Vehicle Miles Traveled and Environmental Impacts from On-Demand Delivery: A Literature Review

Haishan Liu[1]; Peng Hao, Ph.D.[2]; Shams Tanvir, Ph.D.[3]; Anurag Pande, Ph.D.[4]; and Matthew Barth, Ph.D.[5]

[1]Center for Environmental Research and Technology, Univ. of California, Riverside, Riverside, CA. Email: hliu240@ucr.edu
[2]Center for Environmental Research and Technology, Univ. of California, Riverside, Riverside, CA. Email: haop@cert.ucr.edu
[3]College of Engineering, California State Univ. Long Beach, Long Beach, CA. Email: shams.tanvir@csulb.edu
[4]Dept. of Civil and Environmental Engineering, California Polytechnic State Univ. San Luis Obispo, San Luis Obispo, CA. Email: apande@calpoly.edu
[5]Center for Environmental Research and Technology, Univ. of California, Riverside, Riverside, CA. Email: barth@ece.ucr.edu

ABSTRACT

The boom of e-commerce and the increasing demand for fast and reliable delivery services have led to the thriving of on-demand delivery (ODD), which provides delivery services to food takeout, grocery, pharmacy, and other light-weighted goods. The operational efficiency of ODD is subject to many factors—access to curbside, delays at the pick-up and drop-off locations, order dispatching mode, vehicle routing schedule, and vehicle refueling needs. The fast-growing delivery orders coupled with operational inefficiencies of ODD may lead to higher vehicle miles traveled (VMT) and pollutant emissions. Policymakers as well as practitioners need to evaluate the VMT and emissions impact of ODD, given the consumer behavior, operational paradigm, and business models. This paper conducted a systematic review of the existing literature to synthesize and summarize the impacts of ODD with a specific focus on VMT and emissions. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) guideline was employed to systematically search for related studies in multiple databases and to crystallize the review scope. The impact evaluation was delved into three aspects: customer shopping behavior (online shopping vs. in-store shopping), ODD operational strategy (truck/van vs. green vehicles, professional delivery vs. crowdsourcing), and business models (home delivery vs. depot/collection point). Overall, this study found that online shopping with coordinated ODD can achieve significant VMT and emissions reduction compared with in-store shopping. The reduction extent depends on the customer trip chaining, travel mode choice, residential area type, and the ratio of product return. The use of zero-emissions vehicles in ODD, such as electric van/truck/vehicle, cargo-bike, UAV, provides relatively higher emissions reductions, but also brings new issues such as charging needs or capacity limits. Collection points (e.g., parcel locker, retailer store, postal service point) can reduce the VMT and emissions if they are optimally distributed, and customers visit them in zero-emissions modes or through trip chaining.

Keywords: On-demand delivery, Vehicle-Miles-Traveled, Emissions, Systematic Review.

INTRODUCTION

Online shopping has been continuously reshaping customer shopping behavior. Nowadays, people could obtain almost everything needed (e.g., meal, grocery, clothing, electronics) via online shopping. In the U.S., the retail e-commerce sales were 958.7 billion in 2021 accounting for 14.6 % of total sales which represents a growth of 17.1% compared to 2020 (US Census Bureau 2023). During the pandemic, over 60% of Americans younger than 35 would shop online once a week or more, as reported in a study (Ecola et al. 2020).

Along with the increasing online shopping demand, customers have higher expectations to receive the purchased items with shorter delivery time and lower/no delivery cost (Qi et al. 2018), which boosts the proliferation of On-Demand Delivery (ODD) service within the realm of Urban Freight System; especially, during the COVID-19 pandemic (Bezirgani and Lachapelle 2021; Gao et al. 2020; Roggeveen and Sethuraman 2020). ODD service is designated to meet the increasing online shopping demand and the ever-growing customer expectations by providing timely, transparent, and convenient delivery services. Typically, a customer places an order via an online platform, i.e., a website or a smartphone application, and selects the delivery preferences (drop-off location, delivery time slot, etc.). The order is then picked up and delivered to the customer location by the delivery driver to complete the order. The customer can receive notifications about the order status in real-time (Pourrahmani and Jaller 2021).

