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Optimizing investments in design, maintenance, and operations of transportation infrastructure to capitalize on the promise of connected autonomous vehicles

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16. Abstract

Connected Autonomous Vehicles (CAVs) and advanced propulsion systems, like battery-electric vehicles, could significantly impact transportation infrastructure investments. These changes require a reevaluation of how infrastructure projects are planned, focusing on both direct and indirect economic, social, and environmental effects. A key overlooked benefit of CAVs, particularly Road Autonomous Delivery Robots (RADRs), is their potential to reduce the wear on residential street pavements caused by traditional delivery vans.

RADRs are much lighter than conventional delivery vehicles, offering a chance to decrease pavement damage, especially in areas not built to support heavy loads. This study examines the impact of RADRs on pavement service life in Evanston, IL, where increasing delivery volumes have led to rising maintenance costs. While RADRs are currently 65% more expensive than traditional vans, they could become a cost-effective solution if their prices drop and delivery volumes rise. Notably, the city's existing pavement maintenance budget could be used to incentivize the switch to RADRs, thus reducing road deterioration.

This research highlights a potential opportunity for cities to rethink infrastructure spending. By encouraging RADRs, cities can both enhance delivery efficiency and extend pavement life, addressing congestion, pollution, and safety issues while improving the sustainability of infrastructure.

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1 Introduction

Connected Autonomous Vehicles (CAVs), advanced fuel propulsion systems, e.g., battery-electric vehicles, and other advances, are likely to have profound effects on the way transportation infrastructure is used and, therefore, on the tens of billions of dollars that are invested each year both on capital projects and on preservation of roads, bridges, and other facilities in the United States (and elsewhere). Accounting for and responding to fundamental changes in the use of transportation infrastructure motivates the need both to re-optimize the timing, location, and scope of interventions/investments aimed at improving infrastructure condition, as well as to reconsider the design and operation of transportation systems, e.g., parcel delivery operations in residential areas.

The scope of evaluation of investments in design, construction, management and operations of transportation infrastructure typically involves a detailed accounting of direct costs incurred by owners/agencies/operators. This assessment approach, therefore, fails to capture significant indirect economic impact of investments, as well as direct and indirect social and environmental repercussions. Similarly, approaches to evaluate (firms') investments in re-designing transportation services or in technology adoption, e.g., widespread adoption of CAVs, do not capture their effects on the use and wear of public infrastructure, and thus, on the investments needed to keep these systems operating efficiently, i.e., in a state of good repair, which is required to capitalize on the promise of redesigned/new systems and technologies.

In this study, we focus on a particular indirect impact of the adoption of CAVs for parcel delivery operations in residential areas that, to the best of our knowledge, has been overlooked. Specifically, we quantify the benefits of adoption of Road Autonomous Delivery Robots (RADRs) on reducing the deterioration, i.e., extending the service lives, of street surfaces, i.e., pavements. In particular, because RADRs are significantly lighter than conventional delivery vehicles, they have significant potential to help reduce the negative impacts of last-mile delivery to residential streets – partly, because these are not designed to support the loads induced by delivery vehicles. Importantly, the aforementioned indirect benefits are linked to the investments needed to deploy and operate the advanced delivery system.

We apply the framework developed herein to study widespread adoption of RADRs in the city of Evanston, IL, a small city of approximately 75,000 residents in the Midwestern United States, where pavement maintenance expenditures have recently been increasing due, in part, to growing delivery operations. When comparing two potential scenarios for last-mile delivery (one with conventional delivery vans and another one with RADRs), we find that, in the current situation, private firms would need to be provided with financial incentives to decide to switch to RADRs as their main delivery technology, since the costs associated to this alternative are 65% higher than those of conventional delivery vans. If the prices of RADRs go down and the number of parcels to be delivered go up, RADRs are highly likely to become a viable option. We also find that the current expenditures by the city of Evanston on pavement maintenance would be sufficient to incentivize private firms to make this switch, if these funds were to be allocated for that purpose instead. These findings lead us to believe there is opportunity for the city of Evanston to reconsider its maintenance budget allocation in a more efficient way, by encouraging delivery firms to adopt RADRs thus reducing pavement deterioration. These findings were shared with Evanston's Director of Public Works, who has expressed interest in the findings presented herein, and importantly, has provided extensive feedback to the research team.

As far as prior work, Boysen et al. (2021), among others, raise the concern that an increase in parcel volumes to be delivered to customer homes steadily increases the circulation of delivery vans, adding to both congestion and pollution. Fagan et al. (2022) mention that RADRs offer the potential for reducing this congestion through greater vehicle efficiency by "right-sizing" fleets, trip stacking, and operating for longer hours. They also mention that RADRs can potentially provide safety benefits by reducing crashes and accidents. In a similar vein, Hossain (2022) points out that robots can potentially reduce traffic congestion and increase parking availability. He estimates that last-mile delivery costs can be reduced by approximately 40%.

In addition to negative impacts on congestion, pollution and safety, Skiles et al. (2025) show that increasing the number of delivery vehicles in residential areas across the country will lead to quicker wear on the road surfaces. They consider improving the structural design, i.e., increasing the surface thickness, of pavements in residential streets as a strategy to counter the corresponding reduction in service lives.

As far as we are aware, there is no mention in the literature of the positive effects of RADRs on reducing loads, and therefore, extending the service lives of pavements in residential areas, thereby reducing associated maintenance costs. We note, however, that these benefits are predicated on redesigning parcel delivery networks by allowing heavy vehicles only on certain streets to access a number of micro-depots, and using RADRs on all other streets. Furthermore, we present a framework for this purpose.

