Tackling the Urban Last-mile Crowdsourced Delivery Problem at Scale

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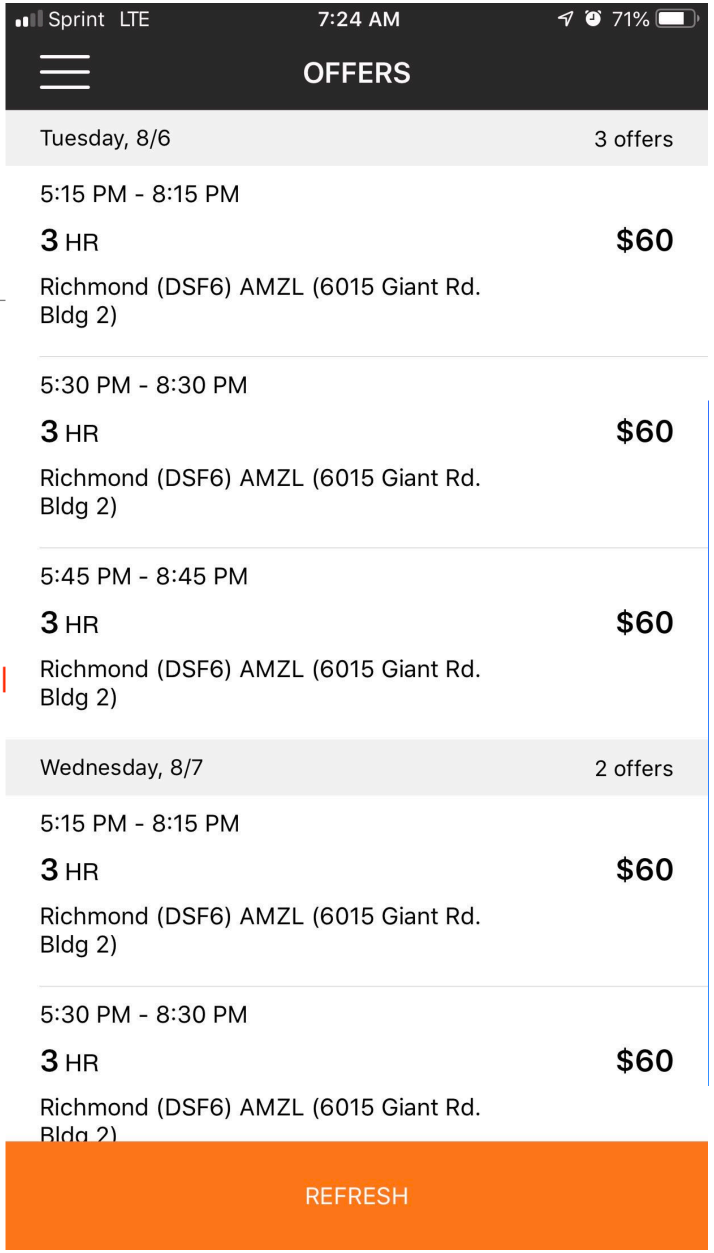
Definition of Crowdsourced delivery

- *"(an **informative connectivity** enabled **concept** that) **matches supply and demand** for logistics services with an **undefined and external crowd** that has **free** capacity with regards to **time** and/or **space**, participates on a **voluntary** basis and is compensated accordingly". (Rai et al., 2017)*

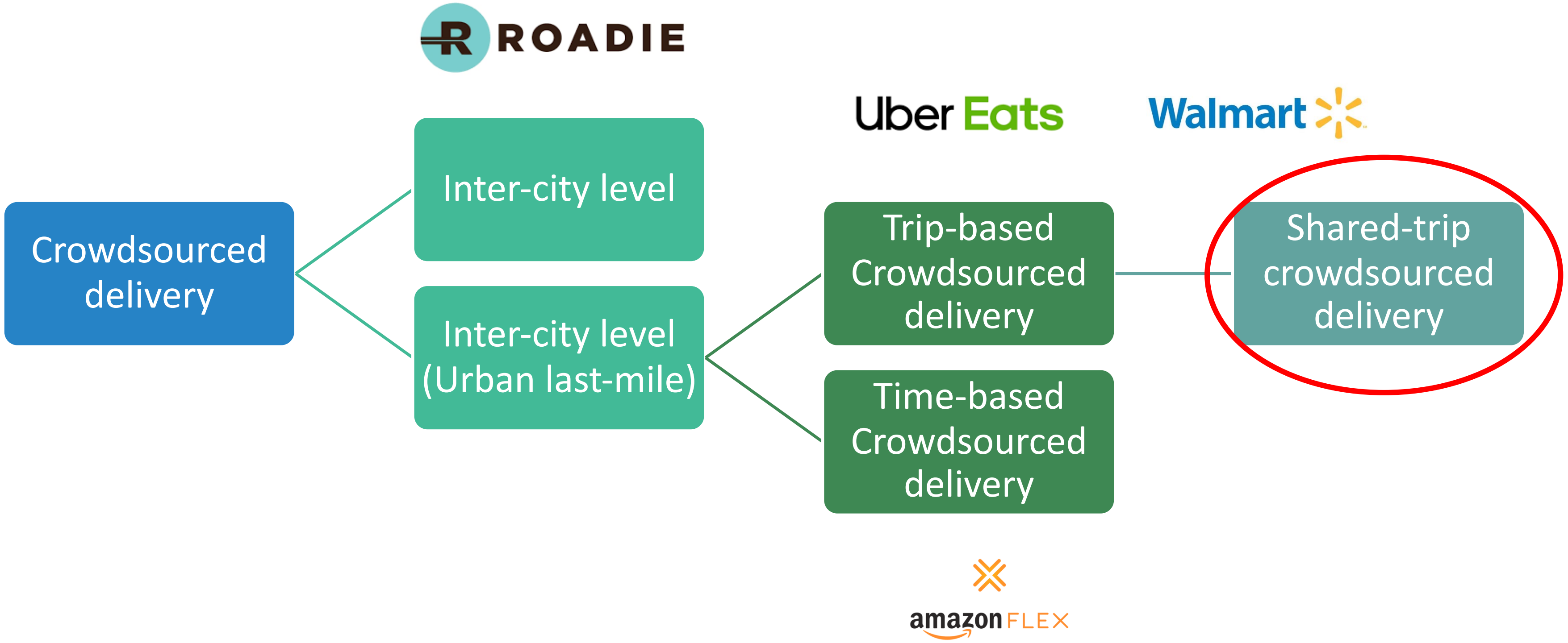
- *"a goods delivery **service** that is outsourced to **occasional carriers** drawn from the public of **private travelers** and is coordinated by **a technical platform** to achieve benefits for the involved stakeholders." (Punel and Stathopoulos, 2017)*