In the last mile sector, ODD typically performs low-volume and high-frequency short trips to complete the orders within the required time window, thus representing more than 25% of the total logistical costs (Goodman 2005). Many factors could lead to inefficiencies – high volume of daily orders, inefficient order dispatching, lead time in preparation of the order at pick-up points, delays at the drop-off locations, diversity of items, driver overtime, vehicle recharge, and refueling needs, among others. Increased delivery orders coupled with operational inefficiencies of individual deliveries made by internal combustion engine vehicles may lead to higher VMT and emissions. On the other hand, new operation paradigms and new technologies such as vehicle electrification and robot/UAV delivery are unfolding great potential in lowering the VMT and emissions. Previous studies have shown a 20%-93% reduction potential on VMT and greenhouse gas emissions for grocery delivery (Durand and Gonzalez-Feliu 2012; Motte- Baumvol et al. 2022; Nock et al. 2022; Siikavirta et al. 2008). Given the evolving nature of ODD, it requires further studies to fully understand the potential impacts of ODD in the urban freight system under the modern operational era.

To fill the research gaps in understanding the negativities stemming from ODD services under the evolving service models, and to facilitate the efficient and sustainable development of ODD in the future, this paper provides a comprehensive literature review on the impacts of ODD in terms of Vehicle Miles Traveled (VMT) and Greenhouse Gas (GHG) emissions and aims to identify the operation strategies to support the operation of ODD. The main contributions of this paper include: 1) identifying the existing and upcoming operation paradigms and business models of ODD by providing a clear categorization considering the parcel size, time urgency, and service sector. 2) conducting a systematic literature review to synthesize the impacts of ODDS related to VMT and GHG. 3) highlighting existing issues and research gaps in ODD.

REVIEW SCOPE

This review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) guidelines to systematically search for related studies in multiple databases and to crystallize our review scope (Moher et al. 2015). PRISMA is an evidence-based minimum set of items for reporting in systematic review and meta-analysis, which has been widely used in systematic literature reviews.

We relied on the following databases: Web of Science (WOS), Scopus, and TRIS, to search for related research without any limitations publication time. The peer-reviewed journal papers, conference proceedings and other gray literature such as research reports and policy briefs were included in the review. The search string is the logical combination of the following terms: "On-demand delivery", "Online delivery", "Online-to-offline delivery", "Shared Delivery", "Crowdsourced delivery", "VMT", "travel distance", "emission", "GHG", "sustainability". The searching and screening process is shown in Figure 1.

After the fast screening via reading the titles and abstracts of 521 records, we reduced the potential inaccuracies stemming from keyword searches and formed an initial pool of 87 records. Then, we applied the exclusion criteria to exclude papers categorized as review papers, those that did not discuss the on-demand delivery in the last-mile setting and those lacking evaluation of VMT and emissions. Finally, we identified 31 papers for our systematic literature review.

