

2019

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

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### Citation Details

Jennings, D., and Figliozi, M. (2019). A Study of Sidewalk Autonomous Delivery Robots and Their Potential Impacts on Freight Efficiency and Travel, Forthcoming 2019 Transportation Research Record.

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1 **A STUDY OF SIDEWALK AUTONOMOUS DELIVERY ROBOTS AND THEIR**  
2 **POTENTIAL IMPACTS ON FREIGHT EFFICIENCY AND TRAVEL**

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29 **Please reference as:**

30  
31 Jennings, D., and Figliozi, M. (2019). A Study of Sidewalk Autonomous Delivery Robots and Their  
32 Potential Impacts on Freight Efficiency and Travel, Forthcoming 2019 Transportation Research  
33 Record.

**1 ABSTRACT**

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

20

21

22 *Keywords:* Last mile, delivery, robot, sidewalk, regulation, cost, time, travel, efficiency

23

24

## 1 INTRODUCTION

2 According to the United States Census Bureau's Quarterly E-Commerce Report (1), E-  
3 Commerce sales in the United States (US) have increased at an average annual rate of 16% in the  
4 past two decades. Considering that the amount of time people deem acceptable for delivery times  
5 is shortening (2) and E-Commerce sales are consistently increasing, delivery companies are  
6 likely to invest in technologies that increase delivery drivers' productivity. Sidewalk Automated,  
7 or Autonomous, Delivery Robots (SADR) are one of these potential technologies and the focus  
8 of this research.

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

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

## 23 BACKGROUND

24 There are scant academic publications studying SADR in a delivery context. For example, there  
25 is some research about SADR optimal wayfinding or optimizing the joint scheduling of both  
26 trucks and SADR (3). There are numerous studies related to the mechanical, electrical, or  
27 computing design of robots in general. However, as of November 1, 2018 performing a Google  
28 Scholar search for the words "Autonomous Delivery Robot characteristics", "Autonomous  
29 Delivery Robot regulation", "Sidewalk Delivery Robot", and "Autonomous Delivery Robot  
30 efficiency," no published or unpublished research addressing SADR characteristics, regulation,  
31 and relative efficiency was found.

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

38 Currently, SADR are mostly used for take-out food deliveries. In March of 2016,  
39 Domino's Pizza Inc., a pizza restaurant chain headquartered in the US, unveiled what it claimed  
40 to be the world's first autonomous pizza delivery vehicle. The vehicle was nicknamed "DRU" or  
41 Domino's Robotic Unit (5). This would be the first of several companies announcing a delivery  
42 robot to operate on sidewalks. Starship Technologies, founded in 2014, launched their 40-pound  
43 delivery robot in March of 2016 in London and has partnered with Domino's to deliver pizzas  
44 (6). At the end of April of 2018, Starship Technologies announced that it will be rolling out its  
45 delivery robot services to corporate and academic campuses in the US and Europe. Starship  
46

1 Technologies has already implemented their delivery services at the Intuit campus in Mountain  
2 View, California, where average delivery times to customers are less than 15 minutes (7).  
3 Dispatch, a startup company based in San Francisco, announced in April 2016 that it had been  
4 working on automatic delivery robots since 2015 and had recently received a \$2 million  
5 investment to continue to expand the company (8). In April of 2017, another San Francisco  
6 based company called Marble, partnering with Yelp and Eat24, announced that it would be  
7 testing its delivery robot (9). In September of 2017, Thyssenkrupp announced that it would  
8 partner with TeleRetail to research the use of delivery robots (10). There are several companies  
9 trying to use SADR for delivering parcels to customers. Starship Technologies (11) and  
10 Dispatch (12) both have plans to enable the use of SADR for parcel delivery in the future.

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

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

28 There are opposing views regarding SADR deployments and/or utilization on public  
29 spaces, hence, regulation is likely to be a key factor that hinders or promotes the utilization of  
30 SADR. Next section discusses the current regulatory environment in the US.

31

## 32 **REGULATORY ENVIRONMENT AND SADR IN THE US**

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

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

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

8  
 9 **[TABLE 1]**

10  
 11 **Size and Weight Limits**

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

20  
 21 **Speed Limits**

22 Almost all places have a speed limit for SADR of 10 miles per hour, the exception being San  
 23 Francisco with a speed limit of 3 miles per hour.

