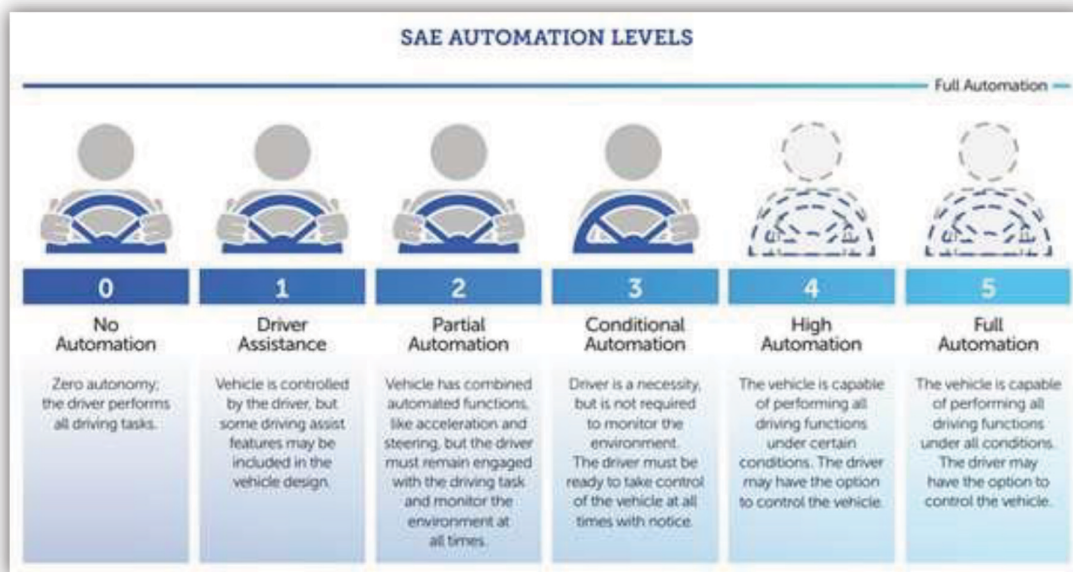


FIGURE 4 | Automation levels (38).

reason is that some research shows that the traveled vehicle miles will increase so that the total emissions will rise (41). They believe automation reduces the opportunity cost of driving. This probably encourages people to take more automobile journeys or accept longer commutes because they would be able to multitask in cars rather than concentrate on the road. Besides, AV technology could allow groups of people who are currently unable to drive—such as the aged, young, and disabled people—to travel alone in AVs, increasing the number of people on the road. Hence, the total emissions will increase.

However, AVs may also contribute to solving parking problems in the long run. In addition to the environmental issues of energy production and consumption, existing cars impact much of the living environment. Even in the crowded city center, traditional cars occupy a considerable amount of space for parking. However, being able to drive and park themselves at some distant location from their users, AVs may need no nearby parking lot for residents, workers, or business establishments, which may be able to restructure the urban environment and allow new construction development because nearby parking lots are unnecessary.

Economic sustainability

Newman et al. (42) argue that qualitative analysis virtually reflects some sort of individual phenomenological perspective. Most quantitative research, however, tends to emphasize the common reality that people can agree. Therefore, pure qualitative cannot illustrate sustainability sufficiently and it is necessary to carry out a quantitative analysis. The following sections apply several mathematical methods to supplement the qualitative analysis to demonstrate sustainability.

This research simulates a model based on a real-life scenario to investigate the cost of autonomous driving for the last mile. This scenario depicts the process of goods transportation from a Lidl storefront to a city center (Hub). There are two transport methods that will be applied to this route, including autonomous driving and manual driving.

First, this route is stipulated as from Lidl supermarket to the courier locker at Hub (L-H). Then, the distance and transport time of this route are calculated from the OPENROUTESERVICE software. OPENROUTESERVICE is an open-source route planner with plenty of features for cars, heavy vehicles, hiking, and cycling. The distance of this route (d_{L-H}) is 4.2 km and the delivery time of manual vehicles (t_2) is 22.5 min.

Develop assumptions

All the calculations and formulas are conducted based on the real context; so, it is necessary to follow the basic requirements of the actual transportation practice. As a result, the mathematical models are established on the following assumptions and existing data values.

1. The daily operating cost of AVs is mainly comprised of electricity consumption.

2. Both autonomous and manual vehicles operate 250 working days per year. However, AVs operated 24 h per day while manual vehicles operated 8 h per day because of the legal limitation on a driver's daily working time.