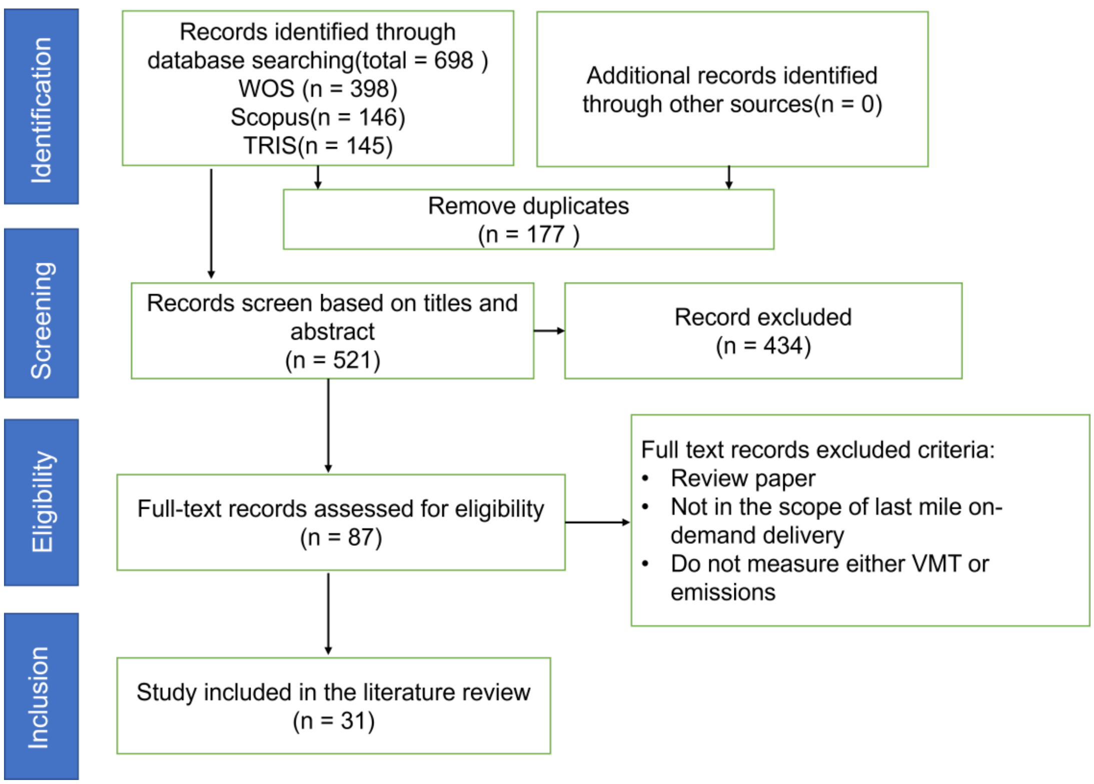

Figure 1. PRISMA flow diagram for literature review for on-demand delivery

SYSTEMATIC LITERATURE REVIEW

Overview of On-Demand Delivery

In the literature, On-Demand Delivery (ODD) is also termed as online delivery, online-to-offline delivery, shared delivery, or crowdsourcing delivery, etc. However, there exists a lack of a clear definition of ODD regarding the service scope. Thus, we proposed a categorization of on-demand delivery based on three primary dimensions (parcel size, industry, and time urgency), as shown in Figure 2. Meal delivery is an example of instant delivery, wherein cooked meals from restaurants are transported quickly, typically involving small-sized parcels and an urgency for instant delivery, often within an hour. Conversely, grocery delivery includes a spectrum of small to medium-sized parcels, usually aiming for same-day delivery. This service is extensively provided by numerous grocery stores and third-party platforms in the U.S., such as Walmart, Amazon Fresh and Instacart. Moreover, for the delivery of general retail items, the parcels vary in size from small to large, and the delivery date is predetermined at the time of customer order placement. This broader category extends beyond immediate perishable goods, catering to a range of consumer products with differing sizes and delivery timelines.