2 Findings

For our analysis, we developed a case study for the city of Evanston, where we compared two potential solutions for a last-mile delivery scenario where around 3,000 packages need to be delivered daily. In our case study, we compare 2 approaches for parcel delivery in residential areas. The first approach involves delivery from one major central depot, with each vehicle driven by a human worker. On a tour along customer homes, the worker stops the vehicle at the roadside, approaches a customer home, and hands over a parcel directly to the customer. The second approach involves the use of RADRs, where micro-depots are scattered throughout the city, and fleets of RADRs are available at each micro-depot. The RADRs are loaded and deployed to customer homes, where the customers need to go outside and pick up their parcels.

We found the total cost of the conventional vans approach for the distribution of packages in the city of Evanston to be $1,830 per day. These costs are summarized in Table 1. The capital expenditures correspond to the cost of opening the central depot and the cost of the vans. The operational expenditures correspond to labor costs for the human drivers and the costs associated to the operation of vans (fuel, maintenance, etc.). The assumptions are explained in Section 3.2.

Capital expenditures: facilities	410	$/day
Capital expenditures: vehicles	160	$/day
Operational expenditures	1,260	$/day
Total expenditures	1,830	$/day

Table 1: Expenditures for conventional vans solution

For the RADRs approach, the optimal solution consists of 7 open micro-depots and a total of 18 RADRs needed. We found the total cost of this approach to be $3,010 per day. Figure 1 presents the location of these open micro-depots in the city of Evanston, and Table 2 presents total expenditures for this solution. In this case, the capital expenditures correspond to the cost of opening the micro-depots and the cost of the RADRs. The operational expenditures correspond to the operation of the RADRs. The assumptions are explained in Section 3.3.

Capital expenditures: facilities	1,010	$/day
Capital expenditures: vehicles	360	$/day
Operational expenditures	1,640	$/day
Total expenditures	3,010	$/day

Table 2: Expenditures for RADRs solution

The current situation still favors conventional vans, as evidenced by the expenditures presented in Table 1 and Table 2. Nevertheless, further exploration of these results shows that the tendency in the future will be for the total costs of a RADR based approach to last-mile delivery to tend towards those of a conventional van based approach (as the number of parcels to deliver increases and the cost of CAVs decreases). Table 3 presents the effects of varying demand on total expenditures for both conventional vans and RADRs: while the cost per delivery remains constant for the conventional vans

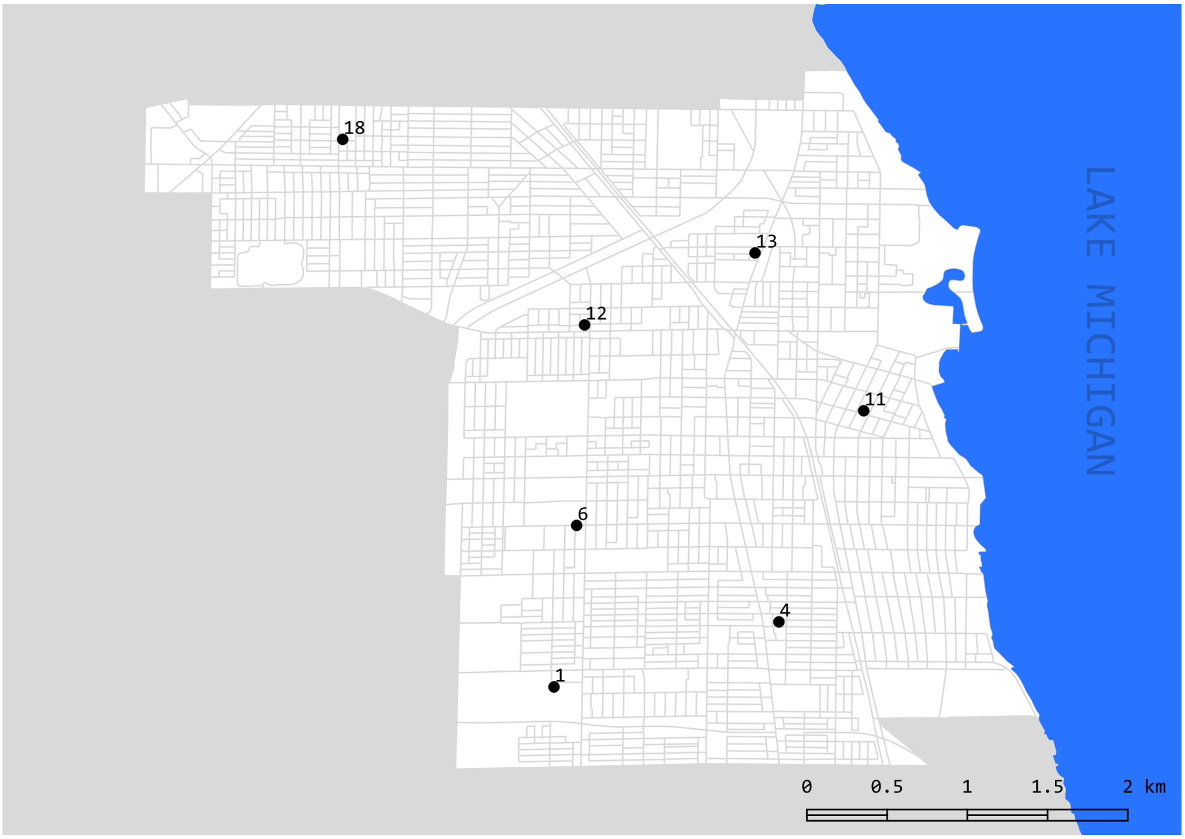


Figure 1: Nodes with open micro-depots

solution regardless of demand, the RADRs solution exhibits economies of scale. Table 4 presents the effects of varying RADR costs. For the base case, we had assumed a cost of \$50,000 per RADR, which comes out to \$20 per RADR per day (considering a 10 year lifespan and a 6% interest rate). We also consider costs of \$5,000, \$10,000, \$15,000, \$25,000, \$75,000 and \$100,000 (which, under the same assumptions, come out to \$2, \$4, \$6, \$10, \$30 and \$40 per day, respectively).