24  
 25 **SADR Characteristics**

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

34  
 35 **[TABLE 2]**

36  
 37  
 38 **METHODOLOGY**

39 The efficiency of SADR will be analyzed utilizing continuous approximations. The notation  
 40 used is summarized below.

41  $n$  = Number of customers served

42  $l(n)$  = Average distance a vehicle travels to serve  $n$  customers

43  $k_l$  = Routing parameter representing non-Euclidean travel on sidewalks and roads

44  $\psi$  = Overlapping factor among SADR service areas

45  $a$  = Area of service area where  $n$  customers reside

- 1  $m$  = Number of van tours necessary to serve  $n$  customers  
 2  $d$  = Distance between the depot and the geometric center of the service area  
 3  $r$  = Radius of the service area  
 4  $\tau$  = Total van time necessary to make  $n$  deliveries  
 5  $s$  = Average speed of the vehicle  
 6  $t_0$  = Time it takes to wait for the customer to pick up their order from the vehicle  
 7  $t_u$  = Time it takes the vehicle and/or driver to unload the delivery

8  
 9 When considering how to quantify the efficiency of a SADR, or any transportation vehicle, one  
 10 of the key numbers to consider is the total distance the vehicle has to travel to make a delivery,  
 11 or multiple deliveries. The average distance  $l(n)$  can be estimated as a function of customer  
 12 density, number of vehicles, network characteristics and route constraint coefficients, and the  
 13 distance between the depot and the delivery area (21). The equation used in this paper to  
 14 calculate the distance traveled to visit  $n$  customers is:

$$15 \quad l(n) = 2md + k_l \sqrt{an} \quad (1)$$

16  
 17 In equation (1),  $d$  represents the average distance from the depot or distribution center  
 18 (DC) to the customer(s) multiplied by two, the number of times the vehicle goes to and from the  
 19 service or delivery area (SA);  $k_l$  is a constant value representing routing constraints in the SA.  
 20 The service area where customers are located is represented by  $a$ . The number of customers or  
 21 stops is represented by  $n$ . For ease of notation and calculations, a circular SADR service area is  
 22 assumed but the method described herein can be used with other SA shapes. As cities are  
 23 generally rectangular rather than circular, the  $k_l$  routing constraint constant adjusts for this and it  
 24 is assumed a Manhattan or L2 norm (21).

25 Taking equation (1) and solving for  $a$  results in a formula that can be used to determine  
 26 the average area a SADR could cover given the maximum  $l(n)$  (vehicle range) is known.  
 27 Assuming a circular service area, the radius  $r$  of the SA that a vehicle (or SADR) could serve  
 28 from the center of the SA is found utilizing equation (2).

$$29 \quad r = \sqrt{\frac{(l(n)-2md)^2}{k_l^2 \pi n}} \quad (2)$$

30  
 31 When the DC is located in the center of the SA, and there is no long-haul distance ( $d=0$ ), the  
 32 previous equations can be simplified.

33 Another important number to consider when dealing with last mile deliveries is the time  
 34 it takes to make  $n$  deliveries. A formula to calculate the route duration time accounting not only  
 35 for driving time but also waiting for the customer and unloading the packages is the following  
 36 (22):

$$37 \quad \tau = \frac{1}{s}(l(n)) + (t_0 + t_u)n \quad (3)$$

38  
 39 The first term of equation (3) represents the driving time and the second term of the equation  
 40 represents the time it takes to park, wait for the customer, and unload the packages.