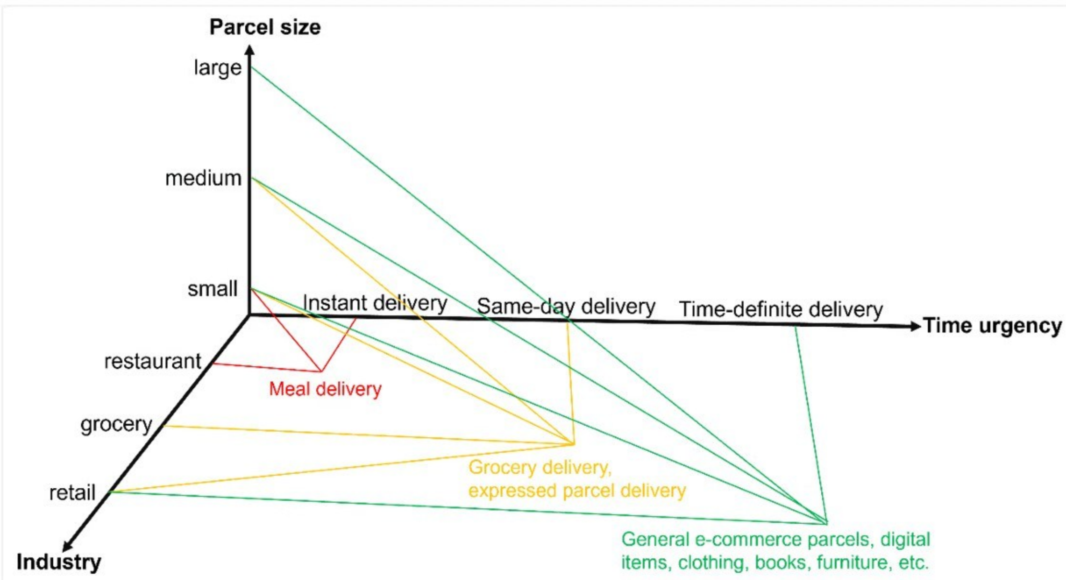

Figure 2. The scope and categorization of On-demand delivery

The collected studies on on-demand delivery and its effects on Vehicle Miles Traveled (VMT) and environmental impact can be categorized into two main streams. The first stream (48% of the collected papers) studied the potential negative or positive externalities of on- demand delivery to serve the boost of e-commerce compared to traditional in-store shopping. Regarding the in-store shopping behavior, researchers have considered the key factors that define the VMT and emission impact of in-store shopping trips. The factors are customer trip chaining, travel mode, and customer resident area type. The other stream (52% of the collected papers) has been focused on comparing different on-demand delivery business modes and operation strategies that are beneficial in saving VMT and emissions. Based on our collected papers, the research can be delved into two aspects 1) Business model comparison: home delivery versus collection point delivery and 2) ODD operation strategies: delivery vehicle comparison (truck/van versus electric van, UAV, unmanned robot), professional delivery versus crowdsourcing delivery in which local neighbors can participate in the delivery process. In the following sub-sections, we presented the key results and findings with the systematic literature review.

Online-shopping versus In-store Shopping

E-commerce has reshaped households' shopping behaviors with an online platform to provide diverse products, transparent prices, and convenient digital payment which allows customers to shop with only a click of mouse. Normally, the ordered goods will be delivered to the home location by delivery companies. Along with the rise of e-commerce, researchers have contributed to studying the potential impact of e-commerce home delivery compared with traditional in-store shopping. To identify which way of shopping is more beneficial at reducing VMT and emissions impact, most research adopted the substitution hypothesis, assuming that customers will substitute their shopping trips to visit the brick-and-mortar store with buying the same items online. The conceptual comparison of in-store shopping and on-demand delivery is shown in Figure 3, where multiple factors were discussed in the literature when comparing the environmental impacts and vehicle miles traveled between the two shopping choices.

