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Autonomous delivery robots and their potential impacts on urban freight energy consumption and emissions

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Abstract

E-Commerce and package deliveries are growing at a fast pace and several start-ups have already began pilot studies to deliver packages and groceries to consumers utilizing Autonomous Delivery Robots (ADRs). Two research questions guide this research effort: (a) What are the existing capabilities of ADRs? and (b) What are the energy and emissions reductions that ADRs can bring about? A model to understand potential ADR energy and emissions reductions is presented and several scenarios are analyzed. Results, insights, and potential implications are discussed. The results show that ADRs have the potential to significantly reduce energy consumption and CO_2 emissions in urban areas.

Keywords: Last mile; delivery; robot; travel; energy; emissions; parking

1. Introduction

The ADR landscape has been evolving rapidly. In March of 2016, Domino's unveiled what it claimed to be the world's first autonomous pizza delivery vehicle, nicknamed "DRU" or Domino's Robotic Unit. Starship Technologies, founded in 2014, launched their 40-pound delivery robot in March of 2016 in London and partnered with Domino's to deliver pizzas (Starship, 2017). At the end of April of 2018, Starship Technologies announced that it will be rolling out its delivery robot services to corporate and academic campuses in the US and Europe. Starship Technologies has already implemented their delivery services at the Intuit campus in Mountain View, California where average delivery times to customers are less than 15 minutes (Starship, 2018). In April of 2017, a startup company based in San

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Francisco called Marble, partnering with Yelp and Eat24, announced that it would be testing its delivery robot. Dispatch, another San Francisco based company, 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. There are other companies such as Nuro and Udelv that are trying to develop and deploy on-road ADRs for delivering parcels to customers. On-road ADRs are going to be tested in Oklahoma City for supermarket deliveries in early 2019 (Mogg, 2018).

ADRs benefits could include cheaper costs of delivery for businesses, faster service to customers, energy conservation and sustainability, safety for delivery personnel, and accuracy delivering the right package to the right customer. However, there are scant academic publications studying ADRs. Some studies have focused on ADRs optimal wayfinding or optimizing the joint scheduling of both trucks and ADRs, for example Boysen et al. (2018). There are numerous studies related to the mechanical, electrical, or computational design of robots but these studies are mostly irrelevant to study the implications of ADRs for last mile logistics.

To the best of the authors' knowledge there are only two publications that are directly related to the topic of this research. Vleeshouwer et al. (2017) utilized 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. These authors suggest that robots can be feasible if companies scale up or cooperate to increase robot utilization. The other studies (Jennings and Figliozzi, 2019a and 2019b) analyzed the regulation and characteristics of sidewalk and road ADRs (respectively) in the USA and studied potential time and cost savings. When compared with a baseline delivery system utilizing only a conventional delivery van-human driver, the results showed that sidewalk ADRs can provide substantial cost, time, and vehicle travel savings in some scenarios. Road delivery robots are also more economical when delivery routes are relatively short, however, due to their limited range vehicle miles tend to increase in most scenarios.

The contribution of this research is to evaluate sidewalk and on-road ADRs potential to reduce last mile travel, energy and CO_2 emissions. The next section describes current ADR characteristics. The methodology and a case study results are discussed afterwards. The final section summarizes conclusions and main insights. The notation used is summarized below.

Nomenclature

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
ψ	Overlapping factor among SADR service areas
a	Area of service where n customers reside
m	Number of tours necessary to serve n customers
d	Distance between the depot and the geometric centre of the service area

2. ADR characteristics

ADRs are electric powered motorized vehicles that can deliver items or packages to customers without the intervention of a delivery person. ADRs can be divided into two types. Sidewalk autonomous delivery robots (SADRs) are pedestrian sized robots that only utilize sidewalks or pedestrian paths. On-road or simply road autonomous delivery robots (RADRs) are vehicles that travel on roadways shared with conventional motorized vehicles.

