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I EXECUTIVE SUMMARY

The motivation for this study was to quantify the environmental and social benefits of autonomous vehicle delivery which includes packages delivery such as aerial drones, ground delivery vehicles, and self-driving trucks and vans to an Arrive smart receptacle. The quantified benefits are then compared to the same parameters but for conventional package delivery. Keramida Inc. (KERAMIDA) evaluated the benefits of autonomous vehicle delivery to an Arrive receptacle, specifically the Greenhouse Gas (GHG) emissions, air pollution emissions and safety.

All calculations conducted for both autonomous vehicle delivery and conventional package delivery were based on the market projection conducted by Technical Consultants International, specifically, "the global autonomous last-mile delivery market is expected to be valued at $11.90 billion in 2021, and is projected to reach $84.72 billion by 2030, registering a CAGR of 24.4%."[1] This estimate of autonomous delivery market value was used in our simulation. Research-based assumptions, based on peer-reviewed literature and market research, were made with regards to autonomous vehicle delivery technology as well as conventional package delivery. For the purpose of this study, it is assumed that the impacts from all other autonomous delivery are similar to drone delivery. Package types considered in this study included ecommerce packages, food delivery, and medical prescription delivery. It is assumed 1% of the households worldwide in 2030 are equipped with Arrive smart receptacles. Emission calculations were conducted using widely accepted U.S. Environmental Protection Agency's (EPA) emission factors and the safety analysis relied on published safety and traffic data primarily from the U.S. Department of Transportation (DOT).

Key findings of our report indicate significant environmental and social benefits of autonomous vehicle delivery to an Arrive receptacle, including:

- The total annual GHG reduction in 2030 is approximately 1.7 billion kg, which is about the same amount of GHG that 841,717 acres of forest can absorb in a year. From another perspective, autonomous vehicle delivery will reduce 682.01 kg GHG emissions for each household that uses Arrive smart receptacle (89.12% reduction rate).
- Will reduce 0.46 kg volatile organic compounds (VOCs) emission for each household (99.70% reduction rate)
- Will reduce 1.00 kg nitrogen oxide (NOx) emission for each household (94.67% reduction rate)
- Will reduce 0.08 kg particulate matter (PM) emission for each household (87.68% reduction rate)
- 192,287,726,032 fewer miles driven due to the implementation of autonomous vehicle delivery
- 16,769,379 fewer vehicles driving due to the implementation of autonomous vehicle delivery • 454,915 fewer car crashes due to the implementation of autonomous vehicle delivery

[1] https://www.alliedmarketresearch.com/autonomous-last-mile-delivery-market

II INTRODUCTION

The global autonomous vehicle delivery service market is expected to experience significant growth in the forecast period 2023-2030 primarily due to the rising demand for fast package delivery in urban and remote areas, evolving legislation[2, 3, 4], and rapid technological advancements, especially in drone and unmanned aerial vehicles[4]. Online e-commerce retailers, and parcel delivery companies such as Amazon[5], UPS[6], Alibaba, DHL and Swiss Post "have been testing drone delivery service since 2005 and are expected to launch their services by 2023" [5]. Many of these companies have filed patents for the development of delivery drones and multi-level fulfillment centers that would allow the deployment of this technology within regulations[7, 8]. Likewise, "the introduction of drones in the delivery service market has rapidly transformed the delivery process, further leading to a change in consumer behavior" [5]. For example, delivery drones are primarily used for delivering small packages (less than 20 pounds) such as medical aids, food, mail, and other retail industry packages – especially in rural areas with less population density.

Considering the growth of autonomous vehicle delivery, a better understanding of the environmental and social issues involved with autonomous vehicle delivery will be important for stakeholders making energy and environmental choices. Numerous studies have looked at various impacts of autonomous vehicle delivery[5, 9, 10, 11, 12], highlighting the advantages of autonomous vehicle delivery in terms of GHG and other pollutant emissions for autonomous vehicles. Although numerous studies have indicated the advantages of autonomous delivery, research still indicates that studies are still needed[12] considering the full range of environmental and social impacts of autonomous vehicle delivery.

In this study, KERAMIDA included Arrive receptacles into the environmental and social evaluation. Arrive receptacles facilitate the secure and automated delivery and storage of autonomous vehicle packages to customers. This receptacle can receive or send food, medicine, groceries, or parcels. It is a secure porch, roof, window, house or building mounted box and may be secured to an existing edifice or mailbox post.

