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Study of Sidewalk Autonomous Delivery Robots and Their Potential Impacts on Freight Efficiency and Travel

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Abstract

E-Commerce and package deliveries are growing at a fast pace and there is an increased demand for same-day deliveries. Established delivery companies and new startups are investing in technologies that reduce delivery times or increase delivery drivers' productivity. In this context, the adoption of sidewalk automated (or autonomous) delivery robots (SADRs) has a growing appeal. SADRs are pedestrian sized robots that deliver items to customers without the intervention of a delivery person. Because SADRs travel on sidewalks they have been the subject of increasing regulation by local agencies in the U.S. The three research questions that guide this research effort are: (*a*) What are the limitations imposed by existing regulations in the U.S.?, (*b*) What are the technical capabilities of existing SADRs?, and (*c*) Given the existing capabilities and regulations, what are the time/cost savings and efficiencies that SADRs can bring about? The first part of the research discusses current U.S. regulations on SADRs and reviews existing SADR devices and their capabilities. Building on this knowledge, the second half of the research presents a novel model to estimate delivery time and number of customers served utilizing a combination of SADRs and a special delivery van. These results are compared with a baseline (or prevailing) delivery system utilizing only a conventional delivery van and human driver. Results, insights, and potential implications are discussed. The results show that SADRs can provide substantial cost and time savings in some scenarios. Furthermore, the introduction of SADRs may significantly reduce on-road travel per package delivered.

According to the United States Census Bureau's *Quarterly E-Commerce Report* (*1*), e-commerce sales in the United States (U.S.) have increased at an average annual rate of 16% in the past two decades. Considering that the amount of time people deem acceptable for delivery times is shortening (*2*) and e-commerce sales are consistently increasing, delivery companies are likely to invest in technologies that increase delivery drivers' productivity. Sidewalk automated, or autonomous, delivery robots (SADRs) are one of these potential technologies and the focus of this research.

SADRs are pedestrian sized robots that deliver items to customers without the intervention of a delivery person. Because SADRs travel on sidewalks, they have been the subject of increasing regulation by local agencies. The three research questions that guide this research effort are: (*a*) What are the limitations imposed by existing regulations in the U.S.?, (*b*) What are the technical capabilities of existing SADRs?, and (*c*) Given the existing capabilities and regulations, what are the time/cost efficiencies and savings that SADRs can bring about? With respect to (*a*), the regulatory review is limited to the U.S. A global review, though important, is outside the scope of the paper and left as a research task for future research efforts that focus mainly on the regulatory aspects of this new technology.

In the first half of this paper current SADR regulations are discussed with a review of current SADR devices and their capabilities. In the second half of this paper a model to study the impact of SADRs in relation to time, cost, and distance traveled is proposed. The research ends with discussion of the results and conclusions. The next section presents the necessary (yet brief) historical background to SADRs and their applications.

Background

There are scant academic publications studying SADRs in a delivery context. For example, there is some research about SADRs' optimal wayfinding or optimizing the

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joint scheduling of both trucks and SADRs (*3*). There are numerous studies related to the mechanical, electrical, or computing design of robots in general. However, as of November 1, 2018, performing a Google Scholar search for the words "autonomous delivery robot characteristics,""autonomous delivery robot regulation,""sidewalk delivery robot," and "autonomous delivery robot efficiency," resulted in the finding of no published or unpublished research addressing SADRs characteristics, regulation, and relative efficiency.

The only publication that is directly related to the topic of this research was authored by Vleeshouwer, Duin, and Verbraeck (*4*). These authors utilize simulations to study a small bakery robot delivery service. Results show that costs can be reduced significantly but that the occupation of the robot capacity is low and that in the studied scenario robots are not economically feasible. The authors suggest that robots can be feasible if companies scale up or cooperate to increase robot utilization.