An extensive initial internet search by the authors found five companies most prominently covered in the news as SADR makers. Among them Starship Technologies has received ample media coverage as of November 1, 2018. Robby and KiwiBot are two additional SADR companies that have surfaced the news since March 2018, however, there is not yet enough information about their specifications. Table 1 compares the five SADRs found. Table 1 shows that most of the vehicles are relatively slow and light (less than 100 pounds) as speed and gross weight are limited by regulations in many cities and states (Jennings and Figliozzi, 2019a).

The internet search by the authors found out that there are less companies prototyping RADRs. Table 2 compares the three RADRs found. Novel designs such as NURO are considerably smaller and lighter than conventional delivery vans. The other two vehicles (uDelv and AutoX) are based on existing conventional vehicles/chassis that have been automated or somewhat modified to fit autonomous deliveries. NURO is smaller and lighter than conventional vehicles but at the expense of a limited range and capacity (Jennings and Figliozzi, 2019b). .

RADRs can be complemented by specialized vans (see Figure 1, left), usually called "mothership" vans, that can be utilized to drop-off and pickup several RADRs. On the other hand, even the small RADRs are designed to operate autonomously and share roadways with conventional motorized vehicles.

Table 1. SADRs Specifications

SADR	Weight (lbs)	Speed (mph)	Capacity (lbs)	Capacity (chambers)	Range (miles)
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

Note: Domino's Robotic Unit has 4 compartments but they are all accessible at the same time

Table 2. RADRs Specifications

RADR	Capacity (parcels)	Capacity (lbs)	Max Speed (mph)	Approx. Size L x W x H in feet	Vehicle Weight (lbs)	Range (miles)
Nuro	40 parc. (*,**) or 12 large grocery bags	250	25	8'x.3,6' x 6'	1,500	10
uDelv	32 parc.	700	25	15'x 6'x 6'	4,167	60
AutoX	11.1 to 15.4 cuft	Unknown	80 (*)	16' x 6' x 5'	3,900	560

Notes: (*) Estimated, (**) Not in separate compartments

Fig. 1. (a) Mothership Van with Starship SADRs (Daimler, 2017) and (b) NURO (Nuro, 2018)

3. Methodology

The energy and emissions efficiency of ADRs is analyzed using derived formulas based on continuous approximations of distribution problems. This type of modeling approach has been successfully used by the authors in the past to model urban deliveries and key tradeoffs of new technologies such as electric vehicles, drones, or tricycles (Davis, 2013; Figliozzi, 2017; Tipagornwong, 2014).

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 (Figliozzi, 2008). The equation used in this paper to calculate the distance traveled to visit n customers is:

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

In equation (1), d represents the average distance from the depot or distribution centre (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 is a constant value representing routing constraints or network characteristics in the SA. The average area of the SA where customers are located is represented by a. The number of customers or stops is represented by n. In equation (1) the first part represents the distance associated to the long haul between depot and service area and the second part the distance travelled inside the service area.

A circular SADR service area is assumed but the method described herein can be used with other SA shapes. The k_l routing constraint constant adjusts for network characteristics and routing constraints. In this research, due to range limitations, more than one vehicle may be required, in this case, the formula to estimate distance travelled is the following:

$$l(n) = m\left[2d + k_l\sqrt{an/m}\right] \quad (2)$$

Equation (1) is a special case of equation (2) when $m = 1$. In this research only range constraints are considered, tour duration or time constraints are not included. Finally, to estimate the number of SADRs that are necessary to cover an area we utilize the result proven by Kershner (1939) that showed that the minimum number of circles to cover an area is approximated by:

$$\frac{\psi\, a}{\pi\, (r)^2} \quad (3)$$

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 that SADRs are used, complementing mothership vans such as the one shown in Figure 1 and that the SADR van drop-offs or picks-up 8 SADRs per tour. The SADR mother ship van shown in Figure 1 can carry up to eight Starships (Daimler, 2017).