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[2] Levin, A. *More drones for hire coming to U.S. skies in landmark rules*, Bloomberg. https://www.bloomberg.com/news/articles/2016-0621/more-drones-for-hire-coming-to-u-s-skies-under-landmark-rules (2016).
[3] FAA. *Unmanned Aircraft Systems* (Federal Aviation Administration, U.S. Department of Transportation, Washington, DC, 2016). [4] EASA. *Civil Drones (Unmanned aircraft)*. https://www.easa.europa.eu/easa-and-you/civil-drones-rpas (European Aviation Safety Agency, Cologne, Germany, 2017).
[4] BIS Research, *Global Drone Delivery Service Market, Focus on Drone Type, Package Size, Range, Application, and Package Receptacle – Analysis & Forecast: 2023 to 2030* (2021).
[5] CBS News. *Amazon unveils futuristic plan: delivery by drone*. *60 Minutes Overtime.* https://www.cbsnews.com/news/amazon-unveils-futuristicplan-delivery-by-drone (2013).
[6] UPS. *UPS tests residential delivery via drone launched from atop package car*. United Parcel Service. https://www.globenewswire.com/newsrelease/2017/02/21/925955/0/en/UPS-Tests-Residential-DeliveryVia-Drone-Launched-From-Atop-Package-Car.html (2017).
[7] Murphy, M. *This is how Google wants its drones to deliver to stuff to you*. Quartz. https://qz.com/670670/this-ishow-google-wants-its-drone-todeliver-stuff-to-you (2016).
[8] Atherton, K.D. *Amazon patents warehouse blimps with packages delivered by drone*. Popular Science. https://www.popsci.com/amazon-patentsairship-warehouses-for-delivery-by-drone Accessed February 2017.
[9] Sarah Lyon-Hill, et al. *Measuring the Effects of Drone Delivery in the United States*. Virginia Tech. 2020.
[10] Stolaroff, J.K. et al. *Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery*. Nature Communications 9(409) (2018). https://www.nature.com/articles/s41467-017-02411-5
[11] Park. K/ et al. *A Comparative Analysis of the Environmental Benefits of Drone-Based Delivery Services in Urban Rural Areas*. Sustainability 10 (3): 888 https://doi.org/10.3390/su10030888 (2018).
[12] Goodchild, A.; Toy, J. *Delivery by drone: An evaluation of unmanned aerial vehicle technology in reducing CO2 emissions in the delivery service industry*. Transp. Res. Part D Transp. Environ. (2017). https://www.sciencedirect.com/science/article/abs/pii/S136192091630133X?via%3Dihub

The goals of this study are listed as follows:

- Evaluate the relative GHG emissions and air pollution impact of autonomous vehicle delivery to an Arrive receptacle as compared to conventional package delivery. KERAMIDA completed a GHG and air emissions (specifically VOCs, NOx, and PM) scenario using autonomous vehicle delivery to an Arrive receptacle compared to conventional package delivery to quantify the difference in GHG and air emissions. In the evaluation of autonomous vehicle delivery, data for drone delivery was used. It is assumed that the impacts from all other autonomous delivery are similar to that of drone delivery.

- Quantify the social impact of autonomous vehicle delivery as compared to conventional package delivery. The introduction of autonomous vehicle-based delivery systems generates a reduction in the number of cars on the road and miles driven, on the assumption that autonomous vehicle deliveries replace conventional deliveries. By reducing the number of miles driven by conventional delivery vehicles, the number of vehicles on the road is in turn reduced – as well as the number of reported vehicle crashes.

III METHODS

To assess the environmental and social benefits of autonomous vehicle delivery, KERAMIDA developed a scenario for an autonomous vehicle delivery from which all calculations were based. Of the plausible scenarios, KERAMIDA adopted a scenario that best captures future market projections and considers Arrive receptacles as the preferred delivery receiver. All calculations conducted for both autonomous vehicle delivery and conventional package delivery were based on the market projection conducted by Technical Consultants International – specifically, the global autonomous last-mile delivery market is projected to reach $84.72 billion by 2030. In this study, it is assumed 1% of the world households in 2030 are equipped with Arrive smart receptacles to receive packages including medical, e-commerce and food packages. In the evaluation of autonomous vehicle delivery, data for drone delivery was used. It is assumed that the impacts from all other autonomous delivery are similar to that of drone delivery.

GHG & Air Pollution Emissions

GHG and air pollution emissions were evaluated for both autonomous vehicle delivery and conventional delivery. GHG and air pollution emissions for this study include indirect emissions from energy consumption of the drone itself, and the Arrive receptacle. KERAMIDA considered the wide variety of energy consumption in published drone delivery research and reports and included the most current research[13] on consensus on standards for drone energy consumption as described below. For conventional ground vehicles such as delivery trucks and cars, we relied on typical fuel consumption rates. Emissions from the Arrive receptacle were calculated using the information provided by Arrive directly and from their website.

[13] Zhang, J. et al. Energy consumption models for delivery drones: A comparison and assessment. Transportation Research Part D (2021). http://doi.org/10.1016/j.trd.2020.102668

Number of Drone-Delivered Package

Weight of Drone-Delivered Package

Prior research[4] characterized drone-delivered packages into three categories in size: small size packages (less than 2 kg), medium packages (2 kg to 5 kg), and large packages (more than 5 kg). KERAMIDA used a weighted average to estimate the average package weight of drone-delivered package in 2030 using economic data for the three categories predicted by BIS Aerospace and Defense and Technical Consultants International, and assuming a constant unit rate of package delivery in dollar per distance per weight transported, and assuming the distribution of a package transport distance for each size category is similar.

GHG emissions for different types of packages using conventional package delivery method largely depend on transport distance and means of delivery. Based on transport distance and means of delivery, whether consolidated or not, packages that are assumed to be delivered by drone (replacing conventional delivery) in 2030 are characterized into: e-commerce packages, medical packages, and food packages.

Technical Consultants International's study shows the global autonomous last-mile delivery market is projected to reach $84.72 billion by 2030. The economic data was classified into e-commerce packages, medical packages, and food delivery packages using data from the BIS Research. The focus of autonomous vehicle delivery in the e-commerce market is last-mile delivery. It is therefore assumed the average distance of e-commerce packages to a recipient using autonomous vehicle delivery is one (1) mile. Based on a study conducted by the University of Toronto[14] and other statistical data from online resources, the unit cost of parcel delivery using the autonomous vehicle in 2030 was estimated. The numbers of packages for each category were therefore estimated using the economic data and estimated unit cost of parcel delivery using the autonomous vehicle in 2030.