Demand multiplier	Total expenditures (\$/day)		Total expenditures per delivery (\$/parcel)	
	Conventional vans	RADRs	Conventional vans	RADRs
0.5	920	2,037	0.61	1.36
1	1,830	3,010	0.61	1.00
1.5	2,730	3,930	0.61	0.87
2	3,640	4,741	0.61	0.79

Table 3: Effect of number of parcels to deliver

Moreover, we can use our models of both approaches to attempt to understand what would be the case if the government were to provide subsidies for the use of RADRs. In particular, we look at the results when the government decides to cover part of the cost of the micro-depots. These results are summarized in Table 5, which shows that higher subsidies encourage private firms to open more micro-depots. Subsidies in the

RADR cost p (\$/day)	2	4	6	10	20	30	40
Number of open facilities	7	7	7	7	7	7	8
Number of RADRs	19	19	18	18	18	18	17
Capital expenditures: facilities ($/day)	1,010	1,010	1,010	1,010	1,010	1,010	1,150
Capital expenditures: vehicles ($/day)	38	76	108	180	360	540	680
Operational expenditures ($/day)	1,636	1,636	1,640	1,640	1,640	1,640	1,539
Total expenditures ($/day)	2,684	2,722	2,758	2,830	3,010	3,190	3,369

Table 4: Effect of RADR cost

75-100% range would bring total costs for private firms down to around the same level as those of the conventional vans approach. A 75% subsidy would add up to a yearly cost of around $670,000 for the government, which is in the same order of magnitude as the cost of the Pavement Patching Program presented on Table 6 (Skiles et al., 2025). This leads us to believe that providing subsidies for the construction of micro-depots could potentially be a viable way to mitigate the social costs of an increase in delivery vehicles, as an alternative to the increase in pavement thickness proposed by Skiles et al. (2025).

Subsidy (% of total facility costs)	0%	25%	50%	75%	100%
Number of open micro-depots	7	8	11	17	18
Number of RADRs	18	17	16	17	18
Capital expenditures: facilities ($/day)	1,010	862	785	610	0
Capital expenditures: vehicles ($/day)	360	340	320	340	360
Operational expenditures ($/day)	1,640	1,539	1,278	932	888
Total expenditures ($/day)	3,010	2,741	2,383	1,882	1,248
Subsidy ($/day)	0	287	785	1,830	2,580

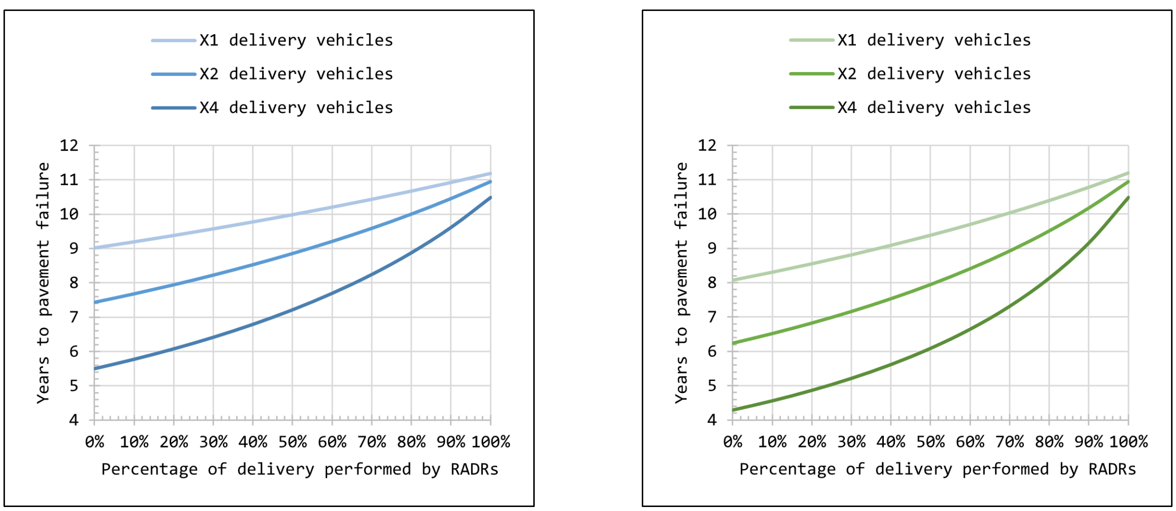
Table 5: Effect of government subsidies

Year	Patching locations	Pavement patching (yd^2)	Total cost (2020 $)
2021	219	31,118	562,000
2022	296	37,500	642,000

Table 6: 2021 and 2022 city of Evanston Pavement Patching Program data

Skiles et al. (2025) study the effects of increases in traffic of delivery vehicles on road wear in the city of Evanston. The authors note that the number of locations where pavement patching was completed has nearly doubled over the past five years: in 2018, there were a total of 152 patching locations, and in 2022, there were 296 patching locations. Patching extends the life of the road surface by approximately 5 years. A decrease in overall traffic, among other factors, suggests that the observed acceleration of residential street deterioration could be explained by an increase in the number of delivery vehicles serving the city of Evanston. The study by Skiles et al. (2025) is presented in further detail in Section 3.4.