4. Results

In the following case study a Starship SADR is utilized because it meets the US regulations and because it is the best known SADR at the time of writing this paper. It is assumed that the range of a Starship SADR is up to 4 miles (Nanalyze, 2016). Starship's SADR is designed to carry up to three grocery bags of items, so it is assumed that it can carry up to six small/medium packages – as a reference most Amazon packages parcels are less than five pounds or 2.3 kg (Pierce, 2013). There are large differences between SADRs, mothership vans, RADRs, and conventional vans in vehicle carrying capacity and efficiency. This section compares the efficiency of: (i) SADRs complemented by a mothership van, (ii) RADRs, and (iii) conventional and electric vans.

Four different scenarios regarding customer density are estimated: (a) 48 customers distributed in an area of 86.7 km^2, (b) 48 customers distributed in an area of 21.7 km^2, (c) 48 customers distributed in an area of 5.4 km^2, and (d) 48 customers distributed in an area of 1.35 km^2. These settings are based on Startship's range. Eight Starship SADRs can serve 48 customers in case (a) using up all the energy/range of a Starship whereas cases (b), (c) and (d) utilize ½, ¼ , and $1/8$ of the Starship's range respectively.

4.1. Distance traveled

For freight planning it is important to quantify changes in commercial vehicle distance traveled. Table 3 shows the percentage reduction of mothership vans on-road travel when SADRs are utilized. The highest reductions are obtained when customer density is low and the SADR depot is surrounded by the service area or $d = 0$. In Table 3 it is assumed the SADR mothership van still has to travel to unload and pickup the SADRs throughout the service region. If the motherships are not required then the travel reductions are 100% (i.e. no on-road travel).

The reduction of on-road travel comes at the expense of new SADR travel on sidewalks. SADR sidewalk travel increases by two, four and eight respectively as density increases. This creates new externalities and potential issues as discussed in the final section.

Table 3. Percentage reduction of on-road distance traveled

Long-haul travel d (kms)	Density			
	Low	Medium	High	Very high
0*	18.4%	18.4%	18.4%	18.4%
5	15.0%	12.7%	9.7%	6.6%
10	12.7%	9.7%	6.6%	4.0%
15	11.0%	7.9%	5.0%	2.9%
20	9.7%	6.6%	4.0%	2.3%
25	8.7%	5.7%	3.4%	1.9%
30	7.9%	5.0%	2.9%	1.6%
35	7.2%	4.5%	2.5%	1.4%
40	6.6%	4.0%	2.3%	1.2%

* Reduction may be 100% if a mothership is not utilized

4.2. Energy consumption

The quantification of the energy necessary to deliver to 48 customers was obtained by multiplying the distance traveled by the energy efficiency of each vehicle. In the case of SADRs it is necessary to estimate the contribution of the delivery robots and the mothership van. Table 4 reports the results for each vehicle type in two extreme scenarios (low density and very high density). Two observations can be made readily: (a) the energy consumption of the eight SADRs is a small fraction of the energy consumption of the mothership van, and (b) high density and short long-haul distance have a high impact on total energy consumption.

Table 5 reports the results for the RADRs, for each vehicle type in the same two extreme scenarios (low density and very high density). Three observations can be made: (a) the energy consumption of the NURO and UDelv is a small fraction of the energy consumption of the mothership van reported in Table 4, (b) the NURO is severely constrained by its limited range of 10 miles (16.09 kilometers) and can only deliver in scenarios with $d < 10$ kilometers, and (c) the NURO outcompetes UDelv in terms of energy efficiency only when the density is very high. These results indicate that the small NURO may be the most efficient vehicle only in high density urban areas with high traffic and limited parking. In all other instances the Udelv is more efficient.

Compared to other vehicle types, ADRs are several times more energy efficient than conventional diesel vans and drones or unmanned aerial vehicles, however ADRs are as energy efficient as electric vans such as the Renault Kangoo (Figliozzi, 2017).

4.3. Emissions, vehicle size, and safety

Emissions are not reported but can be discussed by taking into account that each Kwh generated from diesel fuel generates 22.5 more CO_2e emissions than the emissions generated to produce one Kwh from the electric grid (Figliozzi, 2017). Hence, the conventional SADR mothership van is hardly appealing in terms of CO_2e emissions.