Emissions from Conventional Delivery

It is assumed gasoline light trucks and vans (with consolidation) are used in e-commerce package lastmile delivery and gasoline passenger vehicles (without consolidation) are used in medical and food packages delivery. GHG and air pollution emissions are calculated using package weight, package number, transport distance and appropriate emission factors. The rate of packages per mile of a light truck/van is calculated using data from Highway Statistics. The rate of packages per mile and the total number of e-commerce packages in 2030 were used to estimate the total travel distance for e-commerce package delivery in 2030. Both direct and indirect emissions were included in this study. Direct emissions are emissions from on-road transport while indirect emissions are emissions from fuel production. Gasoline production emission factors of GHG and air pollutants were obtained from Argonne Greenhouse Gas, Regulated Emissions, and Energy Use in Technologies (GREET) model. GHG on-road direct emission factors were obtained from the U.S. EPA Emission Factors for Greenhouse Gas Inventories. Emission factors of air pollutants were obtained from U.S. EPA Emission Standards for Light-Duty Vehicles and Trucks and Motorcycles.

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[14] An Assessment of the Use of Autonomous Ground Vehicles for Last Mile Parcel Delivery, 2020. University of Toronto.

Emissions from Drone Delivery including the Arrive Receptacle

Using an estimated average drone-delivered package weight of 1.58 kg, KERAMIDA estimated the drone energy consumption rate to be 140 J/meter traveled [13]. Since electricity is the only energy source of drone delivery, no direct emission is emitted. All indirect emissions are from electricity generation.

Arrive receptacles have an internal heat source of 200 to 300 W. The higher value of that range was selected to produce a higher estimate of emissions resulting from their electricity consumption. The need for electricity consumption is driven through food deliveries and the need to provide temperature-controlled settings. It should be noted that a solar energy model is available but since it is uncertain to what degree these receptacles will be in circulation it was assumed that all Arrive receptacles require electricity. This study assumed that each food delivery requires two hours of electricity usage by the Arrive receptacle. The assumption was made that they would be operating at a 300W output for two hours each time a food package is delivered using energy supplied by the US grid[16] and appropriate emission factors were used to calculate the GHG emissions from this consumption total. Nationwide US grid average emission factors were utilized because it is assumed mailboxes will be distributed evenly throughout the country.

The first step in estimating PM, NOx, and VOC emissions from electricity consumption was to determine how much total electricity would be consumed by Arrive in 2030. The next step was to establish a breakdown of the energy sources contributing to electricity generation across the United States in 2030. We used the most recent data [17] that shows the energy distribution to be a mix of natural gas (40%), renewable energy (20%), nuclear (20%), coal (19%), and other (1%). This assumption that the current fuel mix applies to 2030 serves as a conservative estimate. It is assumed that the total electricity consumed by drones and the Arrive receptacle is in accordance with this breakdown. PM, NOx, and VOC emissions from these fuel sources (no emissions related to renewable sources) were estimated based on this distribution of energy source.

Safety Benefits

Using the Virginia Tech study [10], KERAMIDA estimated the number of miles saved and the number of reported vehicle crashes reduced through drone delivery. The annual delivery rate (number of packages delivered per mile driven by conventional vehicles) and the annual miles driven for the vehicle type are used to calculate the annual vehicle miles saved for the last-mile deliveries. KERAMIDA estimated the vehicle crash rate using the annual increase in car crashes and the annual increase in vehicle miles traveled over the ten years from 2009-2019 from the U.S. DOT NHTSA Traffic Safety Facts. The estimated number of car crashes avoided is based on the calculated motor vehicle crash (MVC) rate and the number of miles saved for drone-delivered ecommerce, medical and food packages as described below. Calculation details are shown in Appendix 7.

E-Commerce

We assume 52,765,668,270 e-commerce packages will be delivered in 2030 (Appendix 2). On average, 300 packages are loaded onto a light truck/van every day[18] and on average in 2018 a light truck/van traveled 11,453 miles in a year[19] – producing an annual delivery rate of 10 packages delivered via delivery-based light truck/van per mile.

Medical

We assume 23,375,799,798 medical packages will be delivered in 2030 (Appendix 2). We assume medical packages are delivered at a rate of one package per delivery with an average round trip shipping distance of 4.32 miles via passenger cars[20 21] – creating a delivery rate of 0.23 packages delivered per mile. We assume the average passenger car traveled 11,467 miles in 2018 to deliver medical packages[19].

Food

We assume 8,578,531,932 food packages will be delivered in 2030 (Appendix 2). We assume food packages are delivered at a rate of one package per delivery with an average round trip shipping distance of 10 miles via passenger cars[22] – creating a delivery rate of 0.1 packages delivered per mile. The average passenger car traveled 11,467 miles in 2018 [19].

Car Crashes Reduced

The annual number of car crashes reduced was calculated considering the annual motor vehicle crash rate (MVC) increase and the annual vehicle miles traveled increase from 2009-2019. From 2009 to 2019, crashes increased annually at a rate of 2.27%, and the annual vehicles miles traveled increased at a rate of 1.04%[23]. For the purpose of this study, it is assumed that this is a constant annual increase. Based on that assumption, the estimated MVC rate for 2030 is 2.37 crashes per million miles.

IV RESULTS

GHG & Air Pollution Emissions

The derived average drone-delivered package weight of 1.58 kg and the estimated drone-delivered package numbers are summarized in Appendix 1.

The annual emissions from both autonomous vehicle delivery and conventional delivery in 2030 are summarized in Tables 1 and 2. Detailed calculations, data sources, and assumptions are included in the Appendices. The emission reduction rates of GHG, VOCs, NOx, and PM from are 85.88%, 90.80%, 92.94% and 83.72% respectively (Table 1) when the global autonomous reaches $84.72 billion in 2030. The total annual GHG reduction in 2030 is approximately 1.7 billion kg, which is about the same amount of GHG that 841,717 acres of forest can absorb in a year, based on scientific data that the amount of carbon dioxide taken up by forests is around 0.5 kg per square meter per year [24]. From another perspective, autonomous vehicle delivery will reduce 682.01 kg GHG emissions for each household that uses Arrive smart receptacle (89.12% reduction rate) (Table 2).