Given that a Nuro RADR has a gross vehicle weight of 1,150 kg and can carry a payload of up to 190 kg (Ferguson, 2020), putting it below the weight of an average car (Skiles et al., 2025), encouraging firms to make use of RADRs instead of conventional delivery vans could potentially help mitigate the impact of last-mile delivery on pavement maintenance. Figure 2 presents our results graphically, where we gradually replace a portion of the total number of delivery vehicles considered by Skiles et al. (2025) by RADRs. We select a conservative load equivalency factor of 0.0003 for RADRs (Pavement Tools Consortium, 2024), and we assume 100 RADRs are needed for every conventional delivery van (consistent with our selection of capacity of 200 parcels for conventional vans and 2 parcels for RADRs as presented in Table 8). Although RADRs are meant to circulate on surface streets, as opposed to SADRs (Sidewalk Autonomous Delivery Robots), their impact in pavement lifespans is minimal, due to their low weight. Therefore, major increases in delivery demands would have relatively minor impacts in pavement lifespans if the adoption of RADRs was 100%.



(a) Considering conventional delivery vehicles

(b) Considering electric delivery vehicles

Figure 2: Pavement performance versus adoption of RADRs

To put things into perspective, Table 7 presents the increases in pavement surface thickness that would be required to achieve similar pavement lifespans as those resulting from a 100% RADR adoption, under varying assumptions. Each 0.25 in increase in pavement surface thickness has a material cost increase of $17,500 per mile of roadway for an average residential street (Skiles et al., 2025).

Type	Increase in surface thickness (in)		
	1X delivery veh.	2X delivery veh.	4X delivery veh.
Conventional delivery vehicles	0.25	0.40	0.70
Electric delivery vehicles	0.35	0.60	0.95

Table 7: Surface thickness increases to achieve results equivalent to a 100% RADR adoption

3 Framework and Analysis

We take the formulation for distance traveled by a delivery vehicle and time duration of a shift from Jennings and Figliozzi (2020). The average distance traveled by a delivery vehicle to serve n customers $l(n)$ can be estimated as follows:

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

where d represents the distance between the service zone and the depot, k_l corresponds to a routing constant representing non-Euclidean travel on roads, and a represents the area of the service zone. Moreover, the formula that Jennings and Figliozzi (2020) use to calculate route duration time to serve n customers $\tau(n)$ (accounting only for driving time, not taking into account the time of waiting for the customer and unloading the parcels) is as follows:

$$\tau(n) = \frac{2d}{s_h} + \frac{k_l\sqrt{an}}{s}$$

where s_h represents the average speed of a vehicle while traveling to and from the service zone, and s represents the average speed of a vehicle while delivering in the service zone.

3.1 Model Data

Geographic data for the city of Evanston is available through the city's open data portal. Moreover, population data is available through the 2020 Census Demographic Data Map Viewer. Figure 3 shows the population density for the city of Evanston. The population data for each census tract was used directly to estimate demand, by assuming each person receives a total of 14 packages each year (Capital One Shopping, 2024). Multiplying population by 14 and dividing by 365 gave us the number of packages demanded daily for the city of Evanston. The total number of packages would be approximately 3,000 per day.

We created a budget for the distribution facilities, where the fixed costs come from land costs and construction costs. For land cost data, we used sale prices for available land plots on Zillow to estimate an average cost per square foot for the city of Evanston, which led to a value of $56/sqft. For construction costs, we assumed an average cost

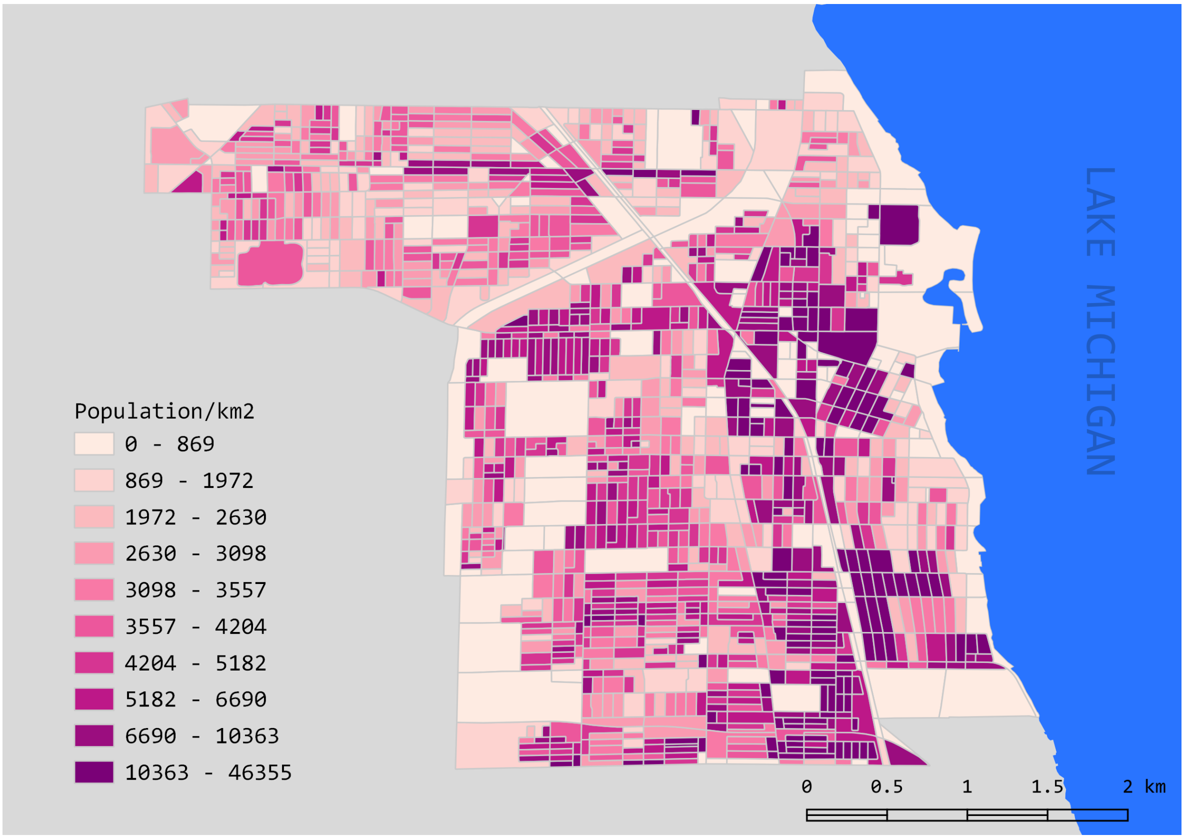


Figure 3: City of Evanston population density by census block

of \$18/sqft (APX Construction Group, 2024). Finally, according to Pahwa and Jaller (2022), we assumed 0.2 orders can be fulfilled per square foot of facility.