Table 4. SADR Energy consumption in Kwh

Long-haul travel d (kms)	Low Density		Very High Density	
	SADR	Van (mothership	High	Very high
0	1.3	36.9*	0.2	4.6
5	1.3	46.9	0.2	14.6
10	1.3	56.9	0.2	24.6
15	1.3	66.9	0.2	34.6
20	1.3	76.9	0.2	44.6
25	1.3	86.9	0.2	54.6
30	1.3	96.9	0.2	64.6
35	1.3	106.9	0.2	74.6
40	1.3	116.9	0.2	84.6

* Value equal to zero if a mothership is not utilized

Table 5. Energy consumption in Kwh

Long-haul travel d (kms)	Low Density		Very High Density	
	NURO	UDelv	NURO	UDelv
0	10.9	8.8	0.8	1.1
5	29.0	10.7	2.2	3.0
10	NA	12.6	NA	5.0
15	NA	14.6	NA	6.9
20	NA	16.5	NA	8.9
25	NA	18.5	NA	10.8
30	NA	35.7	NA	12.7
35	NA	39.5	NA	14.7
40	NA	61.7	NA	16.6

NA: not available due to limited range

It was already shown in Table 3 that the SADR mothership van combination may reduce on-road distance traveled. However, it is important to highlight that the Mercedes Benz Sprinter van, which is used as a prototype to carry the eight SADRs, is 70% and 130% longer than the Udelv and NURO vehicles respectively. Regarding vehicle width, which is important for parking in congested areas, two and ½ NUROs can potentially occupy the same parking space utilized by one mothership van. Considering that the mothership van may require additional space to unload and load the SADRs, SADRs may not be efficient in terms of curb utilization.

Finally, the NURO is slow and smaller and lighter than conventional vans, hence the likelihood of a severe crash with a pedestrian or cyclist is reduced. The NURO is also designed to collapse and reduce damage in case of crashes (Verger, 2018). In the case of the SADR, the reduction of on-road travel decreases the likelihood of mothership van crashes but there may be more, perhaps less severe, crashes on the sidewalk. A driverless and smaller ADR is also more economical and this can lead to a higher utilization of electric commercial vehicles in urban areas; the high electric commercial vehicle purchase cost has been identified as one of the main barriers that precludes widespread adoption of this cleaner technology (Feng and Figliozzi, 2012).

5. Conclusions

Sidewalk autonomous Delivery Robots (SADRs) used in conjunction with a mothership van to transport them to/from service areas could be a viable alternative to standard delivery vehicles. Assuming current SADR characteristics this research shows that SADRs can significantly reduce on-road vehicle miles traveled. Previous research (Jennings and Figliozzi, 2019a, 2019b) have also shown their potential to reduce delivery times and costs when compared to conventional deliveries in some scenarios.

However, this research has shown that the adoption of SADRs may not be as effective as the adoption of RADRs when it comes to energy consumption, emissions, and parking utilization when service areas are located far from the depot. In addition, the reduction of on-road travel when deploying SADRs comes at the expense of SADR travel on sidewalks. This creates new externalities and potential issues related to pedestrian safety and sidewalk congestion. Additionally, while delivery drivers utilize metered regular parking spots or loading zones in downtown areas, it is likely that SADR vans would require more parking space and behave differently than standard delivery vans or RADR, i.e. potentially parking for longer periods and utilizing a larger parking area. In some cases, the cost structure of SADR deliveries may incentivize double parking behavior (Figliozzi and Tipagornwong, 2017).

Given the explosive growth of the package delivery industry and the shift towards one-day and same day (even 1-hour) deliveries, it is important to find efficient ways to deliver packages and online requests in urban areas. However, policy makers and freight planners should carefully evaluate the tradeoffs and potential unintended consequences of new technologies. Future researchers should study the evolution of these new technologies and how they can complement or replace conventional vehicles.

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References

Boysen, N., S. Schwerdfeger, and F. Weidinger (2018). Scheduling Last-Mile Deliveries with Truck-Based Autonomous Robots. *European Journal of Operational Research*.

Burgess, M (2018). Mercedes Vans Filled with Swarming Delivery Bots Could be Heading to Your Hometown. *Wired*. http://www.wired.co.uk/article/mercedes-starship-drones-delivery-van. Accessed July 1, 2018.