Currently, SADRs are mostly used for take-out food deliveries. In March of 2016, Domino's Pizza Inc., a pizza restaurant chain headquartered in the U.S., unveiled what it claimed to be the world's first autonomous pizza delivery vehicle. The vehicle was nicknamed "DRU" or Domino's Robotic Unit (*5*). This would be the first of several companies announcing a delivery robot to operate on sidewalks. Starship Technologies, founded in 2014, launched their 40-lb delivery robot in March of 2016 in London and has partnered with Domino's to deliver pizzas (*6*). At the end of April of 2018, Starship Technologies announced that it would be rolling out its delivery robot services to corporate and academic campuses in the U.S. and Europe. Starship Technologies has already implemented its delivery services at the Intuit campus in Mountain View, California, where average delivery times to customers are less than 15 min (*7*). Dispatch, a startup company based in San Francisco, announced in April 2016 that it had been working on automatic delivery robots since 2015 and had recently received a $2 million investment to continue to expand the company (*8*). In April of 2017, another San Francisco based company called Marble, partnering with Yelp and Eat24, announced that it would be testing its delivery robot (*9*). In September of 2017, Thyssenkrupp announced that it would partner with TeleRetail to research the use of delivery robots (*10*). There are several companies trying to use SADRs for delivering parcels to customers. Starship Technologies (*11*) and Dispatch (*12*) both have plans to enable the use of SADRs for parcel delivery in the future.

SADRs benefits could include cheaper costs of delivery and faster service. However, there are safety concerns. For example, Norman Yee, the San Francisco City Supervisor, says that SADRs pose a threat to "seniors, children, [and] people with disabilities [who] can't maneuver quickly" (*13*). Yee also states that he is "trying to prevent some of the things that we did not prevent with other innovations," referring to the abundance of Uber and Lyft drivers in San Francisco causing traffic jams (*14*). Robert O'Sullivan, the San Francisco police commander, also has concerns about the safety of SADRs, commenting that "if hit by a car, they also have the potential of becoming a deadly projectile" (*15*). Several community groups in San Francisco have also spoken against SADRs, including the Senior and Disability Action group and Walk SF. "The sidewalks are for walking. That's why they're called side *walks*," stated the interim executive director of Walk SF (*16*).

Although lawmakers like Norman Yee might dislike the idea of SADRs using sidewalks, Starship Technologies claims that most pedestrians do not mind the robots. In fact, Starship notes that 70% of pedestrians do not pay any attention to the robots, and most of the rest of the street-goers react positively to the robots (*17*). Additionally, Starship Technologies claims that over the tens of thousands of miles of sidewalks their SADRs have traveled, meeting millions of people, there have been zero accidents (*15*).

There are opposing views about SADR deployments and utilization in public spaces, so regulation is likely to be a key factor that hinders or promotes the utilization of SADRs. The next section discusses the current regulatory environment in the U.S.

Regulatory Environment and SADRs in the U.S

The regulatory review is limited to the U.S. A global review is outside the scope of the paper and left as a research task for future research efforts that focus just on the regulatory aspects of this new technology. SADRs are still a novel and not widely used technology; only a few states and cities have regulations in place. In alphabetical order, the states which have implemented regulations are Arizona, Florida, Idaho, Ohio, Utah, Virginia, and Wisconsin. Additionally, several cities have adopted regulations: Austin, Texas; San Francisco, California; and Washington, D.C.

San Francisco is one of the most restrictive places in its regulations on SADRs; it requires not only a speed and weight limit, but also a permit for each device, with a limit of nine autonomous delivery device permits for the city overall. These permits are valid for up to 180 days, and no more than one permit may be held by one permittee. San Francisco is currently the only place to require permits for SADRs. The device is also required to emit a warning noise to notify pedestrians and cyclists that it is nearby. Interestingly, despite all the other regulations San Francisco has on SADRs, there is no weight limit for SADRs in San Francisco.

Although San Francisco might be the most restrictive place for SADRs in the U.S., Arizona might be the least restrictive. Like San Francisco, Arizona does not have a defined weight limit for SADRs. Arizona requires only that the vehicle is electric, travels at less than 10 mph (16 km/h), is actively controlled or monitored, follows pedestrian laws, and yields to pedestrians. Arizona does not require insurance policies, braking systems, headlight systems, contact information, or a serial number plate, as many other places do. A summary of some key regulatory aspects is included in Table 1.