41 To estimate the number of SADRs that are necessary to cover an area we utilize the result  
 42 proven by Kershner (23) that showed that the minimum number of circles to cover an area is  
 43 approximated by:  
 44

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

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

### [FIGURE 1]

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. Let’s assume that the SADR van drop-offs or picks-up  $y$  SADRs per tour. For the sake of simplicity, let’s assume 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 1-8) at predetermined drop-off/pick-up points along a route.
- Phase 2, intermediate delivery and collection, can be omitted or repeated  $x$  times, where  $x$  is an integer and  $0 \leq x$ . This phase has several sub phases and to exemplify the operation it is assumed below (2a to 2d) that  $x = 1$ .
  - o 2a: the SADR van returns to the DC to pick up eight additional SADRs (numbered 9-16).
  - o 2b and 2c: the SADR van drops them (numbered 9-16) off in the SA (2b) while simultaneously picking up (2c) the first batch of SADRs (numbered 1-8).
  - o 2d: the SADR van drops off the first batch of SADRs at the DC (numbered 1-8) and returns.
- Phase 3, the mothership van picks up then 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:  $1 \leq y \leq 8$  and  $0 \leq x \leq 2$  when  $y = 8$  and assuming 8-hour driver’s shifts. The reader should note that there are other potential scenarios or ways where SADRs and vans can be used together. We focus 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.

### [FIGURE 2]



## 1 CASE STUDY

2 In the following case study a Starship SADR is utilized because it meets the requirement of all  
3 US jurisdictions. The SADR results are later compared to results obtained utilizing conventional  
4 delivery vans.

### 6 SADR Van Results

7 It is assumed that the range of a Starship SADR is up to 4 miles (6.4 km). Starship's SADR is  
8 designed to carry up to three grocery bags of items. Considering most Amazon packages parcels  
9 are less than five pounds (2.3 kg) (24), we assume that one grocery bag is approximately  
10 equivalent in size and weight to two packages. Therefore, we assume that the Starship SADR can  
11 carry up to six packages and serve up to six customers. Note that the Starship SADR only has  
12 one locking chamber; it is assumed that theft is not an issue because SADRs are equipped with  
13 cameras, GPS trackers, and sensors to weigh the cargo. It is possible to record what cargo is  
14 being removed, when, and where. It is also assumed that  $s = 2.8$  mph (4.5 kph) since it is the  
15 speed of the SADR 4 mph (6.4 kph) multiplied by 0.7; the coefficient 0.7 indicates that the  
16 SADR is stopped for 30% of the time it is in transit due to waiting at crosswalks, or waiting for  
17 pedestrians. We assume a value of 0.7 for  $k_l$  as done in previous studies. With these assumptions  
18 we find  $r$ ,  $\tau$ , and density  $\frac{n}{a}$  as detailed in Table 3.

19

### 20 [TABLE 3]

21

22 In Table 3 it is assumed that the average distance that the SADR is traveling remains the  
23 same and equal to the SADR range,  $l(n) = 4$  miles (6.44 km). It takes 1.56 to 2.23 hours for a  
24 SADR to deliver to 1 to 6 customers respectively. We assume for this calculation  $d = 0$  since  
25 this is the area around the SADR drop-off/pick-up point.

26 To estimate the time it takes a mothership van to drop off eight SADRs, its full capacity,  
27 and then pick them back up and return to the DC, it is necessary to estimate the number of  
28 SADRs that are necessary to cover an area. Assuming 8 SADRs and that each SADR delivers to  
29 6 customers, the radius of the largest circular area that 8 SADRs can cover is  $r \cong 2.97$  mi (4.78  
30 km). The value of  $r = 2.97$  mi can be used to estimate the distance  $l(n) \cong 10.42$ mi (16.77 km)  
31 that a van carrying  $n = 8$  SADRs would have to travel to drop off all of the SADRs.

32 Assuming that vans travel at an average speed of 25 mph (40.2 kph) in an urban area and  
33 are stopped due to traffic signals or congestion 30% of the time, the actual average speed is  $s =$   
34 17.5 mph (28.2 kph). We also assume that at each stop it takes  $t_u = 10$  minutes for the driver to  
35 park, load a SADR with its delivery items and send the SADR out of the van. Given these  
36 assumptions, the total amount of time it takes to drop off 8 SADRs is 1.93 hrs. If it takes 1.93  
37 hours for the mothership driver to drop off all of the SADRs, but it takes each SADR 2.23 hours  
38 as seen in (Table 3) to deliver to six customers, then the mothership driver would need to wait  
39 0.30 hours on average for the first SADR they dropped off to be ready to be picked up. Rather  
40 than waiting, the driver could (i) make some deliveries in person, i.e. in the conventional way or  
41 (ii) go back to the DC to get a second round of SADRs to drop off. The second option (ii) is  
42 assumed in this research.