[16] GHG Emission Factors Hub (April 2021) (epa.gov)
[17] Electricity in the U.S. - U.S. Energy Information Administration (EIA)
[18] https://www.businessinsider.com/amazon-delivery-drivers-reveal-claims-of-disturbing-work-conditions-20188#:~:text=Each%20route%2C%20which%20is%20assigned,400%20during%20peak%20holiday%20periods.
[19] https://afdc.energy.gov/data/10309
[20] http://www.nacds.org/pdfs/about/rximpact-leavebehind.pdf
[21] https://www.statista.com/statistics/985183/size-urban-rural-populationus/#:~:text=In%202020%2C%20there%20were%20approximately,people%20living%20in%20urban%20areas
[22] https://www.airbornedrones.co/food-delivery-drone/
[23a] https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/811402
[23b] https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/813141
[24] https://www.carbonindependent.org/76.html

Table 1. Annual Emissions Comparison of Conventional and Autonomous Delivery in 2030 Assuming Households Worldwide in 2030 Is 2 Trillion [15] and 1% of the Households Worldwide Use Arrive Receptacles.

Delivery Methods	Conventional Delivery					Autonomous Delivery				Reduction Rate
Emissions	Direct		Indirect		Total	Direct	Indirect		Total	
GHG (kg)	12,218,031,814	Details in Appendices 1-3	3,430,526,245	Details in Appendices 1-3	15,648,558,060	0	1,703,156,397	Details in Appendices 4-5	1,703,156,397	89.12%
VOCs (kg)	4,896,240	Details in Appendices 1-3	4,585,002	Details in Appendices 1-3	9,481,242	0	28,303	Details in Appendix 6	28,303	99.70%
NOx (kg)	16,806,970	Details in Appendices 1-3	4,890,669	Details in Appendices 1-3	21,697,639	0	1,157,304	Details in Appendix 6	1,157,304	94.67%
PM (kg)	1,344,558	Details in Appendices 1-3	472,394	Details in Appendices 1-3	1,816,952	0	223,796	Details in Appendix 6	223,796	87.68%

Table 2. Emissions Per Household Comparison of Conventional and Autonomous Delivery in 2030.

Delivery Methods	Conventional Delivery			Autonomous Delivery			Reduced	Reduction Rate
Emissions	Direct	Indirect	Total	Direct	Indirect	Total		
GHG (kg/household)	597.53	167.77	765.31	0	83.29	83.29	682.01	89.12%
VOC (kg/household)	0.24	0.22	0.46	0	1.38E-03	1.38E-03	0.46	99.70%
NOx (kg/household)	0.82	0.24	1.06	0	0.06	0.06	1.00	94.67%
PM (kg/household)	0.07	0.02	0.09	0	0.01	0.01	0.08	87.68%

[25] https://en.wikipedia.org/wiki/List_of_countries_by_number_of_households

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Miles Saved and Vehicles Reduced

The safety benefits for drivers and vehicles with autonomous vehicle deliveries replacing conventional deliveries totals to 192,287,726,032 miles saved, 16,769,379 vehicles removed from the road and 454,915 crashes avoided (Table 3).

Table 3. Miles saved, total number of vehicles reduced, and number of crashes reduced in 2030 because of autonomous vehicle delivery

Safety Changes by 2030		
Number of miles saved	**Total number of vehicles reduced**	**Number of crashes reduced**
192,287,726,032	16,769,379	454,915

Conclusions

This study demonstrates significant environmental and social benefits of autonomous vehicle delivery through reduced GHG and pollutant emissions, and reduced motor vehicle crashes. It supports previous work cited in this report, demonstrating reduced GHG and pollutant emissions with autonomous vehicle delivery and provides insight into the additional safety benefits of drone delivery. The future environmental and social benefit of drone delivery depends on the continued reduction in the carbon intensity of the electrical system, energy efficiency improvements in associated warehouses, and improvements in drone efficiency and capacity.

Appendix 1

Less than 2 kg			
Market Size at 2030 ($) [1]	Unit cost ($/kg) [2]	# of Package	Weight per Package (kg) [3]
44,342,444,579	a	n_1	1

$$a \times n_1 = 44{,}342{,}444{,}579$$

2 kg - 5 kg			
Market Size at 2030 ($) [1]	Unit cost ($/kg) [2]	# of Package	Weight per Package (kg) [4]
24,856,673,531	a	n_2	3.5

$$a \times n_2 \times 3.5 = 24{,}856{,}673{,}531$$

More than 5 kg			
Market Size at 2030 ($) [1]	Unit cost ($/kg) [2]	# of Package	Weight per Package (kg) [5]
15,520,881,890	a	n_3	7.0

$$a \times n_3 \times 7.0 = 15{,}520{,}881{,}890$$

So $n_1 : n_2 : n_3 = 44{,}342{,}444{,}579 : 7{,}101{,}906{,}723 : 2{,}202{,}963{,}881$

$$Average\ Weight = \frac{44{,}342{,}444{,}579 + 7{,}101{,}906{,}723 \times 3.5 + 2{,}202{,}963{,}881 \times 7.0}{44{,}342{,}444{,}579 + 7{,}101{,}906{,}723 + 2{,}202{,}963{,}881} = 1.58\ \text{kg}$$ [6]