Examples of Crowdsourced delivery

- Roadie contracts drivers for inter-state package delivery.
- Uber Eats partners with drivers for meal delivery.
- Walmart contracts in-store customers to deliver packages for customers that ordered online.
- Amazon partners with gig drivers to deliver a set of tasks in a short period of time.



Types of Crowdsourced delivery



Benefits of Urban Crowdsourced delivery

Comparing to dedicated delivery

	Crowdsourced Time-based Delivery	Crowdsourced Trip-based Delivery	Crowdsourced shared-trip Delivery
For logistics companies	Saving investment in facilities; savings in labor cost		
For crowdsourced drivers	Additional income; may work full-time as a job		Additional income
For the society	Environmental benefit from replacing trucks by small size vehicles		Reduced VMT, reduced emission

Literature Review

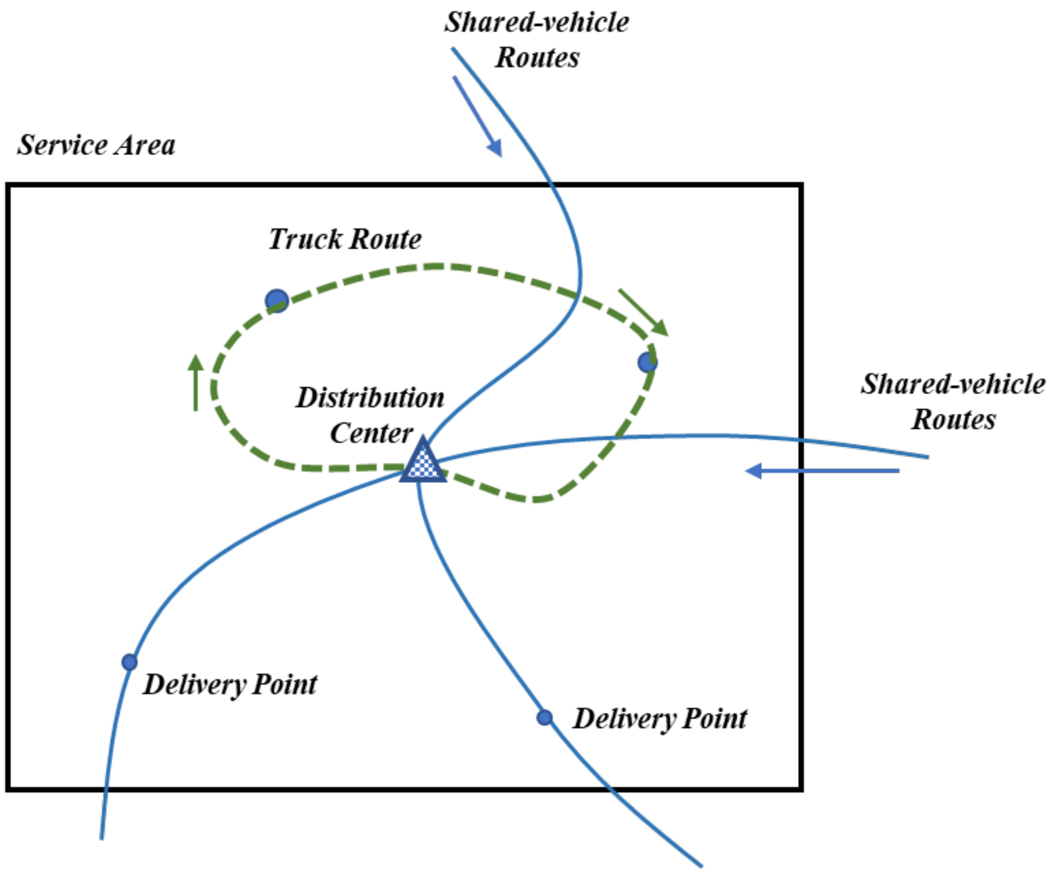
- Operational details
  - Assignment of parcels to vehicles
  - Routing of vehicles
  - Scheduling of drivers
- Planning and management of capacity
  - Number of crowdsourced drivers to contract with
  - Dedicated fleet acquiring
- Pricing and compensations
  - Price charged to customers
  - Compensations paid to crowdsourced drivers

Static Routing, dynamic routing in relatively small scale

This study:

- Aiming large scale problems;
- What packages should be handled by crowdsourced vehicles and dedicated vehicles (trucks/vans)?
- Cost/VMT savings?

Problem Description



- ✓ A distribution center in the service area (DC)
- ✓ Drivers with extra capacity in personal vehicles traveling to DC.
- ✓ Shared personal vehicles (SPVs) pick up package(s) from the DC
- ✓ SPVs deliver packages to delivery points
- ✓ SPVs travel to own destinations after delivery
- ✓ Time windows for both SPVs and packages exist
- ✓ Dedicated vehicles (DVs or trucks) are also considered in matching/routing procedure

Crowdsourced shared-trip delivery

- ❑Mixed fleet (SPVs and DVs) routing problem
- ❑One DC, Single-hop (No transfer of packages)
- ❑Open vehicle routing for SPVs
- ❑Capacitated vehicle routing for SPVs and DVs
- ❑The objective is to minimize total cost of delivering a set of packages
- ❑Formulation 1 based on VRP

?