3. The service life of an AV (T_A) is 8 years.

4. The cost of manual vehicles is amortized into their daily cost, while the cost of AVs is not included in the daily cost and is an initial investment.

5. The maximum capacity of one manual vehicle (W_M) is 5,000 kg (43).

6. The maximum capacity of one AV (W_M) is less than or equal to the maximum capacity of one manual vehicle (W_M).

7. The average running speed of one AV (v_A) is 6.4 km/h (44).

8. The running cost of manual vehicles per kilometer is 1 pound (43).

9. Both autonomous and manual vehicles run at their full capacity.

10. In the United Kingdom, the average electricity price for electromobile (PoE) is £0.25 per kWh (45), and the electricity consumption per kilometer (EpK) is 0.19 kWh (46).

11. The cost of electric vehicles is composed of power only.

12. In 1 day, an AV can deliver the same weight of shipments as a manual vehicle can.

13. The initial purchasing cost of one AV (C_i) is £24,000 (47).

14. During the service life of each AV, the sum of initial purchasing cost and accumulated operating cost should be less than the sum of initial purchasing cost and accumulated operating cost of a manual vehicle; otherwise, AVs are unnecessary.

Calculation

The daily operating cost of running AVs (C_A) can be calculated through:

$$C_A = x_1 \times d_{L-H} \times Epk \times PoE$$

where x_1 refers to how many times on the route L-H can an AV runs during one working day, d_{L-H} refers to the distance of this route, EpK refers to the electricity consumption per kilometer, and PoE refers to the price of electricity.

Input data values are presented in assumption 10:

$$C_A = x_1 \times 4.2 \text{ km} \times 0.19 \text{ kWh/km} \times £0.25/\text{kWh} \times 0.2x_1$$

The daily cost of running manual vehicles (C_M) can be calculated through:

$$C_M = x_2 \times d_{L-H} \times Ppk$$

where x_2 refers to how many times on the route L-H can a manual vehicle runs during one working day, d_{L-H} refers to the distance of this route, and Ppk refers to the running cost of manual vehicles per kilometer. This cost includes the fixed cost (cost for the truck and the insurance), maintenance (including tires), the cost for the driver, and fuel costs.

Input data values are presented in assumption 8:

$$C_M = x_2 \times 4.2 \text{ km} \times £1/\text{km} \times 4.2x_2$$

Define $\Delta C = C_i + 250 \text{ days} \times C_A - 250 \text{ days} \times C_M = 24,000 + 50x_1 - 1050x_2$, and ΔC means the difference of the accumulated cost between AVs and manual vehicles during the service life of an AV. This research aims to find the appropriate x_1 and x_2 that can lead to a minimum ΔC , which is an indicator of the cost between autonomous drive and manual drive. If these optimization values exist, AVs are sustainable in terms of daily operating costs.

Finding minimum ΔC is subjected to the following model constraints:

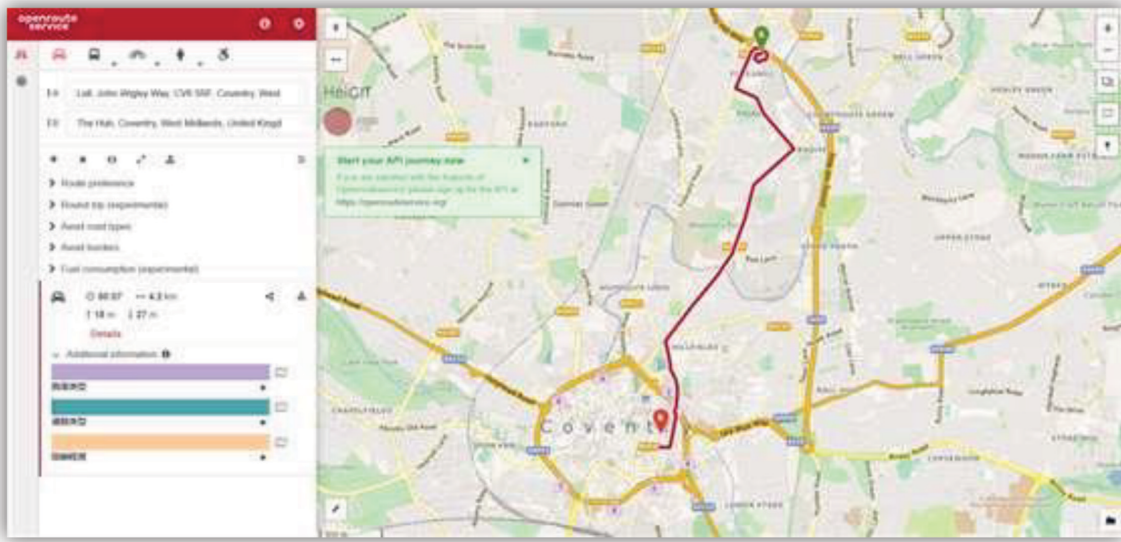


FIGURE 5 | The route from Lidl supermarket to a target locker at Coventry center.

1. In the real context, the number of AVs that run on the route in a working day must not be less than 0 and the number cannot be a decimal.

$$\text{So : } x_1, x_2 \geq 0, \text{ and both are integers} \quad (1)$$

2. The total time that an AV spends on the route per day is no more than 24 h, which is indicated by the product of a daily operating number and the time amount per operation.

$$x_1 \times t_1 = x_1 \times \frac{d_{L-H}}{v_A} = 0.66x_1 \leq 24 \implies x_1 \leq 36 \quad (2)$$

3. Like the time algorithm of an AV, the time that a manual vehicle spends on the same route can be expressed as the following formula. However, according to assumption 2, the operating time of a manual vehicle is 8 h a day.

$$x_2 \times t_2 = 0.38x_2 \leq 8 \implies x_2 \leq 21 \quad (3)$$

4. According to assumption 12, the weight that an AV transports is as much as that of a manual vehicle. Then, it can be expressed by:

$$W_A \times x_1 = W_M \times x_2 : x_1 = \frac{W_M}{W_A} x_2 \quad (4)$$

Thus, the aim is to a minimum $24,000 + 50x_1 - 1050x_2$. This formula can be rewritten as $24,000 + 50(x_1 - 21x_2)$. Therefore, ΔC can achieve its minimum value when achieving the minimum value of $x_1 - 21x_2$. The following simulation focuses on the calculation of the minimum value of $x_1 - 21x_2$ using statistical analysis software.

Simulation

To get the minimum value, let n represent $\frac{W_M}{W_A}$, which is the ratio of the weight of one manual vehicle (MV) to the weight of one AV. This research analyzes four scenarios in terms of different values of n from 1 to 25.

Because the formula includes two independent variables, it cannot be calculated and analyzed manually. However, MATLAB can be used to solve this mathematical problem.

$$\text{First, min } (x_1 - 21x_2) \text{ subject to } \begin{cases} x_1, x_2 \text{ are integers} \\ 0 \leq x_1 \leq 36 \\ 0 \leq x_2 \leq 21 \\ x_1 - nx_2 = 0 \end{cases}$$

Then, input the variables in MATLAB, and the outcomes will be carried out. Figures 6-8 show the outcomes of all the processes of the MATLAB.

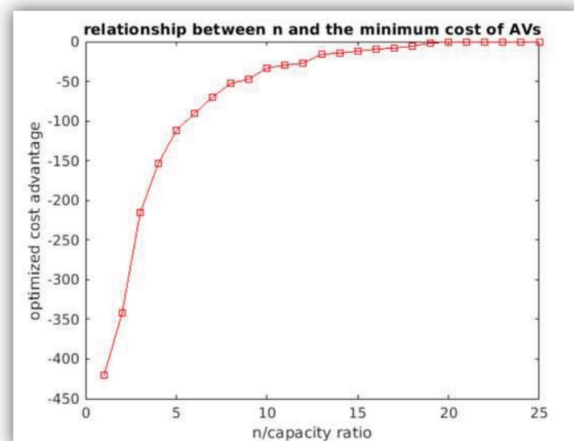


FIGURE 6 | The relationship between cost and n of AV.