43 We l examine different values of  $d$  from the DC to the SA. We assume that in this  
44 segment of the network the van travels faster on freeways or major arterials. We assume an  
45 average speed of 55 mph (88.5 kph) but accounting for a 30% stop adjustment time. The average  
46 speed to travel to/from DC to the SA is  $s = 38.5$  mph (62.0 kph).

1 It takes the SADR van driver 3.86 working hours to drop off and pick up the SADRs  
 2 once in the SA. This time as a function of the distance  $d$  from the DC to the SA is shown in  
 3 Table 4; this table assumes a half-hour lunch break in the middle of the shift that 8 SADRs are  
 4 utilized and that 48 customers are served.

5  
 6 **[TABLE 4]**

### 7 8 **Standard Van Results**

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

15 The SADR-van can serve 48 customers in less than half the time, see for example Table 4  
 16 and the row where  $d = 10$  miles. Table 4 indicates that there is clear increase in productivity  
 17 when a van is complemented by SADRs. The faster delivery time is a bonus as companies are  
 18 moving to shorter delivery periods, for example Amazon has recently expanded its one-day and  
 19 same day (two-hour) delivery services (25).

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

24  
 25 **[TABLE 5]**

### 26 27 **Comparisons**

28 To quantify time savings by using a SADR van over standard vans, we determine the amount of  
 29 tours, and in turn how many  $n$  deliveries, a SADR van could complete in up to a ten-hour shift.  
 30 Then, we calculate how many conventional ten-hour van shifts and time would be needed to  
 31 deliver to the same number of customers. Finally, by comparing results time savings for using a  
 32 SADR van instead of standard vans are estimated (Table 6).

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

42  
 43 **[TABLE 6]**

44

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

#### 4 5 **[TABLE 7]**

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

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

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

#### 24 25 **[TABLE 8]**

## 26 27 28 **CONCLUSIONS**

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

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

39           SADRs can also indirectly reduce the number of on road vehicle miles traveled by  
40 delivery vans. Hence, SADRs have great potential to reduce package related freight travel (per  
41 unit delivered) in urban areas with the associated benefits in terms of congestion and  
42 externalities. However, the reduction of on road travel comes at the expense of new SADR travel  
43 on sidewalks and streets. This creates new externalities and potential issues related to pedestrian  
44 safety and sidewalk congestion. Additionally, while delivery drivers utilize metered regular  
45 parking spots or loading zones in downtown areas, it likely that SADR vans would require more  
46 parking space and behave differently than standard delivery vans (e.g. longer parking). Would

1 the cost structure of SADR deliveries incentivize double parking behavior sometimes found in  
2 express package delivery (30)?

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

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

16

### 17 **ACKNOWLEDGEMENTS**

18 This research project was funded by the Freight Mobility Research Institute (FMRI), a U.S. DOT  
19 University Transportation Center.

20

21 **AUTHOR CONTRIBUTION STATEMENT:** The authors confirm contribution to the paper  
22 as follows: study conception and design: M. Figliozi; data collection: D. Jennings, M. Figliozi;  
23 analysis and interpretation of results: M. Figliozi, D. Jennings; draft manuscript preparation: D.  
24 Jennings, M. Figliozi. All authors reviewed the results and approved the final version of the  
25 manuscript.