Why formulate it as a VRP type of problem?

- The most natural method of handling routing problem
- Able to capture all components of a routing problem
- Search potential solution algorithms from VRP literature

Mathematical Model --- Formulation 1

MFOCVRPTW (Mixed Fleet Open Capacitated Vehicle Routing Problem with Time Window)

$$\min_{x,z,t,u} \boldsymbol{\Theta}_1 = \sum_{k\in S}\left(z_{s_k}\left(\left(c_{0s_k} + \sum_{(i,j)\in A} c^{s}_{ij}x^{k}_{ij} - c_{s_k}\right) + e\times\left(\sum_{(i,j)\in A} x^{k}_{ij} - 1\right)\right)\right) + \sum_{k\in D}\sum_{(i,j)\in A} c^{d}_{ij}x^{k}_{ij} + \sum_{k\in D} F_d u_k \quad (3.1)$$

Binary Indicator variable, equals 0 if an SPV is not used

*Total **Detour** cost of an SPV, i.e., Total distance travelled – original O/D Shortest Path*

Compensation for each for SV

DV Routing Cost + DV Fixed cost

$$\sum_{j\in\{N_p,N_{sv}\},j\neq i}\sum_{k\in V} x^{k}_{ij} = 1, \quad \forall i \in \{N_p\} \quad (3.2)$$

$$\sum_{i\in\{0,N_p\},i\neq j}\sum_{k\in V} x^{k}_{ij} = 1, \quad \forall j \in N\backslash\{h\} \quad (3.3)$$

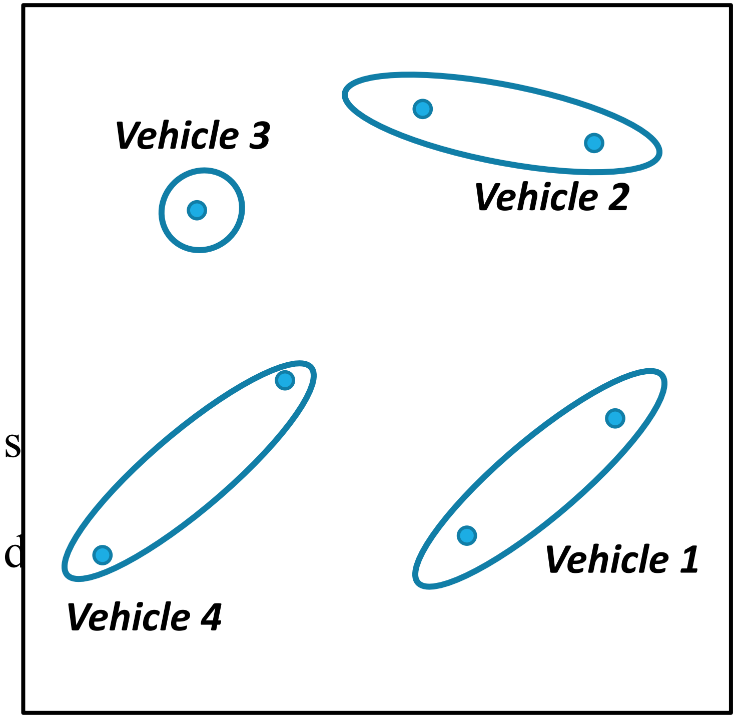
$$\sum_{i\in\{0,N_p\},i\neq j}\sum_{k\in V} x^{k}_{ij} - \sum_{l\in\{N_p,N_{s_v}\},l\neq j}\sum_{k\in V} x^{k}_{jl} = 0, \quad \forall j \in \{N_p\} \quad (3.4)$$

$$\sum_{j\in\{N_{p_i}\}} x^{k}_{0j} - \sum_{i\in\{N_{p_i}\}} x^{k}_{i,h} = 0, \quad \forall k \in D \quad (3.5)$$

(3.2) To (3.5) are standard VRP routing constraints;

Mathematical Model --- Formulation 2

Set Partitioning Formulation



Why set partitioning formulation?

- Partition packages to several disjoint subsets ---- slightly easier task
- Enumerate vehicle routes (different disjoint subsets, different cost)
- Assignment problem ---- minimize the assignment cost

Decision Variables

$y^{s}_{i,k}$, binary decision variable; Whether the i^{th} feasible route of $vehicle\ k$ from s

$y^{d}_{i,k}$, binary decision variable; Whether the i^{th} feasible route of $vehicle\ k$ from d

Parameters

$a^{s}_{i,j,k}$, binary, whether route i of SPV k could serve package j
$c^{s}_{i,k}$, cost of route i of SPV k
$c^{d}_{i,k}$, cost of route i of DV k

Mathematical Model --- Formulation 2

Set Partitioning Formulation

$$\min_{y} \; \Theta_2 = \sum_k \Big(\sum_i y_{i,k}^s \times c_{i,k}^s - c_{s_k} \Big) + e \times \sum_k \sum_j a_{i,j,k}^s \times y_{i,k}^s + \sum_k \sum_i y_{i,k}^d \times c_{i,k}^d \quad (3.17)$$

*Total **Detour** cost of a route of SPV k* | *Compensation for SPV del packages* | *Total DV cost*

subject to

$$\sum_k \sum_j a_{i,j,k}^s \times y_{i,k}^s + \sum_k \sum_j a_{i,j,k}^d \times y_{i,k}^d = 1, \forall i \in \{N_p\} \quad (3.18)$$