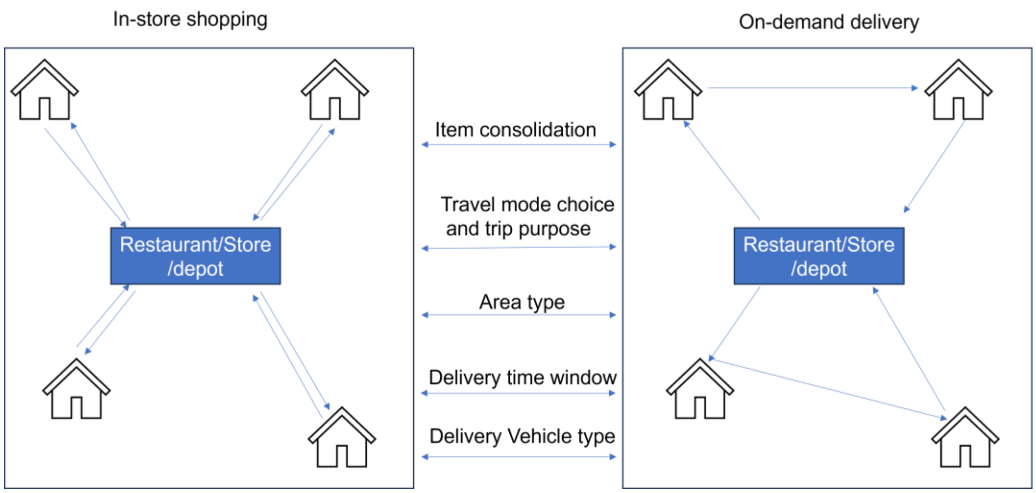

Figure 3. Illustration of in-store shopping and on-demand delivery

Many studies have been focusing on to what extent the substitution of in-store shopping trips could help to reduce the VMT and emissions. The advantage of ODD is to consolidate orders together and perform organized delivery to the customer location, instead of multiple individual trips. The consolidation level depends on the penetration level of on-demand delivery, spatial distribution of the orders, and the delivery time window requirements. As modeled by (Siikavirta et al. 2008), with 100% substitution, the GHG emissions in food and production system in Finland depend on the home delivery model used, order delivery time slot, and vehicle type, and it is possible to achieve 18%-87% of GHG reductions. With a shorter delivery time slot (within 1 hour), the delivery driver needs to make more trips in the delivery area to meet the promised delivery time, which only achieves the lower bound of GHG reduction (17%). The upper bound of GHG reduction (87%) is achieved by better consolidating orders in the same area and delivering orders to the unattended box. Meanwhile, the VMT is decreased by 53%-92% with delivery service compared to individual travel to the supermarket. (Carling et al. 2015) developed a method to measure the CO_2 footprint from the entry point to a region to the consumer's residence. Results demonstrated a substantial reduction (84% reduction) in CO_2 emissions by switching from in-store shopping for electronics products to buying the same product online. This is due to the fact that professional carriers are capable of transporting goods in bulk which is more efficient than individual shopping trips. (Stinson et al. 2019) found that the VMT reduction and emission benefits is sensitive to the e-commerce penetration level. With the household e-commerce rate of three orders per week, a 15% net VMT reduction occurs along with a 40%-50% energy consumption reduction depending on vehicle electrification technologies. An 80% VMT reduction was found when all customers choose to shop online, owing to the fact that adding a new stop to a delivery route only increases a small portion of Medium Duty Vehicle's VMT, but it can replace a much longer Light Duty Vehicle trip. (Motte- Baumvol et al. 2022) points out that for the United Kingdom, online grocery contributes to a 30% trip reduction along with an overall 37% household emissions, although the exact reduction extent depends on whether the household has a private car or not. (Nock et al. 2022) studied online grocery shopping in Seattle and showed that the start location of deliveries has a significant impact on congestion and emissions. If the grocery is not delivered from the closest store, then no beneficial impacts can be achieved. This is partly because only 36% of individual trips are two-way grocery trips and the other customers also tend to optimize the grocery trips themselves by adding a stop in their daily routine trip.

The performance of ODD also depends on other factors. One factor several researchers paid attention to is the delivery location, whether in the urban area or rural area. Customers in the rural area need to travel a longer distance compared to the residents in the urban area, which provides a high potential to reduce the delivery distance by replacing individual trips with coordinated on-demand delivery service. (Goodchild et al. 2014) found a dramatic difference in VMT and CO_2 emissions between Seattle and its rural area. In Seattle, the VMT reduction is 20% when in-store shopping was replaced by on-demand delivery services. In most rural areas, the VMT reduction reached up to 85%. (Mommens et al. 2021) further divided the service area into three types: urban, urbanized (with a population density falling between that of urban and rural areas), and rural and demonstrated the area type has an impact on the sustainability of home delivery. Based on the calculation of transport-related external costs, this research concludes that delivery to the home location via a well-established on-demand delivery service (from a warehouse) in urbanized and rural areas is more sustainable. While in the urban area, collection point delivery is more beneficial.

E-commerce also causes the issue of frequent product returns. Customers return items for different reasons, i.e., wrong product, product damaged during delivery, or unsatisfactory items. Product return will lead to extra travel trips and emissions. The impact of return depends on the way to return the products, either the unwanted item is collected on a subsequential delivery round or customers return to a high-street store. (Edwards et al. 2010a) found that the latter option is the worst case in terms of CO_2 emission. However, customers could reduce CO_2 emissions by trip chaining, e.g., returning items as part of a routine trip. (Wiese et al. 2012) studied the return effect in clothing e-retailing. CO_2 emission per transaction increases with higher return ratios. But online shopping has a lower increasement compared to in-store shopping and can cover a larger service area.

