This is a great work that aims at confirming whether the autonomous vehicles (AV) for last-mile delivery is sustainable in terms of three aspects - social sustainability, environmental sustainability, and economic sustainability. This study finds that it is relatively safe to use AVs for delivery because of the speed limit of actual society and the good road conditions provide the ground that AV runs safely for last-mile delivery in urban areas. Besides, AV has a special advantage when facing pandemic. For environmental sustainability, the emission problem is the main concern. It is concluded that AV has a significant advantage in emission reduction in terms of a series of emissions. As for the economic sustainability of AV, this research adopted a quantitative way to illustrate because the cost of AV is essential to consider because of AV's commercial nature. The research reveals the cost advantage of AV under different carrying capabilities.

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# Evaluate Sustainability of Using Autonomous Vehicles for the Last-Mile

A United Kingdom Case

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## Abstract

This research is aimed at confirming whether the autonomous vehicles (AV) for last-mile delivery is sustainable in terms of three aspects - social sustainability, environmental sustainability, and economic sustainability. The safety was solely considered for the social sustainability because of its importance of AV application for last-mile delivery. This study finds that it is relatively safe to use AVs for delivery because of the speed limit of actual society and the good road conditions provide the ground that AV runs safely for last-mile delivery in urban areas. Besides, AV has a special advantage when facing pandemic. For environmental sustainability, the emission problem is the main concern. It is concluded that AV has a significant advantage in emission reduction in terms of a series of emissions. This mainly results from the driving behaviors difference between AV and human vehicles. As for the economic sustainability of AV, this research adopted a quantitative way to illustrate because the cost of AV is essential to consider because of AV's commercial nature. The research reveals the cost advantage of AV under different carrying capabilities.

**Keywords:** Supply Chain Management, Logistics, Sustainability, Autonomous Vehicles

**JEL Classification:** R1, R4, R5

# Chapter 1

# Introduction

The income in the E-commerce market is US$2,237,481m in 2020 and this figure is anticipated to grow 7.6% annually (CAGR 2020-2024), a trend that results in market value of US$3,003,971m in 2024. The E-commerce market's largest part is made up of fashion, which occupies US$717,993m 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 (Statista 2020). The customers in the e-commerce market rose gradually during the past few years and this number was estimated to go up to 5,060.3m by 2024.

Express delivery is a necessary support for online shopping so that the delivery market was 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 (Mazareanu 2019). 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% (Businesswire 2019). There are three main companies -namely, DHL, FedEx Corp, UPS- to share the couriers and local delivery service. For example, the three delivery giants account for more than 90% of the delivery service business in the world in 2018. Another research (Allied Market

Research 2019) 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 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 is booming 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 flourishing the worldwide express delivery industry. The rise in internet penetration 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 (2016), there are three insights in this industry: consumer expectations are high and these expectations are going up, automation potential is high, competitive dynamics are changing (Mckinsey 2018).

The research aims to identify the sustainability of autonomous drive 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 using strategy of autonomous vehicles (AV) for delivery. To analyze the sustainability, the three pillars - social sustainability, environmental sustainability, and economic sustainability - were discussed step by step. This research first qualitatively analyzes the social and environmental sustainability through identifying the current status of safety status and the emission of AVs. For social sustainability, even though social sustainability has four main components theoretically, the safety was solely discussed because of its importance of AV application for last-mile delivery. The safety issue was divided into context 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 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 conducts 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. Based on the cost advantages of AVs, this research finally proposes some recommendations for the use of AVs.

This paper is mainly organized in light of objectives. After a general introduction about the delivery industry status, research aims, and research objectives, a literature review is presented in the second stage, which includes the background of the autonomous drive for the 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, recommendation, limitation of the research, future research suggestions, and conclusion. The reference list and the ethics certificate are placed in the last.

# Chapter 2

# Literature Review

## 2.1 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. These ways are convenient, of high quality, customized, and enjoyable experiences in the commercial context that has increasingly been dominated by the importance of cheap service and any meaningful connection with customers (Boyer, Frohlich and Hult 2004). In addition, Gramatikov et al. (2019) stated that the amount of online orders is increasing stably; accordingly, it is necessary to deliver goods to the customer efficiently and environmentally friendly. The AVs are obviously becoming the next revolution of the goods delivery-should be the background.