Table 1. Regulations on Sidewalk Autonomous Delivery Robots

State or city and date when code enacted		Required				Legislation
		Yield on sidewalk	Insurance policy	Braking system	Lights (at night)	
Arizona	3/28/2018	Yes, ped. only	No	No	No	Publication HB 2422. State of Arizona
Florida	7/1/2017	Yes	Yes	No	No	Publication SB 460. The Florida Senate
Idaho	7/1/2017	Not specified	No	No	No	Publication HB 204. Idaho State Affairs Committee
Ohio	9/29/2017	Yes, ped. only	Yes	Yes	Yes	Publication 4511.513. Ohio General Assembly
Utah	3/19/2018	Yes, ped. only	Yes	Yes	Yes	Publication HB 217. Utah General Session
Virginia	2/24/2017	Yes, ped. only	Yes	Yes	Yes	Publication 46.2-908.1. Virginia Code
Wisconsin	6/21/2017	Yes	No	Yes	Yes	Publication SB 148. Wisconsin Legislature
Austin, Texas	7/20/2017	Yes	Yes	No	No	City Council Resolution No. 20170810-012. Austin City Council
San Francisco	12/22/2017 revised 3/29/2018	Yes, ped. and cyclists	No, but must pay for damages caused by device	No	No	Publication 244-17. City and County of San Francisco, Board of Supervisors
Washington D.C.	9/15/2016	Yes	No	No	No	Publication Chapter 15C. § 50-1551 to 50-1555. Council of the District of Columbia

Note: ped. = pedestrian.

Size and Weight Limits

Washington, D.C. and Florida have unloaded weight limits of 50 lb. The 50-lb limit restricts SADR companies, as many SADRs weigh more than 50 lb. Starship Technologies' SADR weighs 40 lb unloaded, which provides a competitive advantage in locations with a low weight limit (*18*). Other places such as Wisconsin, Ohio, and Idaho have less strict regulations, with unloaded weight limits of 80 to 90 lb. Finally, there are other places where weight limitations allow essentially all SADRs currently on the market. These include Utah, with an unloaded 150-lb limit, Austin, Texas, with an unloaded 300-lb limit, and Arizona and San Francisco, California, with no weight limits.

Speed Limits

Almost all places have a speed limit for SADRs of 10 mph, the exception being San Francisco with a speed limit of 3 mph.

SADR Characteristics

An extensive initial internet search by the authors in March 2018 found five companies most prominently covered in the news as SADR makers. Among them Starship Technologies has received ample media coverage, as it is the most widespread SADR company as of November 1, 2018. Robby and KiwiBot are two additional SADR companies that have surfaced in the news since March 2018 (*19, 20*), however, there is not yet enough information about their specifications. Table 2 compares the five SADRs initially found, listing details found from various journal sources online about each SADR. Journalists interviewing the companies gathered most of the information contained in Table 2.

Table 2. Specifications for Studied SADRs

Company	Weight (lb)	Speed (mph)	Capacity (lb)	Capacity (chambers)	Range (mi)
Starship Technologies	40	4	40	1	4
Domino's DRU	Unknown	12	21 (approx.)	4[a]	12
Dispatch's Carry	Unknown, but it requires 2 people to lift the device	4	100	4	12-h battery, up to 48 mi
Thyssenkrupp's TeleRetail	60	35	77	1	10
Marble	80	4	Unknown	1	Unknown
Robby	60	Unknown	Unknown	1	20
KiwiBot	Unknown	Unknown	Unknown	1	Unknown

Note: SADR = sidewalk automated (or autonomous) delivery robots.
[a]Domino's Robotic Unit (DRU) has four compartments but they are all accessible at the same time.

Methodology

The efficiency of SADRs will be analyzed utilizing continuous approximations. The notation used is summarized below.

$n =$ number of customers served,
$l(n) =$ average distance a vehicle travels to serve n customers,
$k_l =$ routing parameter representing non-Euclidean travel on sidewalks and roads,
$\psi =$ overlapping factor among SADR service areas,
$a =$ area of service area where n customers reside,
$m =$ number of van tours necessary to serve n customers,
$d =$ distance between the depot and the geometric center of the service area,
$r =$ radius of the service area,
$\tau =$ total van time necessary to make n deliveries,
$s =$ average speed of the vehicle,
$t_0 =$ time it takes to wait for the customer to pick up their order from the vehicle, and
$t_u =$ time it takes the vehicle or driver to unload the delivery.