Notes:

1. According to *Autonomous Last Mile Delivery Market by Application Market Research Report* dated December 2021, conducted by Technical Consultants International, the global autonomous last mile delivery market is projected to reach $84.72 billion by 2030. Based on *Global Drone Delivery Service Market* Figure 3 dated February 2021 conducted by BIS Research, the ratio of global drone delivery service market for packages less than 2 kg, 2 kg - 5 kg, and more than 5 kg is 2592.4 : 1453.2 : 907.4 in 2030. It is assumed that the ratio is also applicable to autonomous last mile delivery market in 2030.
2. Assume unit costs are the same on a per kg per mile basis. Assume average shipping distances for the three scenarios are the same. Therefore, unit costs are the same on a per kg basis.
3. Average of 0 and 1 kg.
4. Average of 2 and 5 kg.
5. Assume maximum of 20 lbs. payload based on https://news.mit.edu/2017/hybrid-drones-carry-heavier-payloads-greaterdistances-0804. Average of 20 lbs. and 5 kg.
6. Average package weight of all autonomous last mile delivery packages in 2030.

Appendix 2

E-Commerce				
Market Size at 2030 ($) [1]	Unit Cost in 2018 ($/package) [2]	Projected Unit Cost in 2030 ($/package) [3]	# of Package in 2030	Average Distance (Mile) [4]
52,765,668,270	3.79	5.56	9,489,623,600	1

Medical Aids				
Market Size at 2030 ($) [1]	Unit Cost in 2018 ($/package) [2]	Projected Unit Cost in 2030 ($/package) [3]	# of Package in 2030	Average Distance (Mile) [5]
23,375,799,798	3.79	5.56	4,204,012,736	2.16

Food Delivery				
Market Size at 2030 ($) [1]	Unit Cost in 2018 ($/package) [2]	Projected Unit Cost in 2030 ($/package) [3]	# of Package in 2030	Average Distance (Mile) [6]
8,578,531,932	3.79	5.56	1,542,803,147	5

Notes:

1. According to *Autonomous Last Mile Delivery Market by Application Market Research Report* dated December 2021, conducted by Technical Consultants International, the global autonomous last mile delivery market is expected to be valued at $11.90 billion in 2021, and is projected to reach $84.72 billion by 2030, registering a CAGR of 24.4%. Based on *Global Drone Delivery Service Market* Figure 4 dated February 2021 conducted by BIS Research, the ratio of global drone delivery service market for ecommerce, medical aids, and food delivery is 3016.4 : 1336.3 : 490.4 in 2030. It is assumed revenue from other delivery is negligible. It is assumed that the ratio is also applicable to autonomous last mile delivery market in 2030.
2. Based on *An Assessment of the Use of Autonomous Ground Vehicles for Last Mile Parcel Delivery*
3. *(*https://uttri.utoronto.ca/research/student-theses/an-assessment-of-the-use-of-autonomous-ground-vehicles-for-last-mile-parceldelivery/*)*, dated 2020 conducted by University of Toronto, the percent cost savings from replacing conventional delivery to autonomous ground vehicles delivery in last mile delivery vary from 35% to 90% depending on vehicle capacity and percent stores served. An average of 62.5% reduction rate is used in this study.
4. Apply inflation rates (https://www.statista.com/statistics/256598/global-inflation-rate-compared-to-previous-year/) to unit cost in 2018. Note, inflation rates between 2027 and 2029 were assumed based on inflation rates in other years.
5. Estimated based on data in http://www.nacds.org/pdfs/about/rxImpact-leavebehind.pdf and https://www.statista.com/statistics/985183/size-urban-rural-populationus/#:~:text=In%202020%2C%20there%20were%20approximately,people%20living%20in%20urban%20areas.
6. Assumption based on https://www.shopfood.com/online-shopping/whats-the-average-distance-for-food-deliveryservices/#:~:text=Uber%20Eats%20generally%20chooses%20to,into%20deciding%20a%20delivery%20range.

Appendix 3

E-Commerce

GHG

# of Package [1]	Total Mileage [2]	MPG [3]	Gallons per mile	Gallons	Production Emission Factors: CO_2 EF (kg/gallon) [4]	Production Emission Factors: CH_4 EF (kg/gallon) [4]	Production Emission Factors: N_2O EF (kg/gallon) [4]	On-Road Emission Factors: CO_2 EF (kg/gallon) [5]	On-Road Emission Factors: CH_4 EF (g/mile) [6]	On-Road Emission Factors: N_2O EF (g/mile) [6]	Indirect: CO_2 (kg)	Indirect: CH_4 (kg)	Indirect: N_2O (kg)	Indirect: CO_{2e} (kg)	direct: CO_2 (kg)	direct: CH_4 (kg)	direct: N_2O (kg)	direct: CO_{2e} (kg)
9,489,623,600	24,573,130	17.50	0.06	1,404,179	2.06	0.01196	0.00028	8.78	8.10E-03	1.50E-03	2,892,608	16794	393	3,467,030	12,328,690	199	36.86	12,344,031

Criteria Pollutants

Production Emission Factors: VOC EF (kg/gallon) [4]	Production Emission Factors: NOx EF (kg/gallon) [4]	Production Emission Factors: PM EF (kg/gallon) [4,7]	On-Road Emission Factors: NMOG EF (g/mile) [8,9]	On-Road Emission Factors: NOx EF (g/mile) [8]	On-Road Emission Factors: PM EF (g/mile) [8]	Indirect: VOC (kg)	Indirect: NOx (kg)	Indirect: PM (kg)	direct: NMOG (kg)	direct: VOC (kg) [10]	direct: NOx (kg)	direct: PM (kg)
3.30E-03	3.52E-03	3.40E-04	0.08425	0.5	0.04	4,634	4,943	477	2070	2,269	12287	983