Daimler (2017). Mercedes-Benz Vans invests in Starship Technologies, the world's leading manufacturer of delivery robots, https://media.daimler.com/marsMediaSite/en/instance/ko/Mercedes-Benz-Vans-invests-in-Starship-Technologies-the-worlds-leading-manufacturer-of-delivery-robots.xhtml?oid=15274799, Accessed August 1, 2018.

Davis, B. A., & Figliozzi, M. A. (2013). A methodology to evaluate the competitiveness of electric delivery trucks. *Transportation Research Part E: Logistics and Transportation Review*, *49*(1), 8-23.

Feng, W. and Figliozzi, M., 2013. An economic and technological analysis of the key factors affecting the competitiveness of electric commercial vehicles: A case study from the USA market. *Transportation Research Part C: Emerging Technologies*, *26*, pp.135-145.

Figliozzi, M. (2008). Planning approximations to the average length of vehicle routing problems with varying customer demands and routing constraints. *Transportation Research Record* (2089), 1-8.

Figliozzi, M. (2017) Lifecycle modeling and assessment of unmanned aerial vehicles (Drones) CO_2e emissions, *Transportation Research Part D*: 2017, 57, 251-261.

Figliozzi, M. A. & Tipagornwong, C. (2017). Impact of Last Mile Parking Availability on Commercial Vehicle Costs and Operations. *Supply Chain Forum: an International Journal*, 18:2, 60-68

Jennings, D., and Figliozzi, M. (2019a). A Study of Sidewalk Autonomous Delivery Robots and Their Potential Impacts on Freight Efficiency and Travel, *Transportation Research Record 2673*(6), 317–326.

Jennings, D., and Figliozzi, M. (2019b). A Study of Road Autonomous Delivery Robots and Their Potential Impacts on Freight Efficiency and Travel, Submitted and presented at Transportation Research Board 99th Annual Meeting. January 2020, Washington DC.

Kershner, R. (1939). The number of circles covering a set. *American Journal of mathematics*, *61*(3), 665-671.

Mogg, T. (2018). Startup inks 'world's largest deal' for driverless grocery deliveries. *Digital Trends*. https://www.digitaltrends.com/cars/autonomous-grocery-delivery-on-its-way-to-oklahoma-city/ Accessed July 1, 2018.

Nanalize (2016). Starship Technologies and Ground Delivery Drones, https://www.nanalyze.com/2016/06/starship-ground-delivery-drones/, Accessed July 1, 2018.

NURO (2018). https://nuro.ai/, Accessed June 1, 2018.

Pierce, D. (2013). Delivery Drones are Coming. *The Verge*. https://www.theverge.com/2013/12/1/5164340/delivery-drones-are-coming-jeff-bezos-previews-half-hour-shipping. Accessed July 22, 2018.

Tipagornwong, C., & Figliozzi, M. (2014). Analysis of the Competitiveness of Freight Tricycle Delivery Services in Urban Areas, *Transportation Research Record* Vol. 2410, pp. 76-84.

Starship (2017). Starship Technologies launches pilot program with Domino's Pizza Enterprises, https://www.starship.xyz/press_releases/starship-technologies-launches-pilot-program-with-dominos-pizza-enterprises/, Accessed July 25, 2018.

Starship (2018). Starship Technologies Launches Commercial Rollout of Autonomous Delivery. https://www.starship.xyz/press_releases/2708/. Accessed July 1, 2018

Vleeshouwer, T., Duin, R. V., and Verbraeck, A (2017). Implementatie van autonome bezorgrobots voor een kleinschalige thuisbenzorgdienst. *ResearchGate*. https://www.researchgate.net/publication/320451527_Implementatie_van_autonome_bezorgrobots_voor_een_kleinschalige_thuisbezorgdienst. Accessed November 1, 2018.

Verger, R. (2018). This self-driving grocery delivery car will sacrifice itself to save pedestrians, https://www.popsci.com/self-driving-grocery-car-nuro, Accessed July 25, 2018.