Package must be served either by an SPV or a DV

$$\sum_i y_{i,k}^s = 1, \forall k \in S \quad (3.19)$$

$$\sum_i y_{i,k}^d = 1, \forall k \in D \quad (3.20)$$

Each SPV or DV could have only one active route

$$y_{i,k}^s, y_{i,k}^d \in \{0,1\} \quad (3.21)$$

Solution Algorithm

Decomposition Heuristic (Algorithm 1)

(If) Enumerate all possible routes for SPVs and DVs → (Maybe) able to match packages to specific routes → Solve the problem

Large-scale linear assignment problem

Enumerate paths for SPVs? → Possible, an SPV has a starting and ending time (Budget) and a pair of O/D

Enumerate paths for DVs? → Hard, need to cover a necessary set of nodes in order to guarantee feasibility of the problem

→ ***Decompose SPV and DV, matching separately***

Solution Algorithm

Decomposition Heuristic (Algorithm 1)

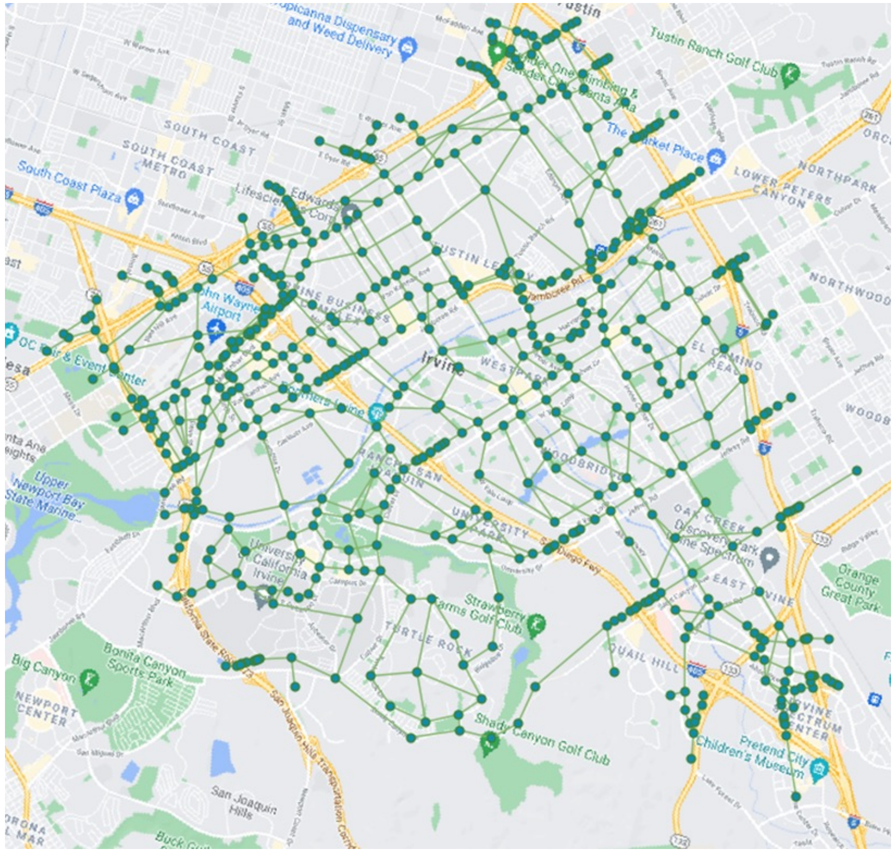
- ***Initialization***: *Slice the total SPV set to m subsets with roughly the same number, start with a random subset of SPVs.*
- ***Step 1***: *SPV Routes Generation. This step generates a set of possible routes for SPVs.* ***Budgeted k-shortest Path***
- ***Step 2:*** *Package-Shared Vehicle Assignment Problem (SVAP). This problem is close to a bi-partite matching problem and could be efficiently solved.* ***A Large-scale non-linear assignment problem***
- ***Step 3:*** *Route DV for a single VRP.* ***Vehicle routing problem***
- ***Step 4:*** *For packages served by SPVs, calculate the insertion cost of the SPV served package if it is served by the truck. Find the smallest one to insert to truck route. Adding additional truck cost to the insertion cost if the current load is larger than a truck load. Terminate when insertion cost > SPV service cost.* ***Package Switching***
- ***Step 5:*** *A Conventional VRP for packages assigned to DVs, reassign SPV set of packages.*
- ***Step 6:*** *Optimality check. Comparing the result with the current best solution, store the result if it < the current best solution.*
- ***Increment*** *SPV set by another subset of SPVs, repeat Step 1 to Step 6.* ***Incremental method to avoid local minimum***
- ***Terminate*** *when all SPVs are added.*

Algorithms

1. Subproblem 1: Budgeted k-shortest Paths
2. Subproblem 2: A Large-scale assignment problem
3. Subproblem 3: Vehicle routing problem for dedicated vehicles
4. Subproblem 4: Decision of package switching