Medical Aids

GHG

# of Package [1]	Average Transport Distance per Package (Mile) [1]	Average Weight per Package (kg) [11]	MPG [12]	Gallons per mile	Total Mileage	gallons	Production Emission Factors: CO_2 EF (kg/gallon) [4]	Production Emission Factors: CH_4 EF (kg/gallon) [4]	Production Emission Factors: N_2O EF (kg/gallon) [4]	On-Road Emission Factors: CO_2 EF (kg/gallon) [5]	On-Road Emission Factors: CH_4 EF (g/mile) [13]	On-Road Emission Factors: N_2O EF (g/mile) [13]	Indirect: CO_2 (kg)	Indirect: CH_4 (kg)	Indirect: N_2O (kg)	Indirect: CO_{2e} (kg)	direct: CO_2 (kg)	direct: CH_4 (kg)	direct: N_2O (kg)	direct: CO_{2e} (kg)
4,204,012,736	4.32	1.58	24.2	4.13E-02	1.82E+10	750,468,389	2.06	0.01196	0.00028	8.78	5.20E-03	1.60E-03	1,545,964,882	8,975,602	210,131	1,852,966,490	6,589,112,457	94,439	29,058	6,599,457,154

Criteria Pollutants

Production Emission Factors: VOC EF (kg/gallon) [4]	Production Emission Factors: NOx EF (kg/gallon) [4]	Production Emission Factors: PM EF (kg/gallon) [4,7]	On-Road Emission Factors: NMOG EF (g/mile) [14,9]	On-Road Emission Factors: NOx EF (g/mile) [14]	On-Road Emission Factors: PM EF (g/mile) [14]	Indirect: VOC (kg)	Indirect: NOx (kg)	Indirect: PM (kg)	direct: NMOG (kg)	direct: VOC (kg) [10]	direct: NOx (kg)	direct: PM (kg)
3.30E-03	3.52E-03	3.40E-04	0.1405	0.5	0.04	2,476,546	2,641,649	255,159	2,551,668	2,646,107	9,080,668	726,453

Food Delivery

GHG

# of Package [1]	Average Transport Distance per Package (Mile) [1]	Average Weight per Package (kg) [11]	MPG [12]	Gallons per mile	Total Mileage	gallons	Production Emission Factors: CO_2 EF (kg/gallon) [4]	Production Emission Factors: CH_4 EF (kg/gallon) [4]	Production Emission Factors: N_2O EF (kg/gallon) [4]	On-Road Emission Factors: CO_2 EF (kg/gallon) [5]	On-Road Emission Factors: CH_4 EF (g/mile) [13]	On-Road Emission Factors: N_2O EF (g/mile) [13]	Indirect: CO_2 (kg)	Indirect: CH_4 (kg)	Indirect: N_2O (kg)	Indirect: CO_{2e} (kg)	direct: CO_2 (kg)	direct: CH_4 (kg)	direct: N_2O (kg)	direct: CO_{2e} (kg)
1,542,803,147	10	1.58	24.2	4.13E-02	1.54E+10	637,521,962	2.06	0.01196	0.00028	8.78	5.20E-03	1.60E-03	1,313,295,241	7,624,763	178,506	1,574,092,725	5,597,442,823	80,226	24,685	5,606,230,629

Criteria Pollutants

Production Emission Factors: VOC EF (kg/gallon) [4]	Production Emission Factors: NOx EF (kg/gallon) [4]	Production Emission Factors: PM EF (kg/gallon) [4,7]	On-Road Emission Factors: NMOG EF (g/mile) [14,9]	On-Road Emission Factors: NOx EF (g/mile) [14]	On-Road Emission Factors: PM EF (g/mile) [14]	Indirect: VOC (kg)	Indirect: NOx (kg)	Indirect: PM (kg)	direct: NMOG (kg)	direct: VOC (kg) [10]	direct: NOx (kg)	direct: PM (kg)
3.30E-03	3.52E-03	3.40E-04	0.1405	0.5	0.04	2,103,822	2,244,077	216,757	2,167,638	2,247,864	7,714,016	617,121

Annual Total [14]

	GHG (kg CO_{2e})	VOC (kg)	NOx (kg)	PM (kg)
Direct	12,218,031,814	4,896,240	16,806,970	1,344,558
Indirect	3,430,526,245	4,585,002	4,890,669	472,394

GWP [15]	
CO_2	1
CH_4	28
N_2O	265

Notes:

[1] See Appendix 2.

[2] See Appendix 7.

[3] MPG for light truck/van. Data obtained from https://afdc.energy.gov/data/10310. Measured in gasoline gallon equivalents.

[4] GREET Model, emission factors for reformulated gasoline (E10) blending and transportation to refueling station

[5] Table 2 of Emission Factors for Greenhouse Gas Inventories: https://www.epa.gov/sites/default/files/2021-04/documents/emission-factors_apr2021.pdf.

[6] Table 3 of Emission Factors for Greenhouse Gas Inventories: https://www.epa.gov/sites/default/files/2021-04/documents/emission-factors_apr2021.pdf. Gasoline light-duty trucks (vans, pickup trucks, SVUs)

[7] Assume PM10

[8] *EPA Light-Duty Vehicles and Light-Duty Trucks: Clean Fuel Fleet Exhaust Emission Standards* (https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100O9ZJ.pdf). Assume light light-duty trucks, transitional low emission vehicle (TLEV) category, and average of intermediate and full useful life standards.