Home Delivery versus Collection Point Delivery

Conventional ODD service usually delivers the ordered goods to customers' home locations. This delivery type requires customers to receive the parcel right at the delivery time, which may cause failed delivery due to the customers not being present. The delivery companies need to perform extra delivery trials or drop the parcel at depots that allow customers to pick up later. Collection point delivery is proposed to avoid failed deliveries and reduce delivery VMT costs. Typical collection points can be divided into two types: unattended and attended. One commonly used unattended collection point is a parcel locker, which can be operated the entire day and provides high flexibility for customers to pick-up. Amazon, a large-scale retail provider in the US, also provides the self-service parcel delivery service where customers can retrieve the orders after receiving the delivery confirmation message (Amazon 2023). Attended collection points have several options: retailer store, postal service point, ‘neighborhood relay’, etc. The VMT and emission impacts of the collection point delivery are the sum of truck delivery to the collection points and from collection points to customer locations, which closely depend on the distribution of collection points, travel trip purposes, and travel modes to visit the collection point.

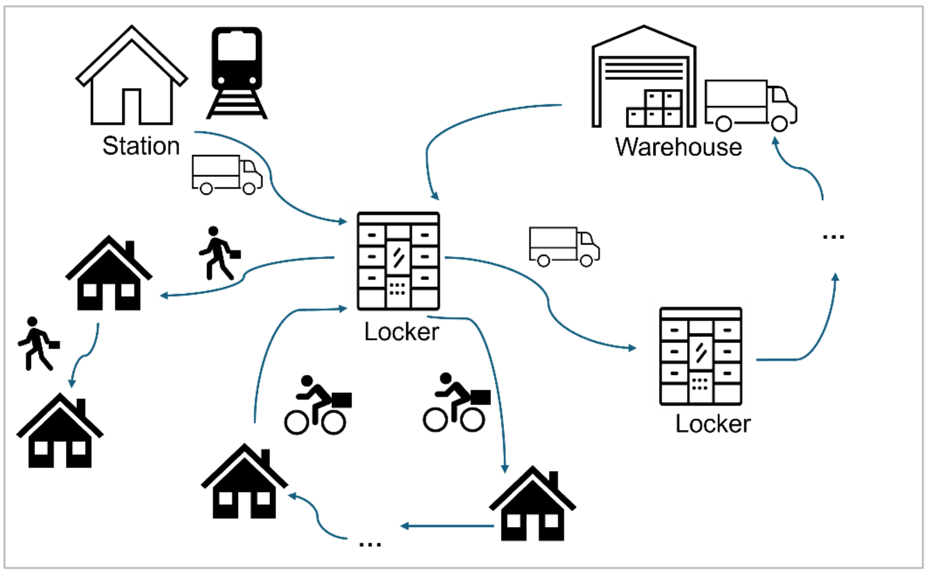

Figure 4. Illustration of on-demand delivery with parcel lockers combined with occasional couriers, referenced from (dos Santos et al. 2022).

In the collection point delivery paradigm, the sizing and sitting of collection points are crucial to support the order delivery. Some researchers studied the collection point optimal location problem with objectives to select collection points that are accessible for all customers with minimal total travel cost for customers’ pick-up trips, which is a classical vehicle routing problem (VRP). A two-phase algorithm with Ant Colony was proposed by (Hong et al. 2019) to solve the collection point selection problem. They conducted a sensitivity analysis regarding the influence of service radius of collection point and the capacity. Numerical experiments showed a negative relationship between the total cost and the service radius of each delivery point as well as its capacity. (dos Santos et al. 2022) further proposed a comprehensive last-mile delivery system in which collection points can be used as transshipment nodes in a 2-echelon delivery system and allows a customer who picks up orders individually to work as an occasional courier to make delivery to another customer along their pick-up trip to the collection point (shown in Figure 4). However, both Hong’s and Santos’ studies only evaluated the scenarios with the generated datasets without considering the real-world networks which fail to quantify the realistic VMT and emission impacts. (Carotenuto et al. 2022) developed a cluster-first-routesecond approach to compare the two delivery options, home delivery and locker delivery, incurred total travel distance and CO_2 emission. The authors also investigate the impact of dedicated trips for customers to visit the locker. An empirical study was conducted in the town of Dolo, Italy, consisting of 65 user zones, 2 depots and 19 lockers. The CO_2 emissions were reduced by 9%-32% depending on the delivery vehicle size, but the emissions benefit of locker delivery is offset if there are 20%-30% dedicated trips to the lockers.