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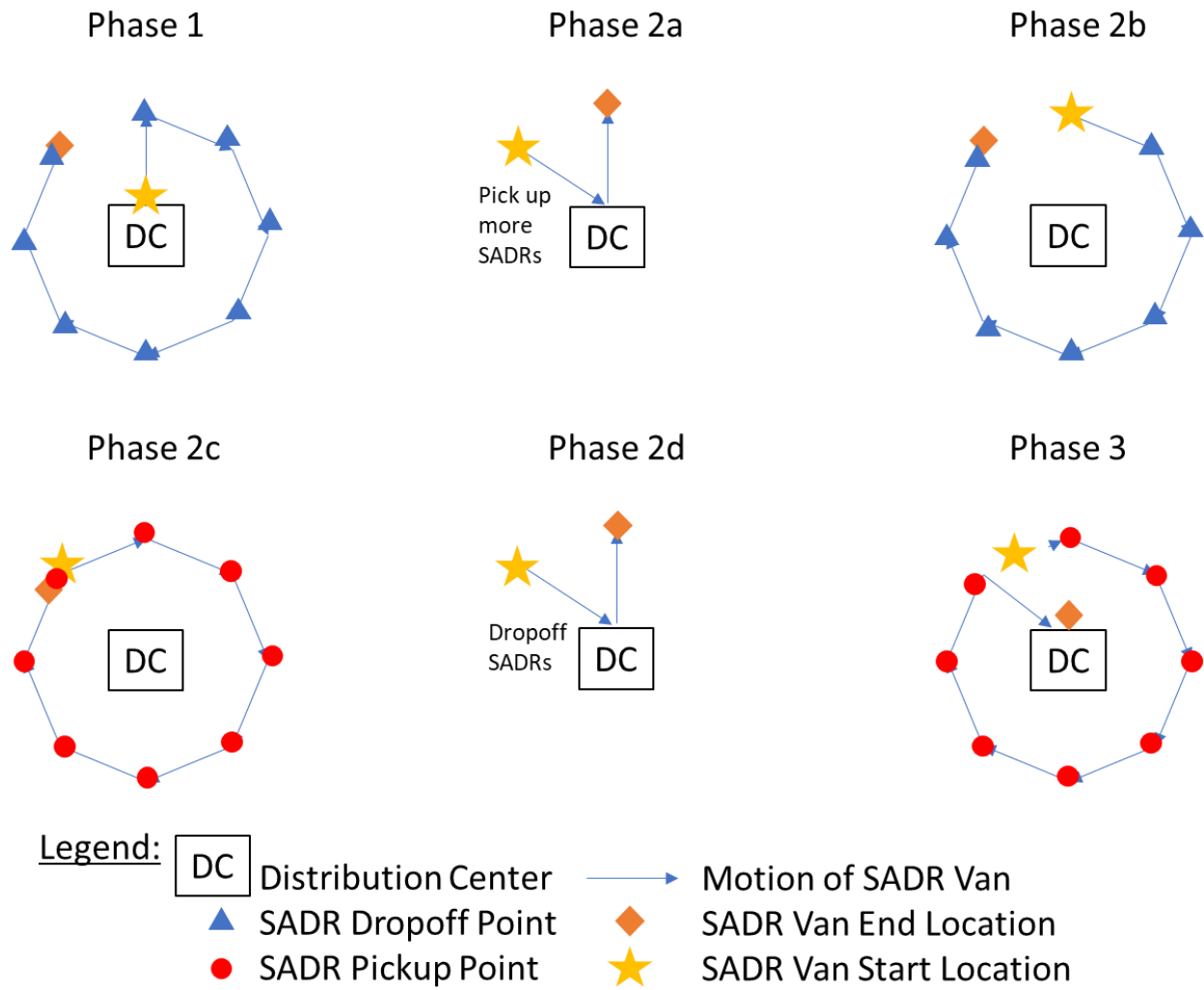
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1

1 **FIGURES**  
2



3 **FIGURE 1 A Mercedes Benz Van Outfitted for Use with Starship Technologies' SADR**  
4 **Source Daimler (11)**  
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**FIGURE 2 SADR Van Operation**



1 **TABLES**  
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**TABLE 1 Regulations on Sidewalk Autonomous Delivery Robots**

State or City and Date when code was 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	12/22/17 revised 3/29/18	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

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1 **TABLE 2 Specifications for Studied SADR**

	Weight (lbs)	Speed (mph)	Capacity (lbs)	Capacity (chambers)	Range (mi)
<b>Starship Technologies</b>	40	4	40	1	4
<b>Domino's DRU</b>	<b>Unknown</b>	12	21 (approx.)	4*	12
<b>Dispatch's Carry</b>	Unknown, but it requires two people to lift the device	4	100	4	12 hr battery, up to 48 miles
<b>Thyssenkrupp's TeleRetail</b>	60	35	77	1	10
<b>Marble</b>	80	4	<b>Unknown</b>	1	<b>Unknown</b>
<b>Robby</b>	60	<b>Unknown</b>	<b>Unknown</b>	1	20
<b>KiwiBot</b>	<b>Unknown</b>	<b>Unknown</b>	<b>Unknown</b>	1	<b>Unknown</b>