[9] NMOG = Non-Methane Organic Gas

[10] Assume VOC=NMOG+CH4

[11] See Appendix 1.

[12] MPG for car. Data obtained from https://afdc.energy.gov/data/10310. Measured in gasoline gallon equivalents.

[13] Table 3 of Emission Factors for Greenhouse Gas Inventories: https://www.epa.gov/sites/default/files/2021-04/documents/emission-factors_apr2021.pdf. Gasoline passenger cars.

[14] *EPA Light-Duty Vehicles and Light-Duty Trucks: Clean Fuel Fleet Exhaust Emission Standards* (https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100O9ZJ.pdf). Assume light-duty vehicles, transitional low emission vehicle (TLEV) category, and average of intermediate and full useful life standards [15] GWP from IPCC Fifth Assessment Report, 100 yr.

Appendix 4

E-Commerce											
# of Package [1]	Average transport Distance per Package (Mile) [1]	Average Weight per Package (kg) [2]	Energy Consumption (J/meter) [3]	Energy Consumption (KWh/mile)	CO_2 EF (lb/MWh) [4]	CH_4 EF (lb/MWh) [4]	N_2O EF (lb/MWh) [4]	CO_2 (kg) [5]	CH_4 (kg) [5]	N_2O (kg) [5]	CO_{2e} (kg)
9,489,623,600	2	1.58	140	6.26E-02	884.2	0.075	0.011	477,397,514	40,494	5,939	480,105,214

Medical Aids											
# of Package [1]	Average transport Distance per Package (Mile) [1]	Average Weight per Package (kg) [2]	Energy Consumption (J/meter) [3]	Energy Consumption (KWh/mile)	CO_2 EF (lb/MWh) [4]	CH_4 EF (lb/MWh) [4]	N_2O EF (lb/MWh) [4]	CO_2 (kg) [5]	CH_4 (kg) [5]	N_2O (kg) [5]	CO_{2e} (kg)
4,204,012,736	4.32	1.58	140	6.26E-02	884.2	0.075	0.011	456,824,030	38,749	5,683	459,415,041

Food Delivery											
# of Package [1]	Average transport Distance per Package (Mile) [1]	Average Weight per Package (kg) [2]	Energy Consumption (J/meter) [3]	Energy Consumption (KWh/mile)	CO_2 EF (lb/MWh) [4]	CH_4 EF (lb/MWh) [4]	N_2O EF (lb/MWh) [4]	CO_2 (kg) [5]	CH_4 (kg) [5]	N_2O (kg) [5]	CO_{2e} (kg)
1,542,803,147	10	1.58	140	6.26E-02	884.2	0.075	0.011	388,071,444	32,917	4,828	390,272,505

Annual Total GHG (kg CO_{2e}) [6]	1,329,792,760.15

GWP [7]	
CO_2	1
CH_4	28
N_2O	265

Notes:

[1] See Appendix 2.

[2] See Appendix 1.

[3] Estimated based on average weight per package using data in *Energy consumption models for delivery drones: A comparison and assessment.* It is assumed other autonomous delivery technology has similar energy consumption rate.

[4] Table 6 of Emission Factors for Greenhouse Gas Inventories: https://www.epa.gov/sites/default/files/2021-04/documents/emission-factors_apr2021.pdf. Use US Average.

[5] Emissions from return trips are included.

[6] From autonomous deliveries in 2030.

Appendix 5

Receptacle Energy Consumption

Per Receptacle

Power (KW)[1]:	0.3
Hours in Operation (h)[2]:	151
Energy Consumption (KWh):	45

GWP [5]

CO2	1
CH4	28
N2O	265

Emissions Projection

# of receptacles at 2030 [3]:	20,447,422
Total Energy Consumption (KWh):	925,681,888
CO_2 EF (kg/KWh) [4]	4.01E-01
CH_4 EF (kg/KWh) [4]	3.40E-05
N_2O EF (kg/KWh) [4]	4.99E-06
CO_2 (kg)	3.71E+08
CH_4 (kg)	3.15E+04
N_2O (kg)	4.62E+03
CO_2e (kg)	3.73E+08

Annual Total GHG (kg CO_{2e})	373,363,637

Notes:

[1] A value of 300 W was used per email correspondence with client

[2] Assuming a run time of one hour per day at full capacity, 365 days per year [3] Assuming 1% of addresses have a Arrive in 2030. Household data obtained from https://en.wikipedia.org/wiki/List_of_countries_by_number_of_households. It is assumed the data is also applicable for 2030

[4] Table 6 of Emission Factors for Greenhouse Gas Inventories: https://www.epa.gov/sites/default/files/2021-04/documents/emission-factors_apr2021.pdf. Assuming US average EFs.

[5] GWP from IPCC Fifth Assessment Report, 100 yr.