Schröder et al. (2018) 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, N & Delila, H (2018) pose some questions on 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 above.

## 2.2 Sustainability

The definition (Portney 2015:3) 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. However, Robert at al. (2001) contend that sustainability is meeting basic human needs while protecting the earth's life support systems. Besides, Lim & Taeihagh (2018) suppose that sustainability is not an objective but a course of continuous advance according to the needs and the context, which can change in space and time. Moreover, the organization 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 (CFI 2020). It seems that they have a reasonable perspective to

define 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 centre, has become pervasive (Purvis, Mao & Robinson 2019). Furthermore, Chokshi (2017) 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-pillars theory is 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.

### 2.2.1 Social Sustainability

There is little literature that pays attention to social sustainability so that a detailed interpretation of this concept is still lacking (Colantonio & Dixon, Timothy 2011). However, a study by the OECD (Le Gallic 2002) 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 & Frostell (2007) believe that social sustainability is the outcome of development while environmental and economic sustainability are both the objectives of sustainable development and tools to its realization.

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

## 2.2.2 Environmental Sustainability

A simple and traditional explanation of environmental sustainability is meeting human needs without jeopardizing the health of ecosystems (Morelli 2011). Similarly, Moldan et al. (2012) suppose that environmental sustainability is the preservation or improvement to the integrity of the earth's life operating systems. Environmental sustainability is the second pillar, which is one of the main concerns of the future of humanity. It indicates how we should study and preserve the ecosystems, air quality, sustainability of our natural resources and focus on the components that hamper our environment (Chokshi 2017). Overall, most of the definition of environmental sustainability is focused on its biogeophysical aspects. When it comes to the environmental sustainability of

autonomous drive for last-mile delivery, this research pays attention to the vehicle's emission in the process of transportation.

### 2.2.3 Economic Sustainability

Economic sustainability is the motivation of businesses and organizations, which is aimed at observing and obeying sustainability guidelines beyond their normal legal requirements. It should also encourage the average person to play their roles wherever they can; an individual rarely achieves much, but a group can go further (Chokshi 2017). As shown in following figure 1, the three pillars theory is a relatively comprehensive definition of sustainability.



**Figure 1.** Three pillars of sustainability

Based on the discussion of sustainability, this research is going the apply the three pillars model to analyze the autonomous drive delivery of last-mile. For the economic aspect, this research is going to investigate the cost of

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

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# Chapter 3

## Sustainability Analysis

### 3.1 Social sustainability (Safety)

The social influence of business is easy to identify but difficult to assess, however, understanding the effects on society and the environment is important to achieve sustainability (The Guardian 2012). Eizenberg and Jabareen (2017) proposed a general conceptual framework (see figure 2) of Social Sustainability, a 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 take all methods of security and adaptation to prevent future casualties and physical injury. This framework and the corresponding definition provide the evidence that it is essential to analyze the safety issues of the autonomous drive for delivery before implementation. Hence, safety issues

related to autonomous drive will be discussed and analyzed in the following paragraphs.
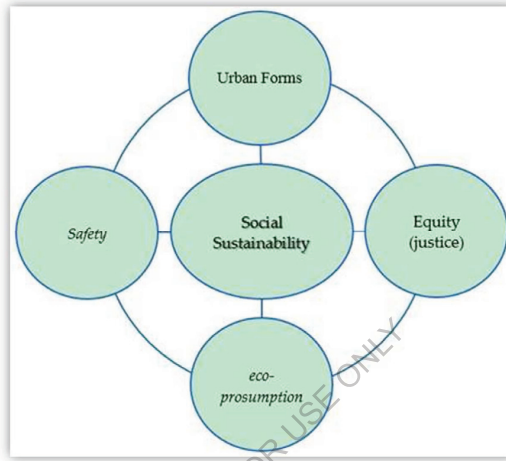


**Figure 2.** Conceptual framework of social sustainability (Eizenberg & Jabareen 2017)

### 3.1.1 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 of cities is normally low. For example, the UK national speed limit is 30 miles per hour in built-up areas (GOV.UK 2020), a limit applied to all kinds of automobiles such as cars, vans,

motorcycles, coaches, buses, and goods vehicles. If the AVs are designed with 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 has a relatively good road condition. AV could be safer when running in those roads compared to bad road condition. For example, AV is not likely to create an overturned accident running on flat roads.