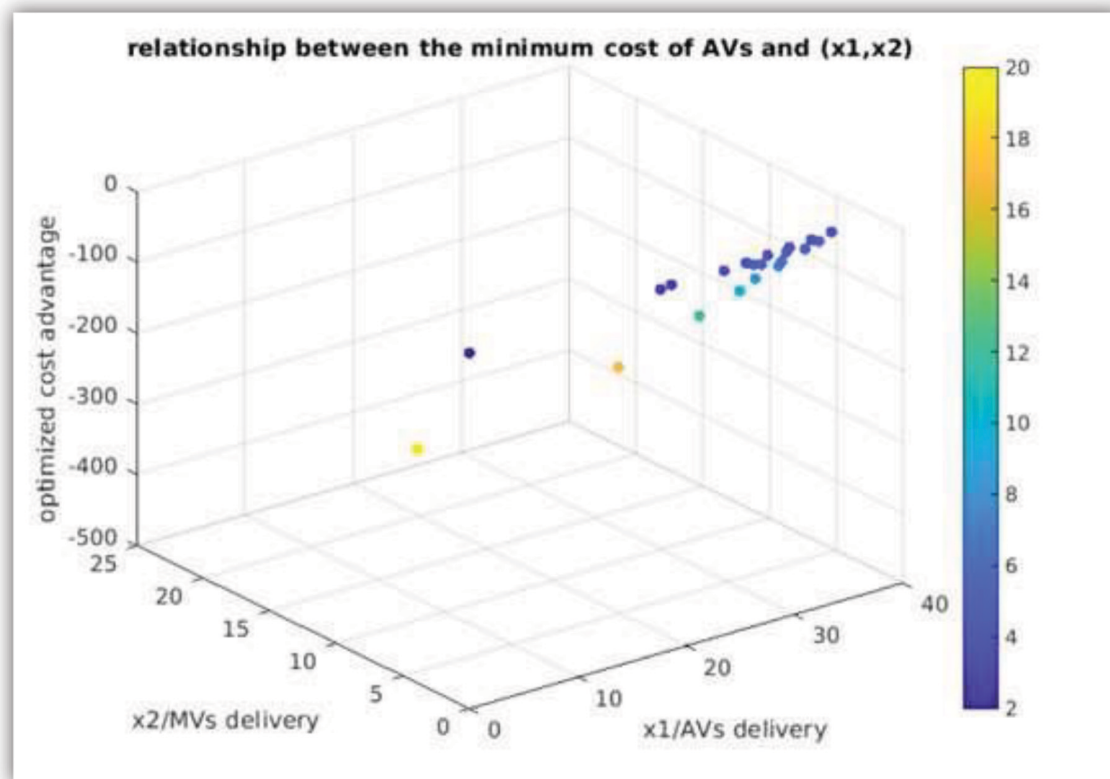


FIGURE 7 | 3D modeling for the relationship between AV and MV.

Figure 6 was generated by MATLAB after inputting the data. It depicts how the cost advantage changes with the change of n . The cost unit is pounds while n units are 1. It can be seen that the relationship between cost and n is a linear relation.

MATLAB provides a series of solutions (**Figure 8**) for the formula, and the optimized cost advantage has been listed in **Figure 8**. However, considering the context, those scenarios where the times of manual vehicles run less than eight times should be ignored because it is unrealistic that a manual vehicle operates only eight times in 8 h. As a result, it is reasonable to choose the solutions that $n = 1, 2, 3,$ and $4,$ respectively, which means a manual vehicle runs more than eight times per day.

As the bottom part of **Figure 8** shows, the four statistics are effective solutions; accordingly, the optimized cost advantage value can be utilized to assess the outcome of using an AV. It shows that an AV has a significant advantage in terms of cost when transporting goods on this route.

Key findings

Social sustainability

For social sustainability and safety consideration, this research result shows that AV has an overall better

performance in safety so that it could have good social sustainability. Firstly, for an AV running context, it is relatively safe because of the speed limit of current society and the good road conditions that provide the ground that AV runs safely for last-mile delivery in urban areas. Secondly, for the driving behavior aspect, AV has a significant advantage over a manned vehicle. The main reason is that AV has no human behavior so it is impossible to make human behavior mistakes when moving. Thirdly, for technology safety, AV's safety technology level is the same as traditional vehicles because their test standards are extremely high and because of the procedure, no vehicle can come into use without passing a strict test. Finally, AV has a special advantage when facing pandemic periods, a result that is in line with the research findings of Xuan Feng (48).

