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

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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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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 ψ = 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 τ = 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 ψ 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 , τ , 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

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20

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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
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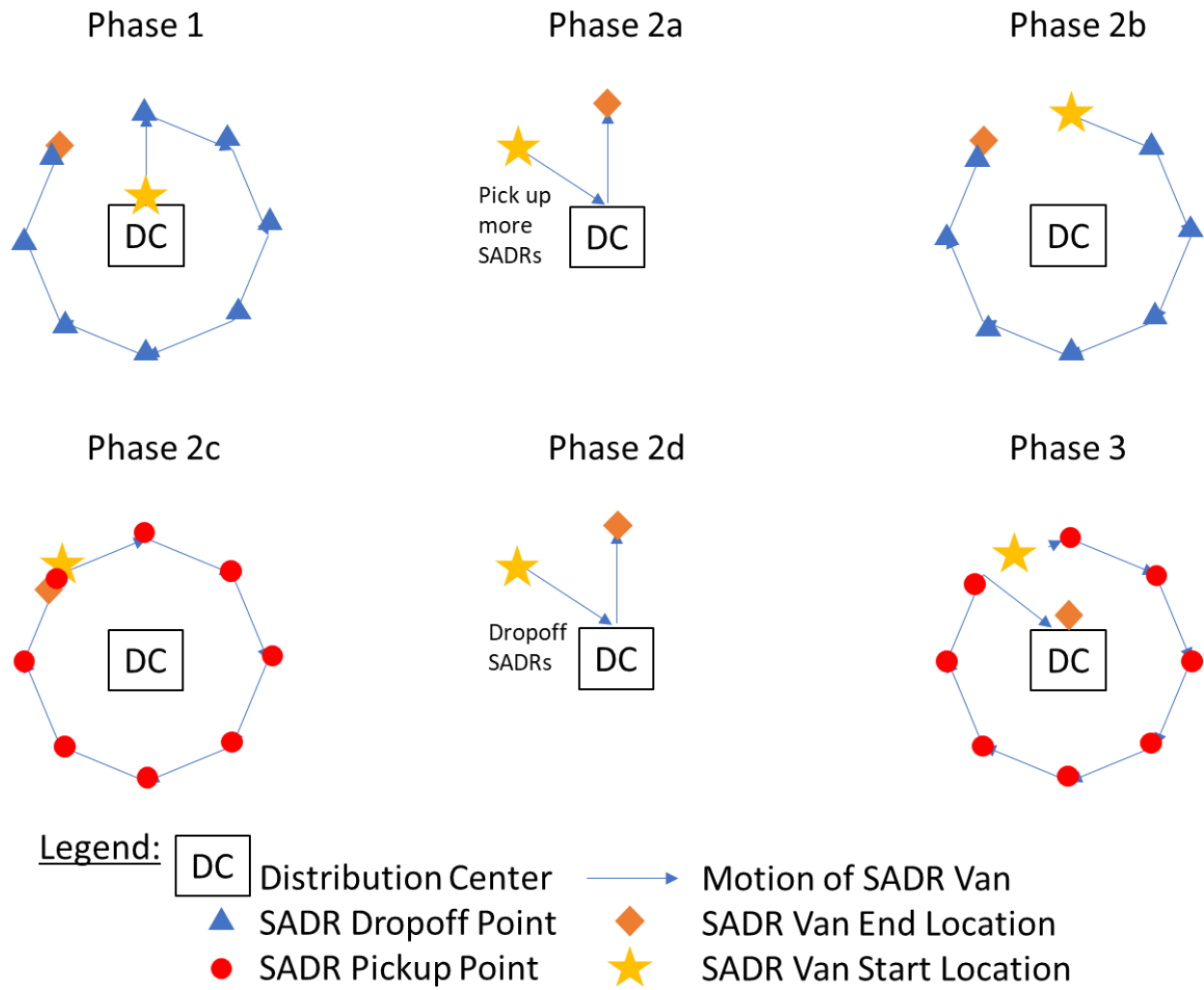
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1

1 **FIGURES**
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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)
Starship Technologies	40	4	40	1	4
Domino's DRU	Unknown	12	21 (approx.)	4*	12
Dispatch's Carry	Unknown, but it requires two people to lift the device	4	100	4	12 hr battery, up to 48 miles
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

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) (τ)	Customer density (customers/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

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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) (τ) 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) (τ) 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.