### 3.1.2 Driving Behaviour Safety

It is true that the misoperation 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 (GOV.UK 2020), those people who drive or attempt to drive while above the legal regulation through drink may get: 6 months' 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 resulted from road accidents all over the world each year (WHO 2020). Besides, another study (OECD 2017) 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 (European Road Safety Observatory 2018), and 4% of fatal crashes in Britain are caused by tiredness (GOV.UK 2015). These data show manned driving has severe disadvantages in terms of the process of manual driving. Also, Araz Taeihagh & Hazel Si Min Lim (2019) 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 (Bertoncello and Wee 2015) expects that in a future where all cars are AVs, people could witness an accident rate that reduces 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 (Baker 2019). Notably, delivery divers for manned vehicles - who work long times with few rests - could be more vulnerable to these faults. Another possible reason why AV is safer is the AV drive system probably performs driving better than humans. For example, human has a visual blind point when driving while AV can avoid this through programming.

### 3.1.3 Technology Safety

The implementation of AV for delivery is unrealistic without enough support from unmanned drive technology. Litman (2020) 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 autonomous drive is fulfilled in terms of the technology aspect.

However, Lim & Taeihagh (2018) argue that despite the removal of driver mistake, risks may generate from a myriad of elements, such as system mistakes, cyber-attacks on safety systems, and incautious behavior from passengers and pedestrians. Moreover, it is believed that vehicles have become increasingly heavy during the past years to meet stricter crash test standards and that no AV will be released to use without meeting those strict test standards.

### 3.1.4 Response to COVID-19



**Figure 3.** COVID-19 confirmed cases statistic (Johns Hopkins University 2020)

Since the first Corona Virus (COVID-19) confirmed in Wuhan city, China On 31 December 2019, there are 3,271,892 confirmed cases (see figure 3) worldwide on 30 April 2020 (Johns Hopkins University 2020).

During such pandemic, autonomous vehicles have a significant advantage when running on the road because it creates no infected risk while servicing people. Thus, it could be utilized to service delivery, healthy materials transportation, and any transportation task related to fighting COVID-19. For example, autonomous vehicles move COVID-19 tests in Florida (Forbes 2020).

## 3.2 Environmental Sustainability

Environmental protection is more and more important in modern society. Any kind of transportation for last-mile delivery should consume less and environment-friendly energy. The emission conducted by transportation is becoming more and more noteworthy. For instance, a carbon dioxide emission figure (Plumer 2016) 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 the autonomous drive harms the environment to assess the sustainability of AV last-mile delivery. In the last-mile delivery scenarios, the first environmental issue that is easy to come into mind is the emission problems. Therefore, an emission analysis of AV in the process of last-mile delivery will be conducted in the following sections.

Greenblatt & Saxena (2015) 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, H., & Babiak, M. (2017) conclude that precise anticipation of the possibility of AV in the decrease of greenhouse gas emission 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 of emissions will only happen after AV becomes more prevalent, and this requires their creators to

20

reach the 5th level of autonomy, at which people will be freed from controlling cars.
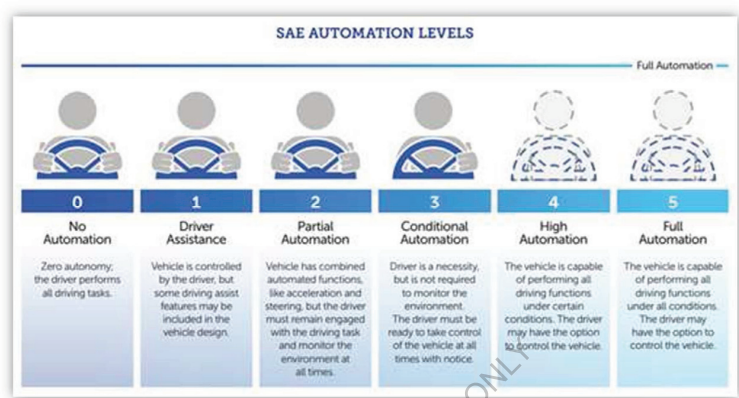