Environmental sustainability

Through the quantitative analysis of the emissions generated by AVs, the AVs have a significant advantage in emission reduction in terms of the series of emissions. This mainly results from the driving behavior differences between AVs and human vehicles. Some research shows that the total emissions will rise because of the use of AV. The phenomenon is generated by the side effect of the AV's use rather than the vehicle itself. So this kind of side effect could

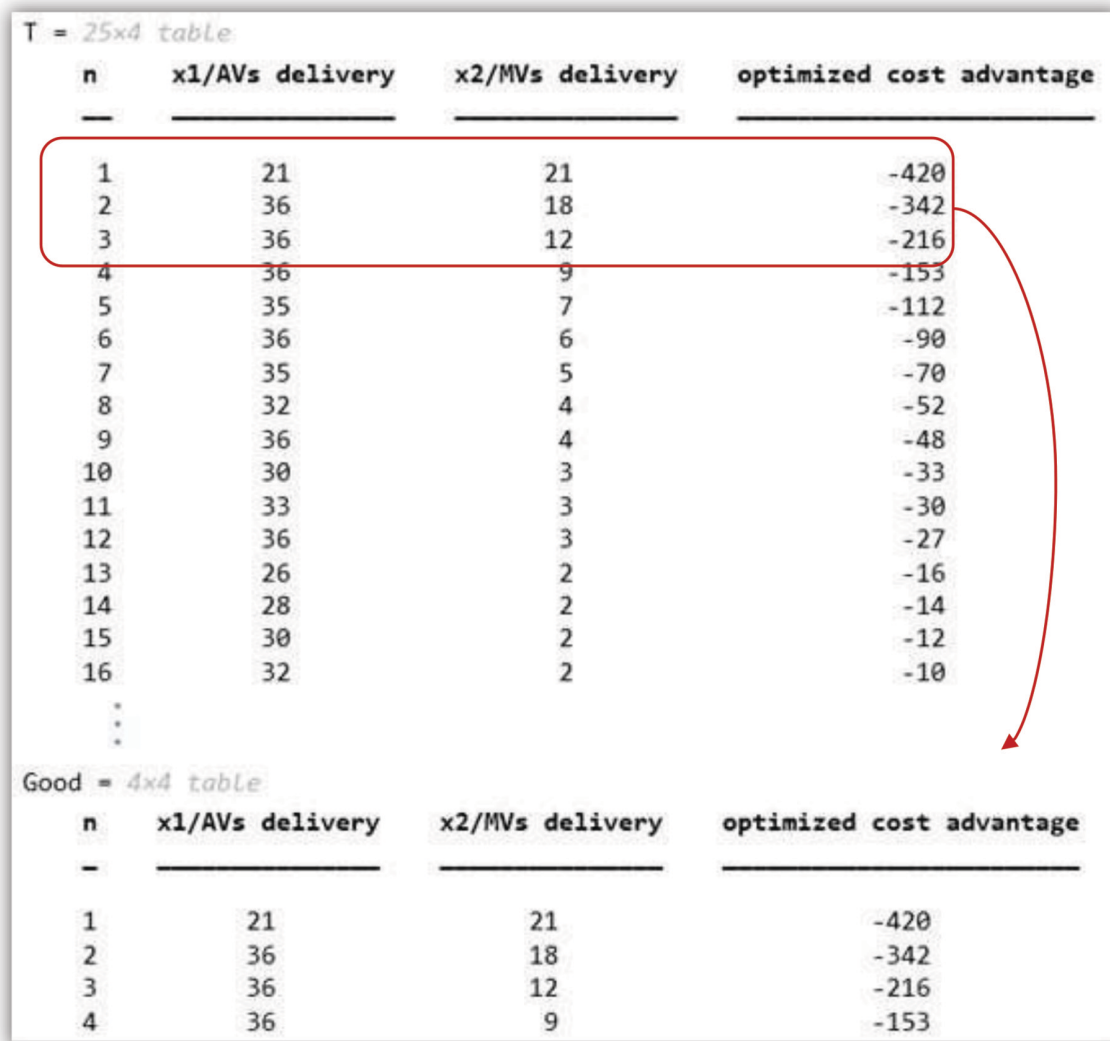


FIGURE 8 | Statistical portfolio of solutions.

be sorted into the management of AV. Then, looking at the quantitative analysis outcome and management aspect outcome of AV simultaneously, it cannot be calculated how much the emissions will be reduced or increased. Even though the emission reduction is clear, the amount of increase from the rising rate of people driving with AV cannot be confirmed. As a result, the total emission change trend is uncertain based on the present analysis. Finally, I found that AVs can, to a large extent, mitigate the pressure from the scarcity of parking places in urban areas.