When considering how to quantify the efficiency of a SADR, or any transportation vehicle, one of the key numbers to consider is the total distance the vehicle has to travel to make a delivery, or multiple deliveries. The average distance $l(n)$ can be estimated as a function of customer density, number of vehicles, network characteristics and route constraint coefficients, and the distance between the depot and the delivery area (*21*). The equation used in this paper to calculate the distance traveled to visit n customers is

$$l(n) = 2md + k_l\sqrt{an} \tag{1}$$

where
$d =$ the average distance from the depot or distribution center (DC) to the customer(s) multiplied by two, the number of times the vehicle goes to and from the service or delivery area (SA);
$k_l =$ a constant value representing routing constraints in the SA,
$a =$ the service area where customers are located, and
$n =$ the number of customers or stops.

For ease of notation and calculations, a circular SADR service area is assumed but the method described here can be used with other SA shapes. As cities are generally rectangular rather than circular, the k_l routing constraint constant adjusts for this and a Manhattan or L2 norm is assumed (*21*).

Taking Equation 1 and solving for a results in a formula that can be used to determine the average area a SADR could cover given that the maximum $l(n)$ (vehicle range) is known. Assuming a circular service area, the radius r of the SA that a vehicle (or SADR) could serve from the center of the SA is found by

$$r = \sqrt{\frac{(l(n) - 2md)^2}{{k_l}^2 \pi n}} \tag{2}$$

When the DC is located in the center of the SA, and there is no long-haul distance ($d = 0$), the previous equations can be simplified.

Another important number to consider when dealing with last mile deliveries is the time it takes to make n deliveries. A formula to calculate the route duration time accounting not only for driving time but also waiting for the customer and unloading the packages is the following (*22*):

$$\tau = \frac{1}{s}(l(n)) + (t_0 + t_u)n \tag{3}$$

The first term of Equation 3 represents the driving time and the second term of the equation represents the time it takes to park, wait for the customer, and unload the packages.

Figure 1. A Mercedes-Benz van outfitted for use with Starship Technologies' SADRs (*11*).

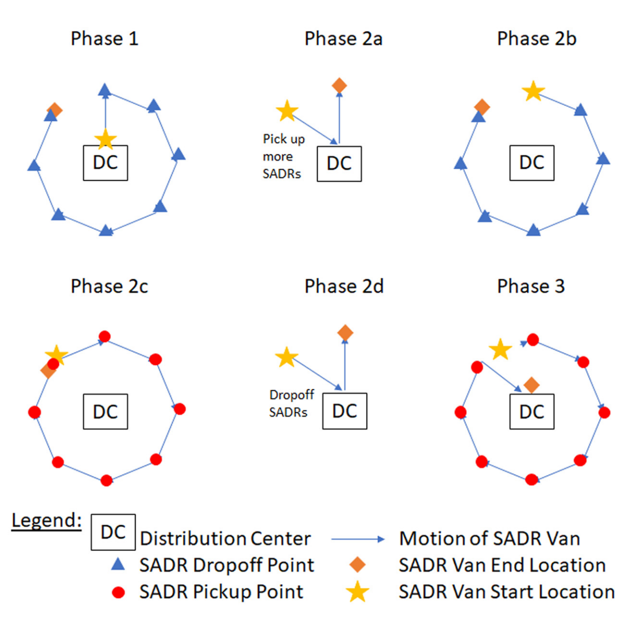

Figure 2. SADR van operation.

To estimate the number of SADRs that are necessary to cover an area the study utilizes the result proven by Kershner (*23*) that showed that the minimum number of circles to cover an area is approximated by

$$\frac{\psi a}{\pi (r)^2} \tag{4}$$

where r is the size of the circle that can be covered by a SADR and ψ is a factor that accounts for the overlap among circular SADR service areas. A low value of $\psi = 1.21$ is assumed. Finally, it is assumed in the case study (next section) that SADRs are used to complement mothership vans such as the one shown in Figure 1. Note that the terms "mothership van" and "SADR van" have the same meaning in this research.

The SADR van can maximize efficiency when d is small by making several tours during a driver's shift. This requires the SADR van (mothership) driver to return to the DC to get more SADRs before picking up the first tour's SADRs. The operation of the SADRs is illustrated in Figure 2. It is assumed that the SADR van drops off or picks up y SADRs per tour. For the sake of simplicity, it is assumed that eight SADRs ($y = 8$) will be dropped off or picked up. Three stages or phases are defined.