**Figure 4.** Automation levels (National Highway Traffic Safety Administration 2017)

A research (Pyper 2014) 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 expecting the emission impacts of AV, carried out by Liu et al. (2017) conclude that AV runs smoother than manned vehicle 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 conduct drastic and continual speed fluctuations (i.e. hard brakes and fast accelerations) and have a long reaction time (e.g. 1.5 seconds) 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 the emission advantages of AVs. Furthermore, Liu et al. (2017) found that the results from their modeling and calculation show that, normally, if human vehicles are substituted by AVs, greater emission benefits (up to 14% emission decrease) are estimated in driving conditions where there are much hard acceleration and braking events, and for drivers with bad driving styles. The outcomes of Austin cycle signify the average emission drops are 10.89% for volatile organic compounds (VOC), 19.09% for fine particulate matter (PM2.5), 13.23% for carbon monoxide (CO), 15.51% for nitrogen oxides (NOx), and 6.55% for sulfur dioxide (SO2) and carbon dioxide (CO2). They also found that the road links 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 emission will drop if the manned vehicle is replaced by AV. The reason is some researches show that the traveled vehicle miles will increase so that the total emission will rise (Alexander-Kearns, Peterson & Cassady 2016) - they believe the automation reduces the opportunity cost of driving. This probably encourages people to take more automobile journeys or accept longer commutes because people would be able

to multitask in cars rather than concentrating on the road. Besides, AV technology could permit groups of people who are currently unable to drive—such as the aged, young people, and disabled people—to travel alone in AVs, making more people on the road. Hence, the total emission will increase.

On the other hand, AVs may also contribute to solving the parking problems in the long run. In addition to the environmental issues of energy production and consumption, the existing cars impact much of the living environment. Traditional car occupies a considerable acre for parking even in the crowded city center. 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.

## 3.3 Economic Sustainability

Newman et al. (1998) 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, sole qualitative can not illustrate sustainability sufficiently and it is necessary to carry out a quantitative analysis. The following sections apply

several mathematic methods to supplement the qualitative analysis to demonstrate sustainability.

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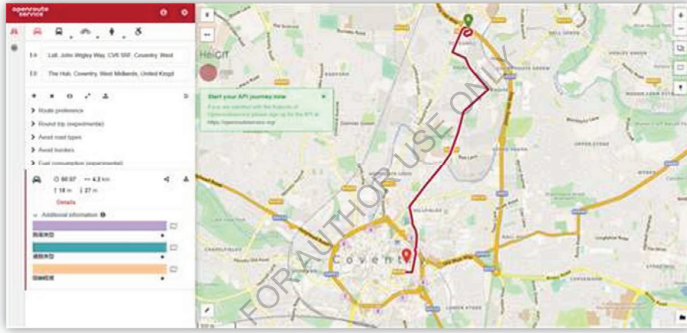


**Figure 5.** The route from Lidl supermarket to a target locker at Coventry center

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 4.2km and the delivery time of manual vehicles ($t_2$) is 22.5min.

### 3.3.1 Develop Assumptions

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

1. The daily operating cost of AVs mainly comprises electricity consumption.

2. Both autonomous and manual vehicles operated 250 working days per year. However, AVs operated 24 hours per day while manual vehicles operated 8 hours per day because of the legal limitation on 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 (Dell'Amico and Hadjidimitriou 2012).

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

7. The average running speed of one AV ($v_A$) is 6.4km/h (Lee et al. 2016).

8. The running cost of manual vehicles per kilometer is 1 pound (Dell'Amico and Hadjidimitriou 2012).

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

10. In the UK, the average electricity price for electromobile ($PoE$) is £0.25 per kWh (Power Compare 2020), and the electricity consumption per kilometer ($Epk$) is 0.19 kWh (Aqua-Calc 2020).