According to Jennings and Figliozzi (2020), three companies are currently developing RADRs in the US: Nuro (based in Mountain View, California), Udelv (based in Burlingame, California) and AutoX (based in San Jose, California). Nuro's R2 delivery robot, which we have selected for the study, has two compartments with doors that swing upwards to release delivery items. Figure 4 presents the vehicles selected for the study.

Table 8 presents the corresponding parameters for each type of delivery vehicle. The routing constant representing non-Euclidean travel on roads k_l is taken from Jennings and Figliozzi (2020). We assume no restriction for the range r of a conventional van, and the restriction for the range r of a RADR is taken from Jennings and Figliozzi (2020). The capacity q of a conventional van is taken from Jennings and Figliozzi (2020), and the capacity q of a RADR is taken from Ferguson (2020). The cost c_{drive} per hour of operation of a van while driving is taken from Jennings and Figliozzi (2020), and c_{drive} for a RADR is assumed to be the same as the one for a van minus the labor cost of the delivery driver. The cost c_{idle} per hour of operation of a van while idle is assumed to come only from the labor cost of the delivery driver, and it is set at \$20/hr. We

(a) Ford Transit 2024 cargo van

(b) Nuro R2 delivery robot

Figure 4: Conventional van and RADR selected for the study

assume no cost per hour of operation for a RADR being idle, since there is no human driver. The average speed s_h of a van while traveling to and from a service area is taken from Jennings and Figliozzi (2020), and the s_h for a RADR is assumed to be the maximum speed taken from Ferguson (2020). The average speed s of a van while delivering in a service area is taken from Jennings and Figliozzi (2020), and the one for RADRs is assumed to be the same. The time t a van is idle during a delivery is assumed to be 0.5 minutes, and a longer t of 1 minute is assumed for RADRs since no human driver is present to speed up delivery. The cost p of purchasing a van is based on a $50,000 price taken from Ford and assuming a 10 year lifespan and a 6% interest rate. The cost p of purchasing a RADR is also based on a $50,000 price and the same assumptions of lifespan and interest rate as for vans; however, since the price of a RADR is not publicly available and it is expected to change significantly in the near future (Lee et al., 2016), the implications of this parameter needed to be explored further, as presented previously in Table 4.

Symbol	Van	RADR	Units	Explanation
k_l	0.7	0.7	-	routing constant representing non-Euclidean travel on roads
r	-	3	km	range of a vehicle
q	200	2	parcels	capacity of a vehicle
c_{drive}	40	20	$/hr	cost per hour of operation of a vehicle while driving
c_{idle}	20	0	$/hr	cost per hour of operation of a vehicle while idle
s_h	70	40	km/hr	average speed of a vehicle while traveling to and from the service area
s	35	35	km/hr	average speed of a vehicle while delivering in the service area
t	0.5	1	min	total time a vehicle is idle during a delivery
p	20	20	$/day	cost of purchasing a vehicle
g	8	8	hr	available hours in a workday

Table 8: Characteristics of delivery vehicles

3.2 Conventional Delivery Vans

For the case of conventional vans, we assume one central distribution facility that covers the entire city of Evanston (an area of about 20.15 km^2). Since there are approximately 3,000 parcels to be delivered within a day, and we are assuming each van can carry about 200 parcels, we estimate a total of 15 shifts needed per day. We calculate the driving time of a van per shift and the idle time of a van per shift as follows:

$$\text{Driving time} = \frac{k_l\sqrt{aq}}{s} = 1.5 \text{ hr}$$

$$\text{Idle time} = qt = 1.7 \text{ hr}$$

Adding these times and considering an 8 hour shift, we estimate a total of 8 vehicles that need to be available at the central depot to cover the 15 shifts. Assuming a 6% interest rate and a 10-year lifespan, we calculate the daily cost of a central depot to serve the 3,000 daily orders, which would require a 15,000 sqft area, to be approximately $410 per day. Considering a $20 daily cost of purchasing a vehicle, the 8 vehicles would add up to a cost of $160 per day. Finally, the operational expenditures, given the number of shifts and the driving and idle times, would add up to approximately $1,260 per day.

3.3 RADRs

The analysis of the use of RADRs for delivery requires the formulation of a facility location model to understand where the micro-depots should be opened and to estimate the size of the fleet required at each of them. We follow Daskin (2013) to formulate a capacitated fixed charge facility location model and we adapt it to our particular situation.

We identify the geometric centroid for each of the 18 census tracts that correspond to the city of Evanston. In our facility location model, these 18 nodes constitute both demand nodes and potential locations for micro-depots where the RADRs will be loaded and deployed. Figure 5 presents the 18 nodes. Euclidean distances between the nodes were measured in order to create the distance matrix. The land area covered by each census tract was associated to each corresponding node.