- Phase 1, initial delivery: The SADR van (mothership) travels from the DC to the SA and drops off the SADRs (numbered 1 to 8) at predetermined drop-off/pick-up points along a route.
- Phase 2, intermediate delivery and collection: This can be omitted or repeated x times, where x is an integer and $0 \leqslant x$. This phase has several subphases and to exemplify the operation it is assumed below (2*a* to 2*d*) that $x = 1$.
    - 2*a*: The SADR van returns to the DC to pick up eight additional SADRs (numbered 9 to 16).
    - 2*b* and 2*c*: The SADR van drops them (those numbered 9 to 16) off in the SA (2*b*) while simultaneously picking up (2*c*) the first batch of SADRs (numbered 1 to 8).
    - 2*d*: The SADR van drops off the first batch of SADRs (numbered 1 to 8) at the DC and returns.
- Phase 3: The mothership van picks up the final $y = 8$ SADRs (numbered $1 + xy,\ y + xy$) and ends at the DC.

Assuming current SADRs and realistic values (described in the next section) the following ranges seem feasible: $1 \leqslant y \leqslant 8$ and $0 \leqslant x \leqslant 2$ when $y = 8$, assuming 8-h driver shifts. The reader should note that there are other potential scenarios or ways in which SADRs and vans can be used together. This study focuses on the proposed scenario because it maximizes the number of deliveries when the SADRs' delivery time is longer than the van travel time between drop-off points. This is explained and estimated in the next section.

Case Study

In the following case study a Starship SADR is utilized because it meets the requirement of all U.S. jurisdictions. The SADR results are later compared with results obtained utilizing conventional delivery vans.

Table 3. SADR Service Area Radius and Tour Time ($t_0 + t_u = 10$)

Customers served (n)	Radius of the SA (mi) (r)	Time (h) (τ)	Customer density (customers per mi^2) (n/a)
2	1.92	1.70	0.17
3	1.86	1.83	0.28
4	1.61	1.96	0.49
5	1.44	2.10	0.77
6	1.32	2.23	1.10

Note: SADR = sidewalk automated (or autonomous) delivery robots.

SADR Van Results

It is assumed that the range of a Starship SADR is up to 4 mi (6.4 km). Starship's SADR is designed to carry up to three grocery bags of items. Considering most Amazon packages are less than 5 lb (2.3 kg) (*24*), it is assumed that one grocery bag is approximately equivalent in size and weight to two packages. Therefore, it is assumed that the Starship SADR can carry up to six packages and serve up to six customers. Note that the Starship SADR only has one locking chamber; it is assumed that theft is not an issue because SADRs are equipped with cameras, GPS trackers, and sensors to weigh the cargo. It is possible to record what cargo is being removed, when, and where. It is also assumed that $s = 2.8$ mph (4.5 km/h) because that is the speed of the SADR (4 mph or 6.4 km/h) multiplied by 0.7; the coefficient 0.7 indicates that the SADR is stopped for 30% of the time it is in transit because of waiting at crosswalks, or waiting for pedestrians. A value of 0.7 is assumed for k_l, as done in previous studies. With these assumptions it is possible to find r, τ, and density $\frac{n}{a}$ as detailed in Table 3.

In Table 3 it is assumed that the average distance that the SADR is traveling remains the same and equal to the SADR range, $l(n) = 4$ mi (6.44 km). It takes 1.56 to 2.23 h for a SADR to deliver to one to six customers, respectively. It is assumed for this calculation that $d = 0$ because this is the area around the SADR drop-off/pick-up point.

To estimate the time it takes a mothership van to drop off eight SADRs, its full capacity, and then pick them back up and return to the DC, it is necessary to estimate the number of SADRs that are needed to cover an area. Assuming eight SADRs and that each SADR delivers to six customers, the radius of the largest circular area that eight SADRs can cover is $r \cong 2.97$ mi (4.78 km). The value of $r = 2.97$ mi can be used to estimate the distance $l(n) \cong 10.42$ mi (16.77 km) that a van carrying $n = 8$ SADRs would have to travel to drop off all of the SADRs.