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

12. In one 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 (Bloomberg 2020).

14. During the service life of each AV, the sum of initial purchasing cost and accumulated operation cost should be lower than the accumulated operating cost of a manual vehicle, otherwise, there is no need to use AVs.

### 3.3.2 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 presented in assumption 10,

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

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 in assumption 8,

$$C_M = x_2 \times 4.2km \times £1/km = 4.2x_2$$

Define $\quad \Delta C = C_i + 250days \times C_A - 250days \times C_M = 24{,}000 + 50x_1 - 1050x_2$, and $\Delta C$ 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 $\Delta C$, 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 $\Delta C$ is subjected to the following model constrains:

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

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

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

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

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 hours a day.

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

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:

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

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, $\Delta C$ 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.

### 3.3.3 Simulation

To get the minimum value, let n represents $\frac{W_M}{W_A}$, which is the rate 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, its result cannot be calculated and analyzed manually. However, MATLAB can be used to solve this mathematical problem.
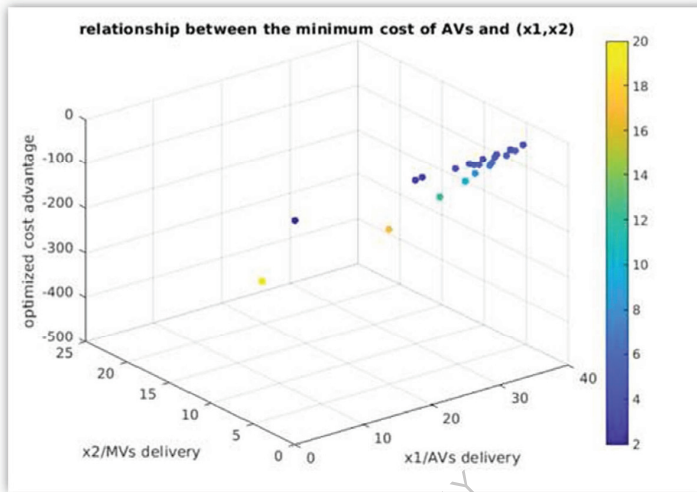
First, $\min(x_1 - 21x_2)$ subject to $\begin{cases} x_1, x_2 \text{ are integers} \\ 0 \leq x_1 \leq 36 \\ 0 \leq x_2 \leq 21 \\ x_1 - nx_2 = 0 \end{cases}$

Then, input the variables in MATLAB, and the outcomes will be carried out. The following figures show the outcomes of all processes of the MATLAB.
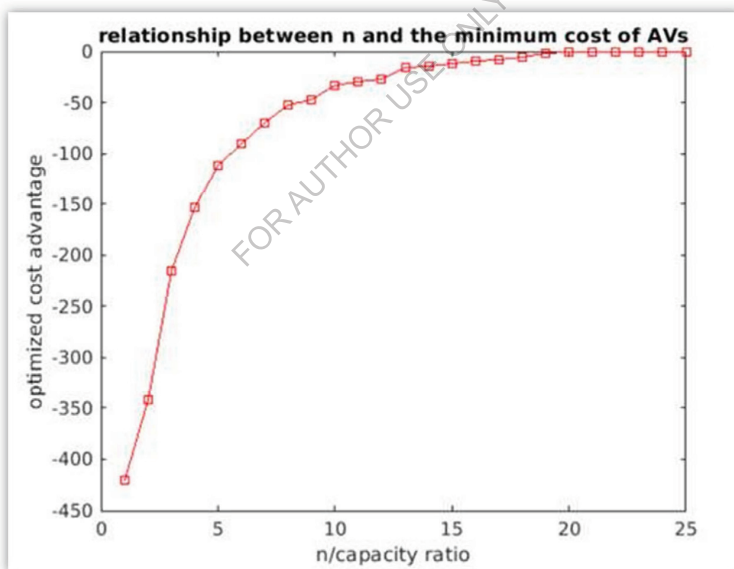