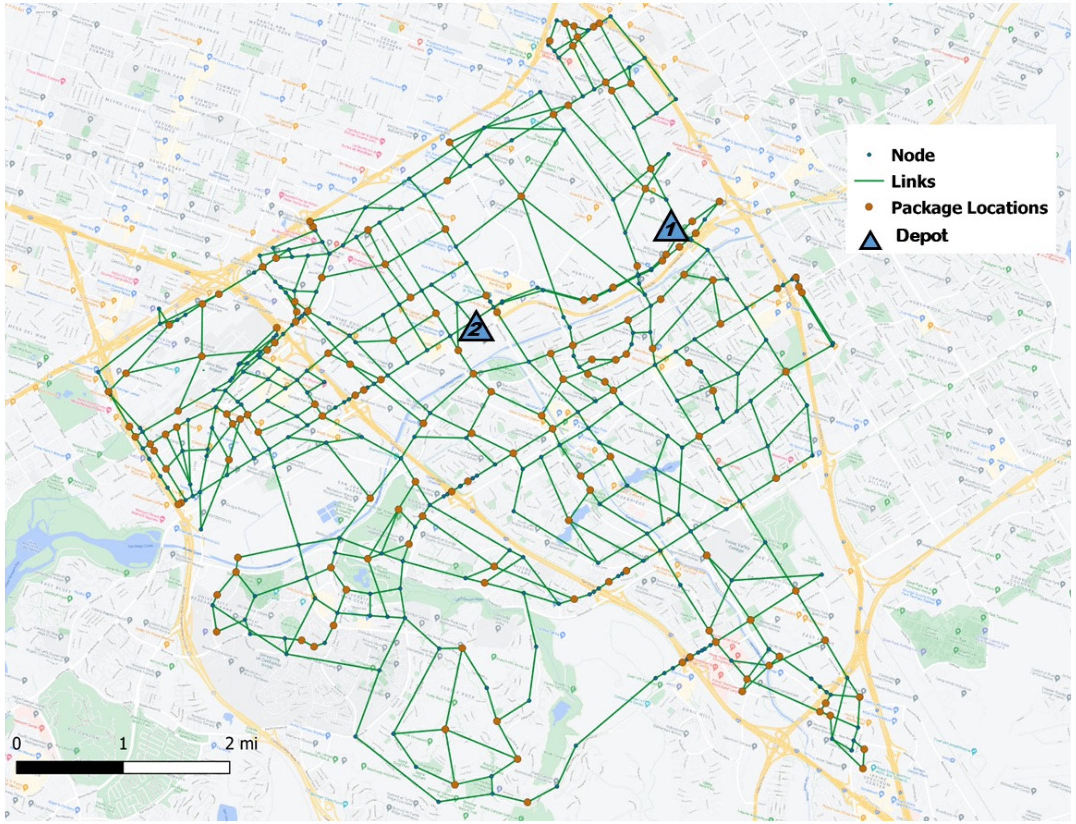
Yang, Dingtong and Hyland, Michael and Jayakrishnan, R, Tackling the Crowdsourced Delivery Problem at Scale Through a Set-Partitioning Formulation and Novel Decomposition Heuristic. Available at SSRN: https://ssrn.com/abstract=4055174 or https://arxiv.org/abs/2203.14719

Case Study



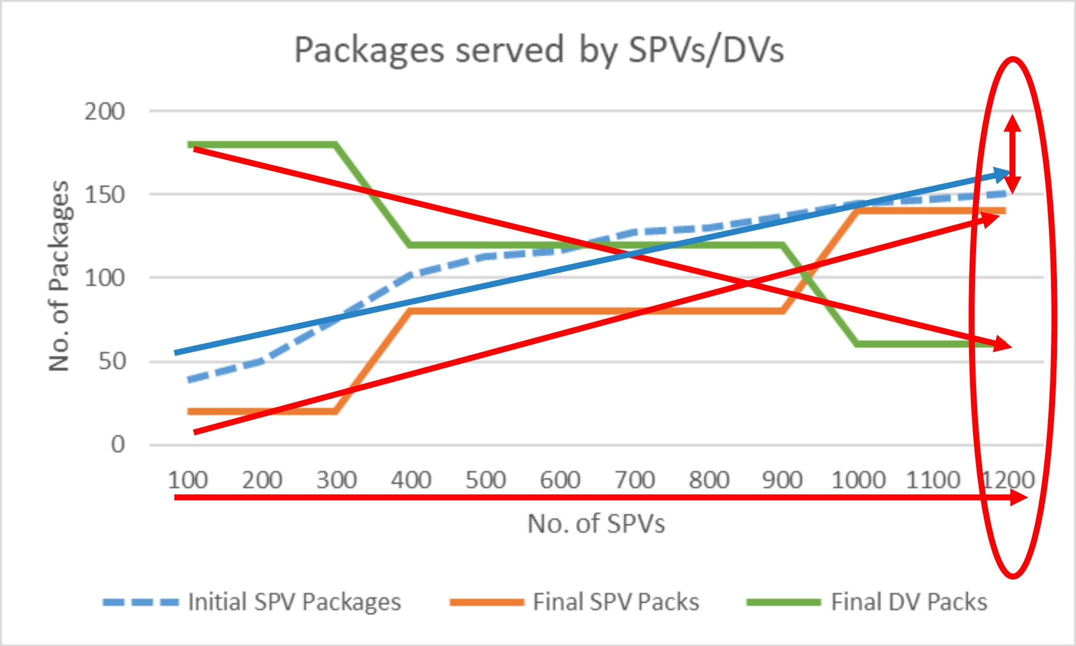
Parameter	Value
Area	City of Irvine
Depot location	156288
Number of nodes	607
Number of package orders	200
Number of SPVs	0 ~ 1,200
SPV capacity	1 ~ 4
SPV detour willingness	10, 15, 20, 25 $mins$
SPV detour compensation rate	\$ 0.56 $/mile$
SPV package deliver compensation	\$ 0.5 $/package$
DV capacity	60
DV per mile cost	\$ 0.56 $/mile$
DV fixed cost	\$ 120 $/vehicle$

Case Study



- Packages: randomly generated, uniformly distributed in the area
- SPV O/D Trips: Subarea analysis of California Statewide Travel Demand Model (CSTDM)
- Depot Location: One on the boundary (Base case), one in the center (sensitivity). Both are large grocery stores

Result – Number of packages served



With the increase in No. of SPVs:

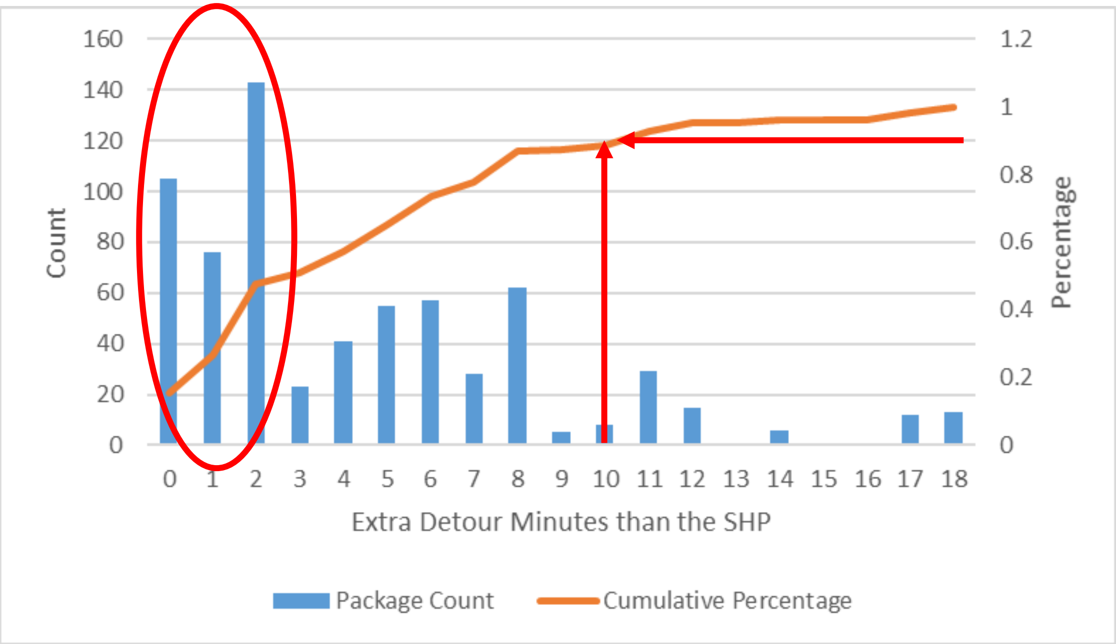
Step-wise increase in SPV served packages;
Step-wise decrease in DV served packages

1. Once a DV is used, it is the most cost efficient to fill up the DV to full truck load

2. The No. of initial SPV served packages has a linear relation with the number of SPVs

3. Even with high number of SPVs, highly likely DV service is still required

Result – Packages served by SPV



Out of all packages served by SPV:

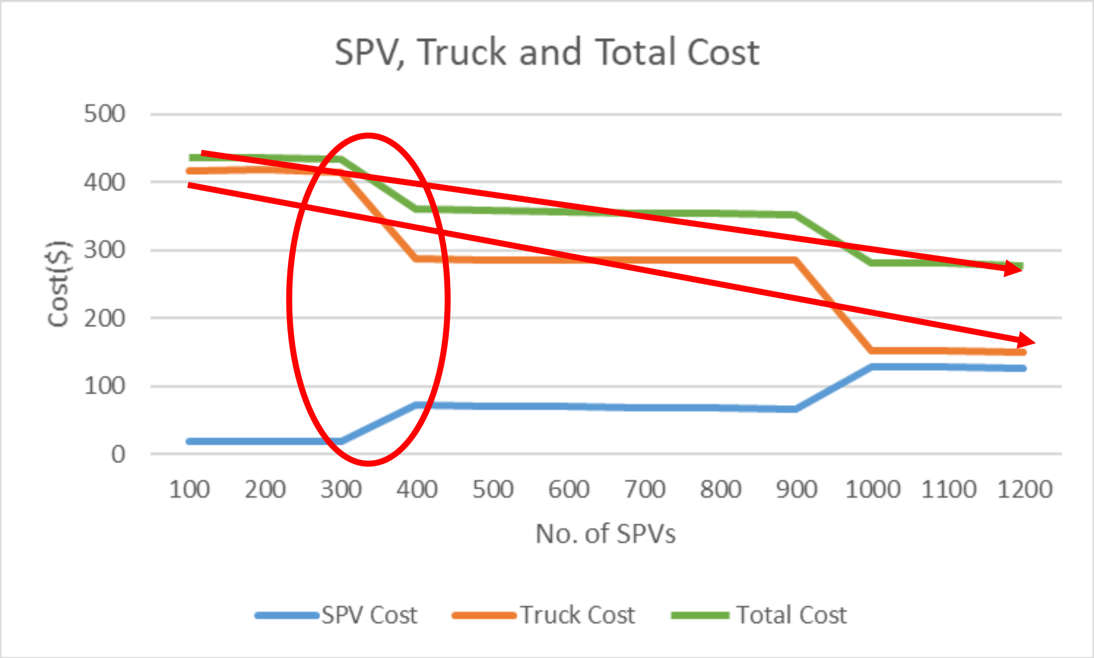
60%+ are served by vehicles with no more than 2 mins detour

90% are served by vehicles with no more than 10 mins detour

In Step 1 of vehicle route generation, vehicles doesn't necessarily need a large budget for the system to be effective