Assuming that vans travel at an average speed of 25 mph (40.2 km/h) in an urban area and are stopped at traffic signals or in congestion 30% of the time, the actual average speed is $s = 17.5$ mph (28.2 km/h). It is also assumed that at each stop it takes $t_u = 10$ min for the driver to park, load a SADR with its delivery items and send the SADR out of the van. Given these assumptions, the total amount of time it takes to drop off eight SADRs is 1.93 h. If it takes 1.93 h for the mothership driver to drop off all of the SADRs, but it takes each SADR 2.23 h as seen in (Table 3) to deliver to six customers, then the mothership driver would need to wait 0.30 h on average for the first SADR they dropped off to be ready to be picked up. Rather than waiting, the driver could (i) make some deliveries in person, that is, in the conventional way or (ii) go back to the DC to get a second round of SADRs to drop off. The second option (ii) is assumed in this research.

Different values of d from the DC to the SA are examined. It is assumed that in this segment of the network the van travels faster on freeways or major arterials. An average speed of 55 mph (88.5 km/h) is also assumed, but accounting for a 30% stop adjustment time. The average speed to travel between the DC and the SA is $s = 38.5$ mph (62.0 km/h).

It takes the SADR van driver 3.86 working hours to drop off and pick up the SADRs once in the SA. This time as a function of the distance d from the DC to the SA is shown in Table 4; this table assumes a half-hour lunch break in the middle of the shift, that eight SADRs are utilized, and that 48 customers are served.

Standard Van Results

The paper will now examine how many customers a standard van without SADRs can serve in an 8- or 10-h shift. It is assumed that the same SA radius of 2.97 mi (4.78 km) and same travel speeds $s = 17.5$ mph (28.2 km/h) apply. In addition, it is assumed that the driver has to wait an average of $t_0 + t_u = 10$ mins per customer. This results in the same amount of time $t_0 + t_u = 10$ used for the SADR van to park, load a SADR with its delivery items, and send the SADR out of the van (equal times allow an easier initial comparison).

The SADR van can serve 48 customers in less than half the time (see, for example, Table 4 and the row

Table 4. Shift Lengths Varying with d and $t_0 + t_u = 10$ (All Vehicles)

	SADR van	Conventional van			
		8-h Shift constraint		10-h Shift constraint	
d (mi)	Shift length (h) (τ) for n = 48	Customers served (n)	Shift length (h)	Customers served (n)	Shift length (h)
0	3.86	40	8.00	50	9.82
5	4.12	38	7.89	49	9.90
10	4.38	37	7.97	48	9.98
20	4.90	34	7.93	45	9.95
30	5.42	31	7.90	42	9.92
40	5.94	29	7.86	39	9.89
50	6.46	25	7.82	36	9.86
60	6.98	23	7.96	33	9.83

Note: SADR = sidewalk automated (or autonomous) delivery robots.

Table 5. Shift Lengths Varying with d and $t_0 + t_u$

	SADR van	Conventional van, 10-h shift constraint			
		$t_0 + t_u = 5$ min		$t_0 + t_u = 3$ min	
d (mi)	Shift length (h) (τ) for n = 48	Customers served (n)	Shift length (h)	Customers served (n)	Shift length (h)
0	3.86	95	9.97	149	9.96
5	4.12	92	9.95	144	9.99
10	4.38	89	9.92	139	9.95
20	4.90	84	9.97	131	10.00
30	5.42	78	9.92	122	9.98
40	5.94	73	9.96	113	9.97
50	6.46	67	9.90	104	9.94
60	6.98	62	9.94	96	9.98

Note: SADR = sidewalk automated (or autonomous) delivery robots.

where $d = 10$ mi). Table 4 indicates that there is clear increase in productivity when a van is complemented by SADRs. The faster delivery time is a bonus as companies are moving to shorter delivery periods. For example Amazon has recently expanded its 1-day and same-day (2-h) delivery services (*25*).

However, the time per delivery $t_0 + t_u$ can be substantially shorter than 10 min per customer. For example, a typical UPS delivery truck in a dense urban area can deliver 200 to 300 pieces and packages and serve on average $n =$ 120 customers (*26*). Decreasing $t_0 + t_u$ to 5 and 3 min produces the following results (see Table 5).