**Figure 6.** The relationship between cost and n of AV

**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 pound while n unit is 1. It can be seen that the relationship between cost and n is a linear relation.

```
T = 25x4 table

    n      x1/AVs delivery    x2/MVs delivery    optimized cost advantage
    _      _____    _____    _____

    1           21                 21                        -420
    2           36                 18                        -342
    3           36                 12                        -216
    4           36                  9                        -153
    5           35                  7                        -112
    6           36                  6                         -90
    7           35                  5                         -70
    8           32                  4                         -52
    9           36                  4                         -48
   10           30                  3                         -33
   11           33                  3                         -30
   12           36                  3                         -27
   13           26                  2                         -16
   14           28                  2                         -14
   15           30                  2                         -12
   16           32                  2                         -10
    :
    :

Good = 4x4 table

    n      x1/AVs delivery    x2/MVs delivery    optimized cost advantage
    _      _____    _____    _____

    1           21                 21                        -420
    2           36                 18                        -342
    3           36                 12                        -216
    4           36                  9                        -153
```

**Figure 8.** Statistic portfolio of solutions

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

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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.

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# Chapter 4

# Key Findings

## 4.1 Social Sustainability

For social sustainability – 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 AV running context, it is relatively safe because of the speed limit of actual society and the good road conditions provide the ground that AV runs safely for last-mile delivery in urban areas. Secondly, for driving behavior aspect, AV has a significant advantage than a manned vehicle. The main reason is that AV has no human behavior so that 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 that no vehicle can come into use without passing the strict test. Finally, AV has a special advantage when facing pandemic periods, a result that is in line with the research finding of Xuan Feng (2021).

## 4.2 Environmental Sustainability

Through the quantitative analysis for the emission generated by AV, the AVs has a significant advantage in emission reduction in terms of a series of emissions. This mainly results from the driving behaviors difference between

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AV and human vehicles. Some researches show that the total emission will rise because of the use of AV. The phenomenon generates by the side effect of AV's use rather than the vehicle itself. So this kind of side effect could 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 emission will be reduced or increased. Even though the emission reduction is clear, the amount of increase from the rising rate that people drive with AV cannot be confirmed. As a result, the total emission changing trend is uncertain based on the present analysis. Finally, I found that the AVs can to a large extent mitigate the pressure from the scarcity of parking places in urban areas.

## 4.3 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 and carry the dame 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 ratio of 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 as that of AV,

the weight impacts the cost advantage markedly. The more MV can transport than AV, the less AV can save in this range. From n=9 to n=19, the figure goes up gradually accompanied by the increase of n. This phenomenon proves that when the weight of MV is 9 to 19 times as that of AV, the weight impacts the cost advantage of AV slightly. From n= 20 to n=25, the figure keeps unchanged no matter how n changes. This means that when the weight of MV is 20 to 25 times as that of AV, MV has the same cost as that of 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. Consequently, autonomous drive cost in this route is no more than that of manual drive through the range of chosen weight rate.

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

## 4.4 Recommendation

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 many 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 the emission. Furthermore, when the manned vehicle capability is 1 to 25 times as AV's and the manned vehicle runs more than 8 times per day, using AVs to replace manned vehicles

can save cost. It is also possible to achieve more AVs by some financial methods. For example, gaining fund from Investment banks such as Goldman Sachs, an international leading investment bank despite various management issues (Xuan Feng 2020).

## Chapter 5

## Conclusion

This research is aimed at confirming whether the AVs for last-mile delivery is sustainable. Several objectives were set up to address the aim. This research introduced a classical framework, which is three pillars of sustainability. This theory was regarded as the ground of this research and the following structure following the framework. To analyze the 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, the safety was solely discussed because of its importance of AV application for last-mile delivery. The safety issue was divided into context 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 and research to show the emission status of AV. Noticeably, quantitative research of AV emission was cited to analyze. 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 way 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 statistic software to calculate, combining a set of assumptions, reality, and actual values of AV. Several portfolios were finally confirmed to compare with manned vehicle cost. The result shows that the AVs can save more cost.

In all, the result of this research shows that the AV's sustainability for last-mile delivery is high. In addition, three suggestions are conducted in terms of how to use AV. Overall, AV is encouraged to replace the manual vehicle for the 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 use.

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 do not mention 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 emission 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; thus, the result could not be precise. Before building the model, we can

interview the financial stuff of the delivery company to get all the cost variables.

Thus, a precise outcome could be expected.

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