Economic sustainability

The result of quantitative analysis shows that the cost advantage of AV in this route is approximately -475, the smallest value in the meantime when n equals 1, i.e., one AV carries the same weight as one traditional vehicle. This point means that the cost of AV is 475 less than that of MV. Accordingly, AV can save 475 pounds when AV transports

the weight as much as that of MV. 475 pounds is the maximum cost advantage of AV compared to MV in this context. The value of the weighting capacity of one Av to that of one traditional vehicle matters. From $n = 1$ to $n = 8$, this figure rises significantly along with the increase of n . This means when the weight of MV is 1 to 8 times that of AV, the weight impacts the cost advantage markedly. MV can transport more than AV, but AV can save less in this range. From $n = 9$ to $n = 19$, the figure goes up gradually, accompanied by an increase in n . This phenomenon proves that when the weight of MV is 9 to 19 times that of AV, the weight impacts the cost advantage of AV slightly. From $n = 20$ to $n = 25$, the figure stays unchanged no matter how n changes. This means that when the weight of MV is 20 to 25 times that of AV, MV has the same cost as AV. More specifically, when the manual vehicle is big enough, AV has no cost advantage anymore. Over the change range of n , the figure does not exceed 0, which means the same cost of the two drive types. As a result, the cost of autonomous drive in

this route is no greater than the cost of manual drive through the chosen weight rate range.

In all, the autonomous drive for the last-mile delivery is sustainable because it can save money compared to manual driving for the last-mile delivery.

Recommendations

The result of this research has important practical implications for real business. Firstly, to achieve safer road traffic, corporates should replace manned vehicles with AVs as much as possible for last-mile delivery. This replacement keeps pace with the audit procedure of AV. Moreover, increasing the number of AV runs for last-mile delivery is helpful for reducing emissions. Furthermore, when the manned vehicle capability is 1 to 25 times that of AV's and the manned vehicle runs more than eight times per day, using AVs to replace manned vehicles can save money. It is also possible to achieve more AVs through some financial methods. For example, gaining funds from investment banks such as Goldman Sachs, an international leading investment bank, despite various management issues (Xuan (49)).

Conclusion

This research is aimed at confirming whether the AVs for last-mile delivery are sustainable. Several objectives were set up to address this aim. This research introduced a classical framework, which consists of three pillars of sustainability. This theory was regarded as the basis of this research, and the following structure followed the framework. To analyze sustainability, the three pillars—social sustainability, environmental sustainability, and economic sustainability—were discussed step by step. First, even though social sustainability has four main components theoretically, safety was solely discussed because of the importance of AV application for last-mile delivery. The safety issue was divided into three contexts: safety, driving behavior safety, and technology safety. The result shows that the AV's safety status is relatively good. Besides, a brief and special part about the response to COVID-19 was discussed in the last. Second, because the emission is the most significant part of AV related to the environment, the main topic in this part is the emission of AV. This research cites a large number of data points and research to show the emission status of AV. Notably, quantitative research on AV emissions was used to conduct the analysis. However, because of the adverse impact of AV that cannot be figured out thoroughly, the outcome is uncertain. Lastly, a brief living environment influenced by AV was discussed. Third, as for the economic sustainability of AV, this research adopted a quantitative approach to illustrate because the cost of AV is essential to consider because of AV's commercial nature. To figure out the cost of AV, this research

built a mathematical model and used statistical software to calculate, combining a set of assumptions with reality and actual values of AV. Several portfolios were finally confirmed to compare with manned vehicle costs. The result shows that the AVs can save more.

In all, the result of this research shows that the AV's sustainability for last-mile delivery is high. In addition, three suggestions are made in terms of how to use AV. Overall, AV is encouraged to replace the manual vehicle for delivery. Even though the process of analysis may not be thorough, this research still conducts a relative right and objective conclusion—namely, AV is sustainable for last-mile delivery. Several recommendations are also carried out completely, and the main point is that more AVs are encouraged to be used.

However, this research is not flawless due to limited research time and research conditions. Firstly, this research covers only the safety of social sustainability while neglecting the other three aspects of the social framework. Therefore, the analysis outcome of social sustainability may not be objective enough. Secondly, this research does not find a solution to expect the trend of choice after people using AV, so that the total amount of emissions cannot be acquired. Finally, the quantitative model designed to find the cost of AV does not include all the potential variables that could exist in actual scenarios, such as insurance cost, so the result could not be precise. Before building the model, we can interview the financial staff of the delivery company to get all the cost variables. Thus, a precise outcome could be expected.

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