Comparisons

To quantify time savings by using a SADR van over standard vans, it is necessary to determine the number of tours, and in turn how many n deliveries, a SADR van could complete in up to a 10-h shift. Then, the method calculates how many conventional 10-h van shifts and how much time would be needed to deliver to the same number of customers. Finally, by comparing results, time savings for using a SADR van instead of standard vans are estimated (Table 6).

Time savings can also be translated into cost savings. Assuming a vehicle-driver cost for light trucks is $40 per hour (*27*), then if a SADR van is an hour more efficient than a standard van there is a cost saving of $40. However, the SADRs themselves have an operational cost well. Table 6 shows the cost savings for each d assuming that SADRs cost $1 and $2 per delivery—Starship Technologies has stated its devices will eventually cost $1 per delivery to operate (*28*). From Table 6 it can be estimated that each SADR delivery would have to cost around $3 to $5 per delivery, $t_0 + t_u = 10$, to cost more than a standard van. Based on the results presented in Table 4, it can be concluded that using a SADR van can be both more cost efficient and more time efficient in some scenarios.

However, the results are reversed when the delivery time per customer is $t_0 + t_u = 3$ min for both types of vans. Table 7 below shows no cost savings although SADR delivery vans are more competitive and can make more deliveries especially when d is small.

Table 6. Time and Cost Savings for SADR Van versus Standard Van, $t_0 + t_u = 10$ (All Vehicles)

d (mi)	SADRs used	Customers served (*n*)	Time savings using SADRs (h)	Daily cost savings SADRs with $1 cost per delivery	Savings per delivery with $1 cost	Cost savings SADRs with $2 cost per delivery	Savings per delivery with $2 cost
0	16[a]	96[a]	11.13	$349	$3.64	$253.38	$2.64
5	16[a]	96[a]	11.16	$350	$3.65	$254.24	$2.65
10	16[a]	96[a]	11.20	$352	$3.67	$256.00	$2.67
20	16[a]	96[a]	11.43	$361	$3.76	$265.07	$2.76
30	8	48	5.92	$189	$3.93	$140.69	$2.93
40	8	48	6.23	$201	$4.19	$153.29	$3.19
50	8	48	6.69	$219	$4.57	$171.47	$3.57
60	8	48	7.32	$245	$5.10	$196.73	$4.10

Note: SADR = sidewalk automated (or autonomous) delivery robots.
[a]The SADR van can maximize efficiency in areas with small *d* values by making two tours in a 10-h shift as described in Figure 2. Therefore, it can serve 96 customers utilizing 16 SADRs instead of eight.

Table 7. Time and Cost Savings SADR Van versus Standard Vans, $t_0 + t_u = 3$ (All Vehicles)

d (mi)	SADRs used	Customers served (*n*)	Time savings using SADRs (h)	Cost savings SADRs with $1 cost per delivery	Savings per delivery with $1 cost	Cost savings SADRs with $2 cost per delivery	Savings per delivery with $2 cost
0	32[a]	192[a]	4.65	($5.83)	($ 0.03)	($197.83)	($1.03)
5	24[a]	144[a]	2.23	($54.80)	($ 0.38)	($198.80)	($1.38)
10	24[a]	144[a]	0.99	($104.48)	($ 0.73)	($248.48)	($1.73)
20	16[a]	96[a]	–1.04	($137.67)	($1.43)	($233.67)	($2.43)
30	8	48	–1.41	($104.54)	($2.18)	($152.54)	($3.18)
40	8	48	–2.14	($133.80)	($2.79)	($181.80)	($3.79)
50	8	48	–2.83	($161.29)	($3.36)	($209.29)	($4.36)
60	8	48	–3.47	($186.80)	($3.89)	($234.80)	($4.89)

Note: SADR = sidewalk automated (or autonomous) delivery robots.
[a]The SADR van can maximize efficiency in areas with small *d* values by making multiple tours in a 10-h shift as described in Figure 2. Therefore, it can make many deliveries, using more than eight SADRs.

From Tables 6 and 7 several observations can be made. SADRs may be more efficient than standard vans when the average delivery time per customer is high. Moreover, SADRs can be faster and more cost efficient than standard delivery vans when customer density increases. This second finding seems to agree with Vleeshouwer et al.'s results (*4*). Finally, the additional cost of using SADRs is small when $d \leqslant 10$ mi and customers may prefer to pay a bit more for faster or time sensitive deliveries if the SADR van can deliver faster or more reliably.