Instead of a decision variable Y_{ij} indicating the fraction of demand from node $i \in I$ that is satisfied by a micro-depot $j \in J$, we propose a decision variable V_{ij} indicating the number of RADR trips that depart micro-depot $j \in J$ to cover demand at node $i \in I$. Just like in Daskin (2013), we use the problem constraints to ensure that all demand is covered, that a micro-depot has to be open in order to be able to satisfy demand, and that micro-depot capacity is not exceeded at any location. Moreover,

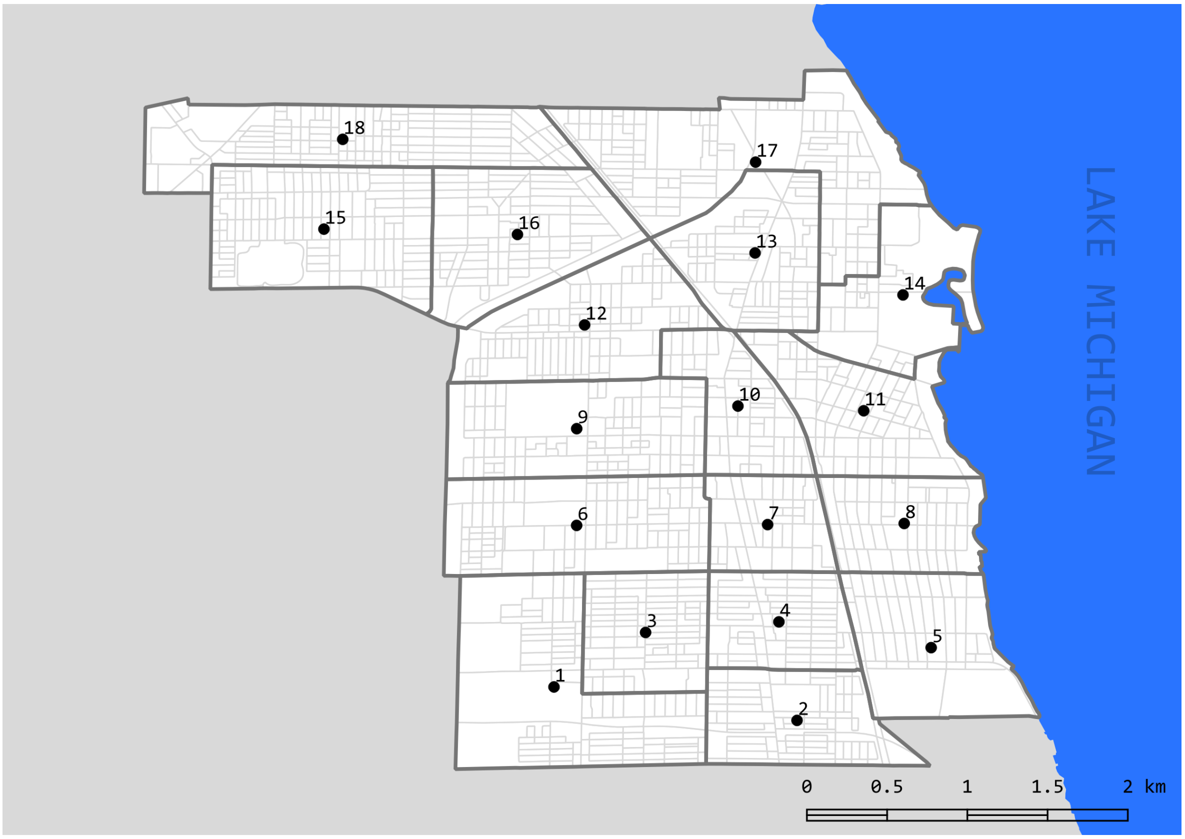


Figure 5: Census tracts with geometric centroids

we add another decision variable to the model: Z_j, indicating the number of RADRs available at site $j \in J$. We also add an additional constraint to ensure a sufficient number of RADRs are available to cover all trips departing a certain micro-depot. See Appendix A.1 for the formulation. Available data for the city of Evanston was used to run the model, considering micro-depots that serve a maximum of 1,000 customers (with a cost of \$140 per day and a 20% extra for the two downtown census tracts).

3.4 Pavement Performance

Skiles et al. (2025) assume a traffic mix where 5% of traffic corresponds to delivery vehicles (14,000 lb), 5% to heavy vehicles (18,000 lb), and 90% to personal vehicles (assumed to be evenly split between an average 4,000 lb car and an average 8,000 lb SUV/pickup truck). They consider a daily traffic of 200 vehicles per day for the average Evanston residential street. The authors use the AASHO equation to find the number of equivalent single axle loads that cause pavement quality to decline to the point where resurfacing is required, N:

$$N = A_0 * (D + 1)^{A_1} * (L_1 + L_2)^{-A_2} * (L_2)^{A_3} \tag{1}$$

where D represents pavement thickness, L_1 and L_2 are parameters determined by the weight and whether the axle is single or tandem, and A_0, A_1, A_2 and A_3 are coefficients that vary slightly depending on whether the pavement is rigid or flexible. L_1 is fixed at 18 and L_2 is fixed at 1 for the study. The authors use a set of Small-Winston coefficients A_0, A_1, A_2 and A_3, which are presented in Table 9 (Small et al., 1989).

$ln(A_0)$	A_1	A_2	A_3
12.062	7.761	3.652	3.238

Table 9: Flexible pavement coefficient estimates for AASHO road wear equation

An increase in the number of delivery vehicles causes a significant decrease in pavement lifespan. The authors also consider the effects of replacing conventional delivery vehicles with electric delivery vehicles, which they assume to be 1,444 lb heavier. Their results are summarized in Table 10, for a two-fold and four-fold increase in the number of delivery vehicles (Skiles et al., 2025).