A small budget also reduces computational time

Result – Delivery Cost

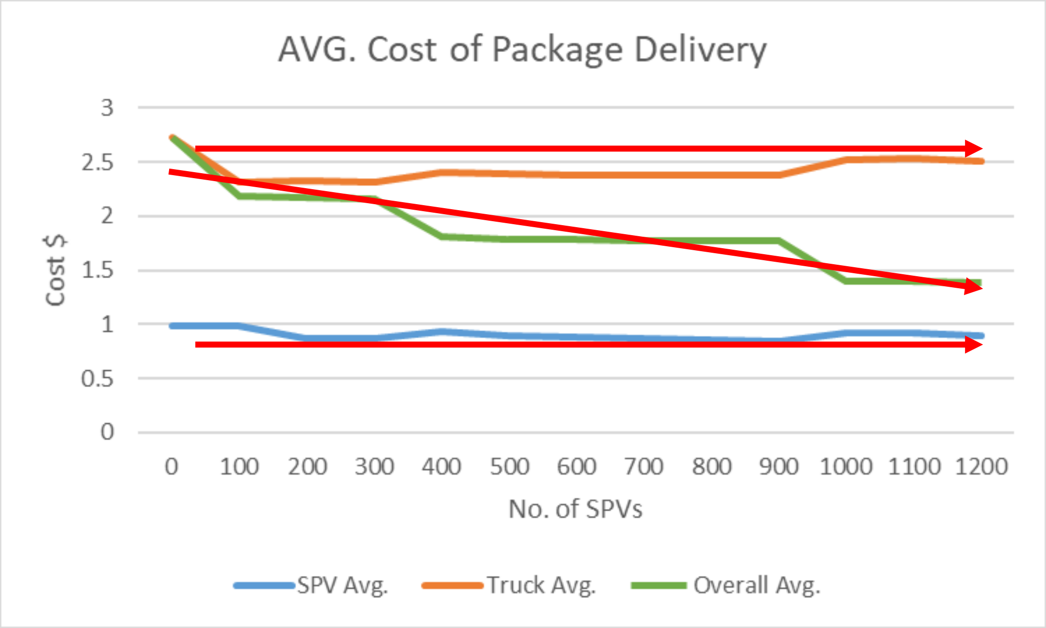


1. Step-wise change again: Using DV to full-load is the most cost-efficient

2. Total cost savings from 20% to 50%

3. Major savings from DV side, due to reduced number of DV usage (facility cost)

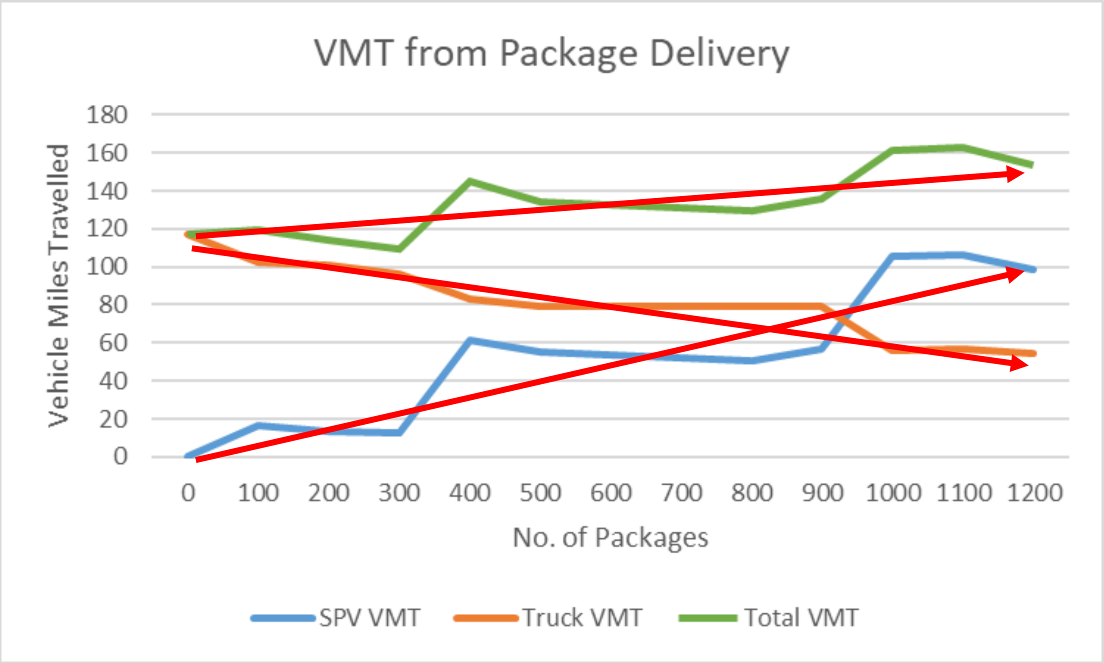
Result – Delivery Cost



1. Average cost to serve a package by SPV and DV are both stable;

2. Average cost to serve a package by the system is reducing as No. of SPVs increases

Result – VMT

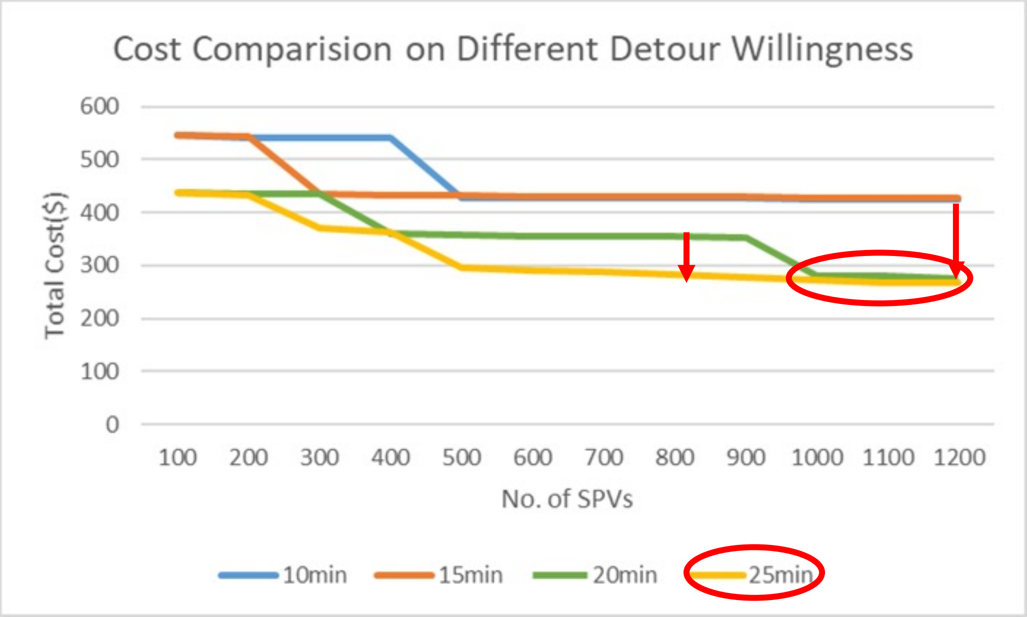


1. More SPV usage leads to more VMT

Does it mean crowdsourced delivery is not environmentally-friendly?