Appendix 6

Electricity Generation Emissions

Electracy Generation by Source [1]

Natural Gas	40%
Renewable Energy	20%
Nuclear Energy	20%
Coal	19%
Petroleum/Other	1%

Total Electricity Consumption from Autonomous Delivery [2]: 4,215,711,940 KWh

Criteria Pollutant Emissions by Source [3]

Natural Gas [4]							
Quantity Consumed per year	Unit	PM EF (lb/10^6 scf)	NOx EF (lb/10^6 scf)	VOC EF (lb/10^6 scf)	PM (Total) (kg)	NOx (kg)	VOC (kg)
5,755,238,143	scf	7.6	280	5.5	19,882	732,485	14,388

Coal [5]							
Quantity Consumed per year	Unit	PM EF (lb/ton) [8]	NOx EF (lb/ton)	VOC EF (lb/ton) [7]	PM (Total) (kg)	NOx (kg)	VOC (kg)
98,475	ton	4.4	9	0.3	196,950	402,853	1.34E+04

Petroleum/Other [6]							
Quantity Consumed per year	Unit	PM EF (lb/10^3 gal)	NOx EF (lb/10^3 gal)	VOC EF (lb/10^3 gal) [7]	PM (Total) (kg)	NOx (kg)	VOC (kg)
1,028,222	gal	14.9	47	1.04	6,964	21,967	4.86E+02

Total Criteria Pollutant Emissions from Electricity Generation [7]

Annual Total Emissions		
PM (kg)	**NOx (kg)**	**VOC (kg)**
223,796	1,157,304	28,303

[2] Total electricity consumption from autonomous delivery and receptacle consumption

[3] Emission Factors for each source taken from the AP-42. Emissions for renewable energy and nuclear energy were neglected and assumed to be zero

[4] Emission factors taken from AP-42 section 1.4 (https://www3.epa.gov/ttnchie1/ap42/ch01/final/c01s04.pdf#:~:text=Because%20natural%20gas%20is%20a%20gaseous%20fuel%2C%20filterable,result%20from%20poor%20air%2Ffuel%20mixing%20or%20maintenance%20problems); Conversion for KWh to scf: http://www.kylesconverter.com/energy,-work,-and-heat/kilowatt--hours-to-cubic-feet-of-natural-gas

[5] Emission factors taken from AP-42 section 1.2 (https://www3.epa.gov/ttn/chief/ap42/ch01/final/c01s02.pdf#:~:text=PM%20emissions%20from%20anthracite%20coal%20combustion%20are%20a,problem%2C%20because%20of%20anthracite%E2%80%99s%20low%20volatile%20matter%20content.); Conversion for KWh to tons of coal: http://www.kylesconverter.com/Energy,-Work,-and-Heat/Tons-of-Coal-Equivalent-to-Kilowatt--Hours

[6] Emission factors taken from AP-42 section 1.3 (https://www3.epa.gov/ttnchie1/ap42/ch01/final/c01s03.pdf); Conversion for KWh to gallons of fuel consumption: http://www.waterprofessionals.com/wp-content/uploads/fuel-energy.pdf

[7] Using TOC emissions factors since VOC emission factors are not provided in source. TOC factors provide a conservative overestimate

[8] Combining condensable and filterable PM emission factors, assuming an ash content of A=5 (5%)

Appendix 7

E-Commerce						
Number of packages delivered by autonomous at 2030[1] (packages)	Number of packages per light truck/van, 2018 (Per day)[2]	Number of packages on one truck (per year)	Light Truck/Van annual miles traveled, 2018 [3] (miles)	2030 Annual delivery rate for light truck/van (# packages per mile)	Miles Saved in 2030 (miles)	Total number of vehicles reduced in 2030 [4]
52,765,668,270	300	109,500	11,453	9.56	5,518,951,586	481,878

Medical Aid						
Number of packages delivered by autonomous at 2030[1] (packages)	Assuming 1 medical aid package delivery per trip	Average Shipping Distance per package (round trip, miles)	2018 Passenger car annual miles traveled [3] (miles)	Delivery rate (# packages per mile)	Miles Saved in 2030 (miles)	Total number of vehicles reduced in 2030 [4]
23,375,799,798	1	4.32	11,467	0.23	100,983,455,126	8,806,441

Food						
Number of packages delivered by autonomous at 2030[1] (packages)	Assuming 1 food package delivery per trip	Average Shipping Distance per package (round trip, miles)	2018 Passenger car annual miles traveled [3] (miles)	Delivery rate (# packages per mile)	Miles Saved in 2030 (miles)	Total number of vehicles reduced in 2030 [4]
8,578,531,932	1	10	11,467	0.10	85,785,319,320	7,481,060

2009 Police Reported MVC [5]	2009 Vehicle Miles Traveled (million miles) [5]	2019 Police Reported Motor Vehicle Crashes[6]	2019 Vehicle Miles Traveled (million miles) [6]	Annual increase in crashes rate	Annual increase in Vehicle miles traveled
5,505,000	2,953,501	6,756,000	3,261,772	2.27%	1.04%
Estimated 2030 Reported MVC	Estimated Vehicle Miles in 2030 (million miles)	Estimated MCV per million miles traveled in 2030 (crash rate)	# Crashes reduced - E-commerce [7]	# Crashes reduced - Medical Aid [7]	# Crashes reduced - Food [7]
8,650,402	3,656,432	2.37	13,057	238,907	202,951
Total number of crashes reduced			454,915		

[1] Appendix 2.

[2] According to Business Insider, one Amazon truck has 250-300 packages per day, https://www.businessinsider.com/amazondelivery-drivers-reveal-claims-of-disturbing-work-conditions-2018-8

[3] Highway statistics 2018, Average annual delivery truck miles traveled, https://afdc.energy.gov/data/10309. It is assumed that the data is also applicable to 2030.

[4] The total number of cars reduced is calculated using the vehicle miles saved annually divided by the annual distance a delivery truck travels annually, https://cece.vt.edu/content/dam/econdev_vt_edu/projects/technology/Virginia%20Tech%20%20Measuring%20the%20Effects%20of%20Drone%20Delivery%20in%20the%20United%20States_September%202020.pdf

[5] 2009 National Statistics from US DOT National Highway Traffic Safety Administration, https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/811402

[6] 2019 National Statistics from US DOT National Highway Traffic Safety Administration, https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/813141

[7] Crash rate times miles saved