	Years to pavement failure		
Type of delivery vehicle	1X delivery veh.	2X delivery veh.	4X delivery veh.
Conventional	9.01	7.43	5.50
Electric	8.08	6.24	4.29

Table 10: Pavement performance of conventional and electric delivery vehicles

As an approach to mitigate the service life reduction from the increased traffic loads associated with an increase in delivery vehicles, Skiles et al. (2025) discuss increasing the surface thickness of the pavement.

4 Conclusions and Recommendations

We study a benefit of the use of RADRs which is often overlooked when considering the possible repercussions of adoption of CAVs: using lighter delivery vehicles on residential streets would decrease the need for regular pavement maintenance. An increase in delivery demands generated by e-commerce can have a significant negative impact in pavement lifespans in residential areas, and the use of heavier electric delivery vans only exacerbates this problem. For instance, a four-fold increase in the number of delivery vehicles could make pavement lifespans up to four years shorter than they currently are. However, the gradual adoption of RADRs has the potential to offset the effects of this externality.

For our analysis, we developed a case study for the city of Evanston, where we compared two potential solutions for a last-mile delivery scenario where around 3,000 packages need to be delivered daily. On one hand, we considered a central depot where conventional delivery vans are deployed. On the other hand, we considered a set of micro-depots scattered throughout the city, where RADRs replaced the conventional vans and their human drivers. We found the daily cost of the RADRs approach to be 65% higher than that of the conventional delivery vans approach, which indicates that private firms are unlikely to shift to using RADRs as their main delivery vehicles in the current situation.

The difference in cost between the two approaches depends on many parameters we assumed in our model. It is necessary to take into account that these parameters are likely to change as newer technology is developed and costs go down, and as market demands for last-mile delivery services increase. By changing the original parameters, we found that, as the prices of RADRs go down and the number of parcels to be delivered go up (like they are both predicted to), RADRs are likely to become a more viable option than they are today. For example, we originally assumed the cost of a RADR to be $50,000. If this cost was lowered to $25,000, the overall cost of the RADRs approach would be 55% higher than that of the conventional delivery vans approach, instead of the original 65%. Moreover, if instead of RADR cost we focused on the effects of an increase in demand for last-mile delivery, we can see that doubling the number of parcels to deliver would imply that the RADRs approach is only 30% more expensive than the conventional delivery vans approach, instead of the original 65%.

We suggest that private firms could choose to shift to using RADRs as their main delivery vehicles in the current cost and demand situation if they were to be provided with financial incentives. Our proposal to the city of Evanston is that they could allocate part of their yearly pavement maintenance budget to providing financial incentives to private delivery firms for the use of RADRs, thus reducing the overall amount of heavy delivery vans circulating and with it the rate at which surface roads deteriorate. Subsidies for the construction of micro-depots of around 75% of construction costs would bring the total costs of the RADRs approach to about the same as that of the conventional delivery vans approach. Moreover, for the city of Evanston, a 75% subsidy would add up to a cost in the same order of magnitude as the total cost of the Pavement Patching Program, which shows that these subsidies could potentially be feasible within the city's current budget.

By reviewing the current literature, we realized that the positive effects RADRs could potentially have on pavement maintenance have not yet been explored. Other social benefits of RADRs are mentioned in the literature, such as lower labor costs, reduced congestion and pollution, and increased traffic safety. This represented a challenge, in the sense that we did not have an existing framework to compare our results with, but also an opportunity, in that we believe we were able to make a contribution to the current discussion regarding RADRs.

As further recommendations, it would be useful for the city of Evanston to gather more data on the current use of delivery vehicles. This would allow them to further monitor the effect that delivery vehicles can have on pavement maintenance, and more accurately assess the types of subsidies they would be able to provide. It is also important to keep track of changes in delivery demands, as an increase in demands has the potential to significantly increase pavement deterioration in the current situation where conventional delivery vans are used. Furthermore, changes in RADR costs should also be monitored as this data becomes publicly available, and the corresponding parameters in the models presented in this report must be updated accordingly.

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A Outputs Description

A.1 Facility Location Model

We developed a capacitated facility location model that takes into consideration the limitations or RADRs (such as limitations in maximum range of a vehicle and number of parcels carried) and optimizes for the lowest cost of a set of micro-depots.

A.1.1 Decision Variables

- $X_j = \begin{cases} 1 & \text{if locating a micro-depot at candidate site } j \in J \\ 0 & \text{otherwise} \end{cases}$
- Z_j = number of RADRs available at site $j \in J$
- V_{ij} = number of trips departing site $j \in J$ to cover demand at node $i \in I$

A.1.2 Parameters

- f_j = fixed cost of locating a micro-depot at candidate site $j \in J$
- k_j = processing capacity of facility at candidate site $j \in J$
- h_i = number of RADR trips required to cover demand from node $i \in I$
- a_i = service area represented by demand node $i \in I$
- d_{ij} = distance between demand node $i \in I$ and facility site $j \in J$
- k_l = routing constant representing non-Euclidean travel on roads
- q = number of parcels carried by a RADR
- s_h = average speed of a RADR while traveling to and from the service area
- s = average speed of a RADR while delivering in the service area
- c = cost per hour of operation of a RADR
- p = cost of purchasing a RADR
- t = time a RADR is idle during a delivery
- g = available hours in a workday
- M = arbitrarily large constant, used for constraint definition

A.1.3 Objective Function

The objective is to minimize the total expenditures, which consist of the capital expenditure of opening the micro-depots, the capital expenditure of purchasing the RADRs, and the operational expenditures of delivery.

$$\text{minimize} \quad \sum_{j \in J} f_j X_j + p \sum_{j \in J} Z_j + c \sum_{i \in I} \sum_{j \in J} V_{ij} \tau_{ij}$$

where $\tau_{ij} = \frac{2d_{ij}}{s_h} + \frac{k_l \sqrt{a_i q}}{s}$.