It is also important to consider initial investment costs of the SADRs. The Starship SADR currently costs $5,500 (*29*) and there is also the additional cost of the specialized SADR vans. Therefore, there is a significant initial investment cost. A detailed study of investment flows and the financial feasibility of SADRs is left as a future research task.

Finally, from a freight planning and societal perspective, it is important to quantify changes in vehicle miles traveled. In Table 8, the final column reports the van travel distance reduction when moving from conventional deliveries to SADR van deliveries. The travel distance reductions are substantial. Therefore, SADRs have a great potential to reduce package-related freight travel and associated externalities. However, the reduction of on-road travel comes at the expense of new SADR travel on sidewalks and streets. This creates new externalities and potential safety issues as discussed earlier.

Conclusion

Sidewalk autonomous delivery robots (SADRs) used in conjunction with vans to transport them to service areas could be a viable alternative to standard delivery vehicles. As discussed in the first half of this paper, regulations are likely to play a large role in hindering or promoting SADR usage on a large scale by the parcel delivery industry. Speed, size, and weight limits may greatly decrease SADR effectiveness.

Table 8. Distance Traveled to Serve the Same Number of Customers and $t_0 + t_u = 10$ (All Vehicles)

d (mi)	On-road distance traveled by SADR van (mi)	On-sidewalk distance traveled by SADRs (mi)	On-road distance traveled by standard vans (mi)	% On-road van travel distance reduction
0[a]	41.5	64	50.1	17%
5[a]	61.5	64	70.1	12%
10[a]	81.5	64	91.0	10%
20[a]	121.5	64	138.0	12%
30	80.8	32	95.9	16%
40	100.8	32	126.8	21%
50	120.8	32	162.8	26%
60	140.8	32	205.4	31%

Note: SADR = sidewalk automated (or autonomous) delivery robots.
[a]The SADR van can maximize efficiency in areas with small d values by making two tours in a 10-h shift as described in Figure 2. Therefore, it can serve 96 customers utilizing 16 SADRs instead of eight.

Assuming current SADR characteristics and strict regulation, this research shows that vans complemented by SADRs can significantly reduce delivery times, on-road vehicle miles traveled, and costs when compared with conventional deliveries in some scenarios. The average time spent per customer or delivery may have a major impact on the feasibility and cost efficiency of this new technology.

SADRs can also indirectly reduce the number of on-road vehicle miles traveled by delivery vans. Therefore, SADRs have great potential to reduce package-related freight travel (per unit delivered) in urban areas with the associated benefits for congestion and externalities. However, the reduction of on-road travel comes at the expense of new SADR travel on sidewalks and streets. This creates new externalities and potential issues related to pedestrian safety and sidewalk congestion. Additionally, whereas delivery drivers utilize metered regular parking spots or loading zones in downtown areas, it likely that SADR vans would require more parking space and behave differently than standard delivery vans (e.g., longer parking). Would the cost structure of SADR deliveries incentivize double parking behavior sometimes found in express package delivery (*30*)?

Policy makers may need to consider regulations for SADR vans such as: How much parking space is required by SADR vans? How long can the SADR van stop to drop off or pick up a SADR? Can the SADR van stop in a metered zone without paying the meter? Where can the SADRs themselves wait; can they idle on the sidewalk or do they need to get out of the way of pedestrians by parking on the street? Is there a limit to how many SADRs are allowed on a sidewalk or block at any given time? Future research efforts should focus on the potentially many new regulatory challenges posed by SADRs.

This research presents novel results and insights about SADR van time, cost, and on-road travel efficiency. However, future research efforts should analyze alternative SADR deployments and scenarios as well as carrying out a deeper analysis of the tradeoffs and problems generated by shifting freight road traffic to sidewalks. Given the explosive growth of the package delivery industry and the shift towards 1-day and same-day (even 1-h) deliveries, these issues are likely to become even more relevant in the near future.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: MF; data collection: DJ, MF; analysis and interpretation of results: MF, DJ; draft manuscript preparation: DJ, MF. Both authors reviewed the results and approved the final version of the manuscript.

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