There are several studies utilized agent-based simulation to model the real-world collection point delivery. (Calabrò et al. 2022) proposed an agent-based model to simulate both home delivery and collection point delivery including the possible matching customers and collection points with a minimum detour from the routine trip. The authors highlighted the importance of locker density and customers' willingness to make a detour to visit the collection point. The results illustrated that the percentage of customers choosing collection point delivery goes up from 26% to 58% with the increasing density of lockers. But the total travel distance did not show a clear decreasing trend. When the customer willingness to detour increases from 6 min to 10 min, the average transport intensity(km/parcel) reduces slightly. (Edwards et al. 2010b) studied the real-world scenario where failed delivered parcels will be dropped at alternative locations, such as supermarkets, post offices and railway stations. The results suggest that the alternative location has great capability to reduce CO_2 emissions of failed deliveries. In their case study, they found the post office was the most environmentally favorable choice since a package left there only accounts for 13% of CO_2 generated by a collection from local depot. (Mommens et al. 2021) utilized the agent-based freight transport model TRABAM to investigate the sustainability of collection point and home delivery in Belgium. They specifically studied the area type difference in terms of the two delivery options and found that collection point delivery is sustainable in the urban area. (Wygonik and Goodchild 2018) instead employed regression models to study the factors that influence the impact of last-mile good movements. The high road density can reduce the VMT and emission impacts.

Electric Vehicles, UAV/Robot and Crowdsourcing Delivery

With the development of new technologies, some researchers also focused on the transformation of delivery fleets to decrease the environmental impact of urban logistics. This transformation is mainly introducing green vehicles, such as electric van/truck, cargo-bike, UAV, to partially substitute the traditional truck/van. (Perboli et al. 2021) studied the economic and environmental benefits of introducing cargo bikes into the on-demand parcel delivery. A numerical study is conducted within the city of Turin (Italy). Compared to traditional van delivery, with cargo-bike, the VMT-related economic cost and CO_2 emissions are reduced by 20% and 17% respectively. (Llorca and Moeckel 2021) exclusively investigated the potential of cargo bikes for last-mile delivery through agent-based simulation. Their results showed that due to the speed and capacity limitations of cargo bikes, the total time required time for delivery increased by 6% and VMT doesn't reduce compared to van delivery. However, the use of cargo bike in all cases represents a reduction of CO_2 emissions, even considering the emissions related to electricity production. With 100% of cargo bikes delivering light-weighted goods, CO_2 emission can be reduced by around 23%. Besides, with van electrification, the total CO_2 emission of parcel delivery presents significant reductions. Considering the performance of electric vehicles (EVs) and internal combustion engine vehicles (ICEVs) in the urban last-mile scenario, (Siragusa et al. 2022) conducted a life cycle assessment of EV and ICEV to compare their emission and efficiency performance in last-mile delivery in B2C e-commerce. The assessment results showed that EV can save 17%-54% of GHG emissions compared to ICEV. The substitution of an ICEV with an EV allows a saving of 2700 tonnes of CO_2 emissions per year. Another factor discussed in this paper is the battery autonomy. It turns out that battery autotomy does not represent a barrier to EVs in last-mile delivery because most EVs' travel range can cover the delivery distance per day. (Goodchild and Toy 2018) evaluated the VMT and CO_2 impact of unmanned aerial vehicles (UAV) delivery compared to truck delivery. Experimental results illustrated that drones' CO_2 efficiency depends on the average energy required to charge a drone. If the energy cost of the drone is less than 20 Wh/mi, then drone delivery can reduce around 20% of CO_2 emissions. On the other hand, if the delivery address is far away from the depot, then truck is favorable. Drones only tend to have emissions advantages over trucks when the service zones are close to the depot, or the number of orders is small. This research concluded that a blended system would perform best, with drones serving nearby addresses and trucks serving far destinations.