2 \*NOTE: Domino's Robotic Unit has 4 compartments but they are all accessible at the same time

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4  
5 **TABLE 3 SADR Service Area Radius and Tour Time -  $t_0 + t_u = 10$**

Customers served ( $n$ )	Radius of the SA (mi) $r$	Time (hours) ( $\tau$ )	Customer density (customers/mi <sup>2</sup> ) ( $n/a$ )
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

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8 **TABLE 4 Shift Lengths varying with  $d$  and  $t_0 + t_u = 10$  (all vehicles)**

$d$ (miles)	SADR-van Shift Length (hours) ( $\tau$ ) for $n = 48$	Conventional Van			
		8 Hour Shift Constraint		10 Hour Shift Constraint	
		Customers served ( $n$ )	Shift Length (hours)	Customers served ( $n$ )	Shift Length (hours)
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

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**TABLE 5 Shift Lengths varying with  $d$  and  $t_0 + t_u$**

$d$ (miles)	SADR-van Shift Length (hours) ( $\tau$ ) for $n = 48$	Conventional Van, 10 Hour Shift Constraint			
		$t_0 + t_u = 5$ minutes		$t_0 + t_u = 3$ minutes	
		Customers served ( $n$ )	Shift Length (hours)	Customers served ( $n$ )	Shift Length (hours)
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

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**TABLE 6 Time and Cost Savings SADR Van vs. Standard Vans,  $t_0 + t_u = 10$  (all vehicles)**

$d$ (mi)	SADRs used	Customers served ( $n$ )	Time Savings Using SADRs (hours)	Daily Cost Savings SADRs w/\$1 Cost per delivery	Savings per delivery w/\$1 Cost	Cost Savings SADRs w/\$2 Cost per delivery	Savings per delivery w/\$2 Cost
0	16*	96*	11.13	\$349	\$3.64	\$253.38	\$2.64
5	16*	96*	11.16	\$350	\$3.65	\$254.24	\$2.65
10	16*	96*	11.20	\$352	\$3.67	\$256.00	\$2.67
20	16*	96*	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

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\*NOTE: The SADR van can maximize efficiency in areas with small  $d$  values by making two tours in a ten-hour shift as described in (Figure 2). Therefore, it can serve 96 customers utilizing 16 SADRs instead of 8.

1  
2 **TABLE 7 Time and Cost Savings SADR Van vs. Standard Vans,  $t_0 + t_u = 3$**  (all vehicles)  
3

$d$ (mi)	SADRs used	Customer s served ( $n$ )	Time Savings Using SADRs (hours)	Cost Savings SADRs w/\$1 Cost per delivery	Savings per delivery w/\$1 Cost	Cost Savings SADRs w/\$2 Cost per delivery	Savings per delivery w/\$2 Cost
0	32*	192*	4.65	(\$5.83)	(\$0.03)	(\$197.83)	(\$1.03)
5	24*	144*	2.23	(\$54.80)	(\$0.38)	(\$198.80)	(\$1.38)
10	24*	144*	0.99	(\$104.48)	(\$0.73)	(\$248.48)	(\$1.73)
20	16*	96*	-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)

4  
5 \*NOTE: The SADR van can maximize efficiency in areas with small  $d$  values by making multiple tours in a ten-  
6 hour shift as described in (Figure 2). Therefore, it can deliver many deliveries, using more than 8 SADRs.  
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9 **TABLE 8 Distance traveled to serve the same number of customers and  $t_0 + t_u = 10$**  (all  
10 vehicles)  
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$d$ (miles)	On-road distance traveled by SADR van (miles)	On-sidewalk distance Traveled by SADRs (miles)	On-road distance traveled by Standard vans (miles)	% on-road van travel distance reduction
0*	41.5	64	50.1	17%
5*	61.5	64	70.1	12%
10*	81.5	64	91.0	10%
20*	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%

12  
13 \*NOTE: The SADR van can maximize efficiency in areas with small  $d$  values by making two tours in a ten-hour  
14 shift as described in (Figure 2). Therefore, it can serve 96 customers utilizing 16 SADRs instead of 8.