Depends, if we use sedan-size SPVs to replace large size vehicles (trucks) in delivery, which may lead to even less emission

Result – Detour Willingness

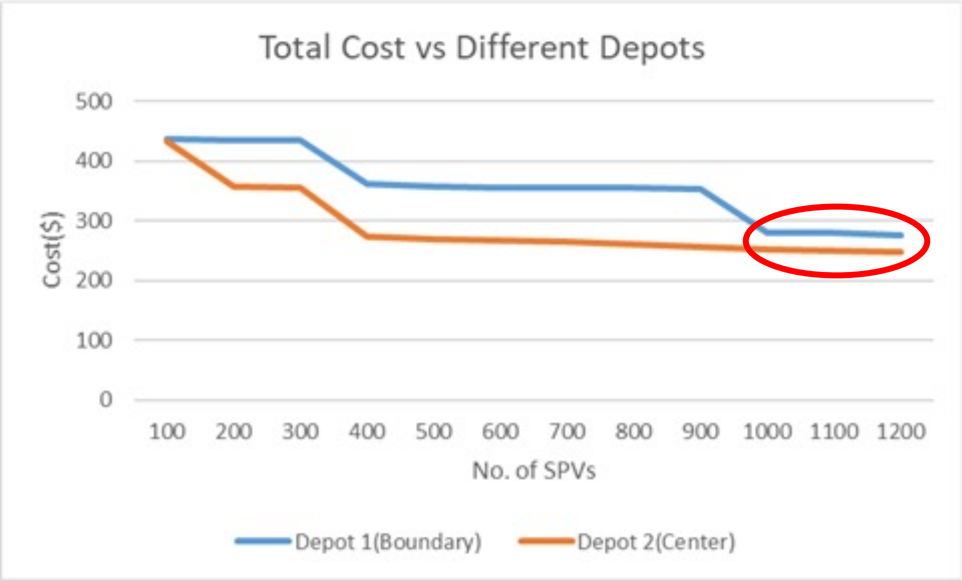


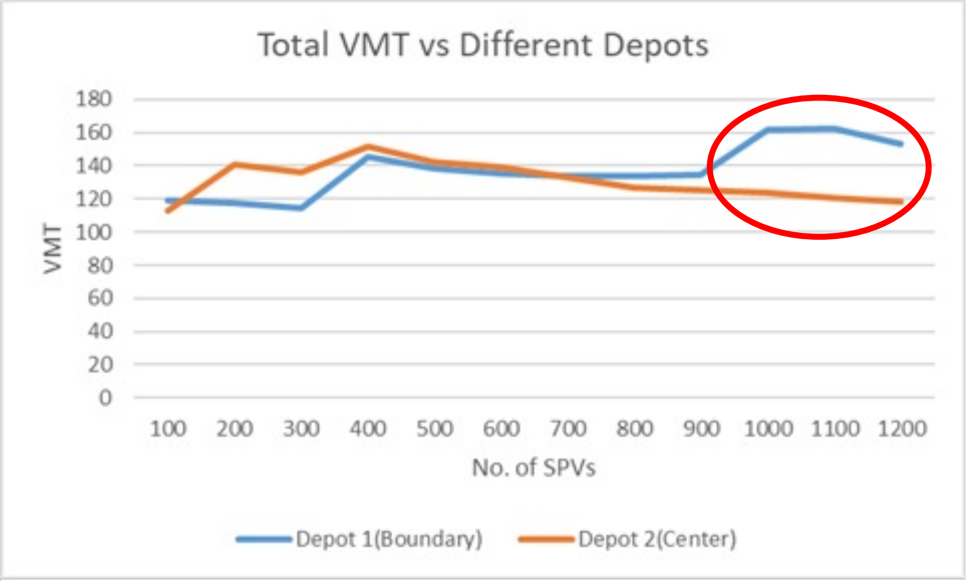
Longer detour willingness of SPVs leads to less total cost than the total cost of shorter ones

The total cost between 20-min and 25-min detour willingness are close for large number of vehicles

Detour willingness does not need to be too long; When the number of SPV is large, the impact of detour willingness is not significant.

Result – Depot location





When the number of SPVs is large, the impact of depot location on cost is insignificant

Center located depot could save VMT at around 20% comparing to boundary located depot

Companies may not need to have depots in popular area, but the crowdsourced delivery service needs large number of vehicles to be effective.

Findings and Conclusions

- **Cost savings range from 20% to 50%**
- **Most cost savings are from reduced facility cost**
- **VMT savings depends on the SPV origin to the depot**
- **Longer driver detour willingness produce better results, but it is not a necessity**
- **90% packages are served by routes within 10 mins detour**
- **Center located depot reduces cost**
- **Large number participated drivers mitigates the impact of low detour willingness and boundary located depot**

The End

Thanks !

Tackling the Crowdsourced Delivery Problem at Scale Through a Set-Partitioning Formulation and Novel Decomposition Heuristic. Available at SSRN: https://ssrn.com/abstract=4055174 or arXiv: https://arxiv.org/abs/2203.14719