A.1.4 Constraints

$$\sum_{j \in J} V_{ij} \geq h_i \quad \forall i \in I \tag{1}$$

$$V_{ij} \leq M X_j \quad \forall i \in I, \forall j \in J \tag{2}$$

$$q \sum_{i \in I} V_{ij} \leq k_j X_j \quad \forall j \in J \tag{3}$$

$$\sum_{i \in I} V_{ij} \left(\tau_{ij} + tq \right) \leq g Z_j \quad \forall j \in J \tag{4}$$

$$X_j \in \{0, 1\} \quad \forall j \in J \tag{5}$$

$$Z_j \in \mathbb{N} \quad \forall j \in J \tag{6}$$

$$V_{ij} \in \mathbb{N} \quad \forall i \in I, \forall j \in J \tag{7}$$

- Constraint (1) ensures that demand is satisfied at each each node $i \in I$.
- Constraint (2) ensures that a shift can only depart from a site $j \in J$ if a micro-depot is open at that site.
- Constraint (3) ensures that the capacity k_j of a micro-depot $j \in J$ is not exceeded.
- Constraint (4) ensures that the RADRs available at micro-depot $j \in J$ are sufficient to cover the shifts departing from that micro-depot.

Additionally, we can check off-line for the maximum distance traveled by a RADR not to exceed a range limit r.

A.2 MATLAB Code for Facility Location Model

```
% Parameters
q = 2;
```

```
% Matrices
f = readmatrix('fixedCost.csv');
k = readmatrix('capacity.csv');
h = ceil(readmatrix('demand.csv')/q);
a = readmatrix('serviceArea.csv');
d = readmatrix('distance.csv');

% Constants
kl = 0.7;
r = 3;
cd = 20;
ci = 0;
sh = 40;
s = 35;
t = 1/60;
T = 8;
p = 20;
g = 8;
M = 1000;

% Decision variables
X = optimvar('X',length(f),'Type','integer','LowerBound',0,'
    UpperBound',1);
Z = optimvar('Z',length(f),'Type','integer','LowerBound',0);
V = optimvar('V',length(h),length(f),'Type','integer','
    LowerBound',0);

% Objective function

% Vehicle operation times
for i = 1:length(h)
    for j = 1:length(f)
        opTimeDrive(i,j) = V(i,j)*(2*d(i,j)/sh + (kl/s)*sqrt(a(i
           )*q));
        opTimeIdle(i,j) = V(i,j)*(t*q);
    end
end

% Capital expenditure
```

```
capExF = sum(f(:).*X);
capExV = sum(Z)*p;

% Operational expenditure
opExV = sum(sum(opTimeDrive))*cd + sum(sum(opTimeIdle))*ci;

% Total expenditure
totalEx = capExF + capExV + opExV;
prob = optimproblem('Objective',totalEx,'ObjectiveSense','min');

% Constraints
demand = optimconstr(length(h));
for i = 1:length(h)
    % demand(i) = q*sum(V(i,:)) >= h(i);
    demand(i) = sum(V(i,:)) >= h(i);
end

assign = optimconstr(length(h),length(f));
for i = 1:length(h)
    for j = 1:length(f)
        assign(i,j) = V(i,j) <= M*X(j);
    end
end

capacity = optimconstr(length(f));
for j = 1:length(f)
    capacity(j) = q*sum(V(:,j)) <= k(j)*X(j);
end

range = optimconstr(length(h),length(f));
for i = 1:length(h)
    for j = 1:length(f)
        range(i,j) = V(i,j)*(kl*sqrt(a(i)*q) + 2*d(i,j)) <= V(i,
           j)*r;
    end
end

vehicle = optimconstr(length(f));
for j = 1:length(f)
    vehicle(j) = Z(j) >= (sum(opTimeDrive(:,j))+sum(opTimeIdle
```

```
        (:,j)))/g;
end

prob.Constraints.demand = demand;
prob.Constraints.assign = assign;
prob.Constraints.capaci = capacity;
prob.Constraints.range = range;
prob.Constraints.vehicle = vehicle;

% Solver
sol = solve(prob);
```

B Final documentation of outputs, outcomes, and impacts

B.1 Synopsis

We emphasize the impact of the adoption of RADRs on pavement maintenance in residential areas as a benefit of this technology that seems to have been overlooked so far in the literature. By understanding the potential benefit of companies adopting RADRs as the main means of delivery when it comes to pavement maintenance, in that the use of lighter vehicles would lower the need for repairs and save taxpayers money in the long run, our research could spark collaboration between city governments and last-mile delivery companies. Providing incentives to private firms for the creation of micro-depots to facilitate the deployment of RADRs could potentially accelerate the adoption of this technology and increase welfare, while ensuring the transportation system remains in a state of good repair even with lower maintenance schedules.

B.2 Outputs

Teixeira Manion, P. and Durango-Cohen, P.L. (2025), "Shifting last mile delivery operations to Road Autonomous Delivery Robots: Effects on residential streets" *working paper*

This work was presented to the Director of Public Works in the City of Evanston and his staff in January of 2025.

Parts of this work will be presented at the 2025 Annual meeting of the International Transportation Economics Association taking place in June 2025 in Evanston, IL.

B.3 Outcomes

The Director of Public Works in the City of Evanston was interested in the work; especially, in the impact of conventional delivery vehicles on reducing the service life of residential streets. The prospects and expenses associated with keeping the system in a state of good repair are even more daunting as delivery operations continue to increase, and as comapanies are considering transitioning to electric delivery vehicles that are significantly heavier.

B.4 Impacts

The work described herein has potential to improve the safety and operations of transportation systems–residential streets in particular. The work presents a framework to support adoption of RADRs. As such, impacts are likely to realize as the technology matures and companies scale their deployment for residential deliveries.