The prevalence of information and communication technology has catalyzed many new shared mobility services. Crowdsourced delivery is one of the emergent services provided by online platforms, i.e., UberEATS, DoorDash. The online platforms outsource the delivery tasks to crowds of local non-professional agents to finish the delivery tasks and the agent will receive a delivery fee as compensation. Crowdsourced delivery has attracted much attention given its capability to provide fast and low-cost service. On the other hand, crowdsourced delivery could also contribute to sustainable efforts by using the excess capacity of vehicles and existing routing trips. The operational challenges and opportunities are well summarized in (Pourrahmani and Jaller 2021). In urban parcel delivery, (Perboli et al. 2021) evaluated a scenario with the crowdsourced driver. Compared to professional van delivery, crowdsourced delivery reduced the VMT-related economic cost by 21% and saved 16% CO_2 emissions. The identified most environmentally friendly strategy with high service quality is combined crowdsourced delivery with green vehicles (e.g. cargo bikes), which reduces the economic cost and CO_2 emission by 44% and 46% respectively. (Devari et al. 2017) modeled and evaluated the benefits of exploiting customer's social network for last-mile delivery with friendship modeling and agent-based transportation simulation. Crowdsourced drivers can reduce the truck delivery miles by 57% and bring substantial savings in NO_x, $PM_{2.5}$, PM_{10} by 55%. CO and THC emissions increase because gasoline cars emit more CO and THC compared to diesel engines powering trucks. (Liu et al. 2023) investigated the VMT and emissions impacts of food delivery with a comprehensive framework to quantify those impacts with the consideration of COVID-19 Pandemic. With the optimized delivery results, on-demand food delivery (ODFD) shows great potential to curb dinning-related VMT and emissions. The VMT was estimated to be reduced by 38% during the pandemic and 6% - 9% after the pandemic depending on the penetration level of ODFD in the future scenario. Besides, the author also conducted the emission sensitivity analysis with the delivery fleet electrification. With a fully electrified delivery fleet, the ODFD service can reduce 14% - 22% of emissions in the post-COVID period.

GAP ANALYSIS

On-demand delivery (ODD) has reshaped people's shopping behaviors by offering reliable, faster, and affordable delivery services. To form an efficient and sustainable urban freight system, it is necessary to understand the impact of ODD from the perspective of vehicle miles traveled and emissions. While there have been attempts to evaluate those impacts under multiple scenarios, several areas still need extensive research and standardization to enable fair comparison and a better understanding of ODD. Firstly, a clear and well-structured taxonomy for classifying the ODD services is yet established, resulting in multiple vague synonyms in the ODD system. Secondly, more innovative delivery modes need to be evaluated, such as combining delivery with human rides, truck and drone delivery, truck and robot coordination, etc. Thirdly, more realistic traffic network settings and emission models should be integrated into the evaluation process instead of simply assuming the static traffic speed, euclidian travel distance and simple emission rate. Fourthly, more research is needed to understand customer's behavior and preferences when choosing delivery options, which will be valuable in designing the ODD delivery strategies.

CONCLUSIONS

The paper conducted a systematic literature review to understand the VMT and emission impacts of on-demand delivery (ODD). We have delved into three perspectives: Online-shopping versus In-store Shopping, Home Delivery versus Collection Point Delivery, and emerging new technologies including Electric Vehicles, UAV/Robot and Crowdsourcing Delivery. Related studies were reviewed in each subsection. Finally, we identified the potential gaps and pointed out future research directions in ODD. The extensive literature review shows that online shopping with coordinated ODD can achieve significant VMT and emissions reduction compared with in-store shopping. The reduction extent is influenced by multiple factors: customer trip chaining, travel mode choice, residential area type, delivery time window, delivery vehicle type, etc. Collection points (e.g., parcel locker, retailer store, postal service point) can reduce the VMT and emissions if they are optimally distributed and customers visit them in zero- emission modes or through trip chaining. The use of zero-emission vehicles in ODD, such as electric van/truck/vehicle, cargo-bike, UAV, provides relatively higher emissions benefits, but also brings new issues such as charging needs or capacity limits.

ACKNOWLEDGEMENT

This study is funded by the California Air Resources Board. The contents of this paper reflect only the views of the authors, who are responsible for the facts and the accuracy of the data presented.

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