Express Package Delivery Optimization Using On-Foot Personnel, Cargo Tricycles and Delivery Trucks

A Case Study for Downtown Toronto

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Agenda

1. Introduction
2. Research Context
3. Methods
4. Results
5. Discussion
6. Conclusion

1.1 Introduction

- Vehicle Routing: an industry-wide challenge
- Urban delivery modes
  - Existing: walk, van
  - Emerging: cargo bicycles
- Idea: Viability of Cargo Bicycles

Figure 1. Cargo bicycle and delivery van (Yokler, 2019)

1.1 Introduction

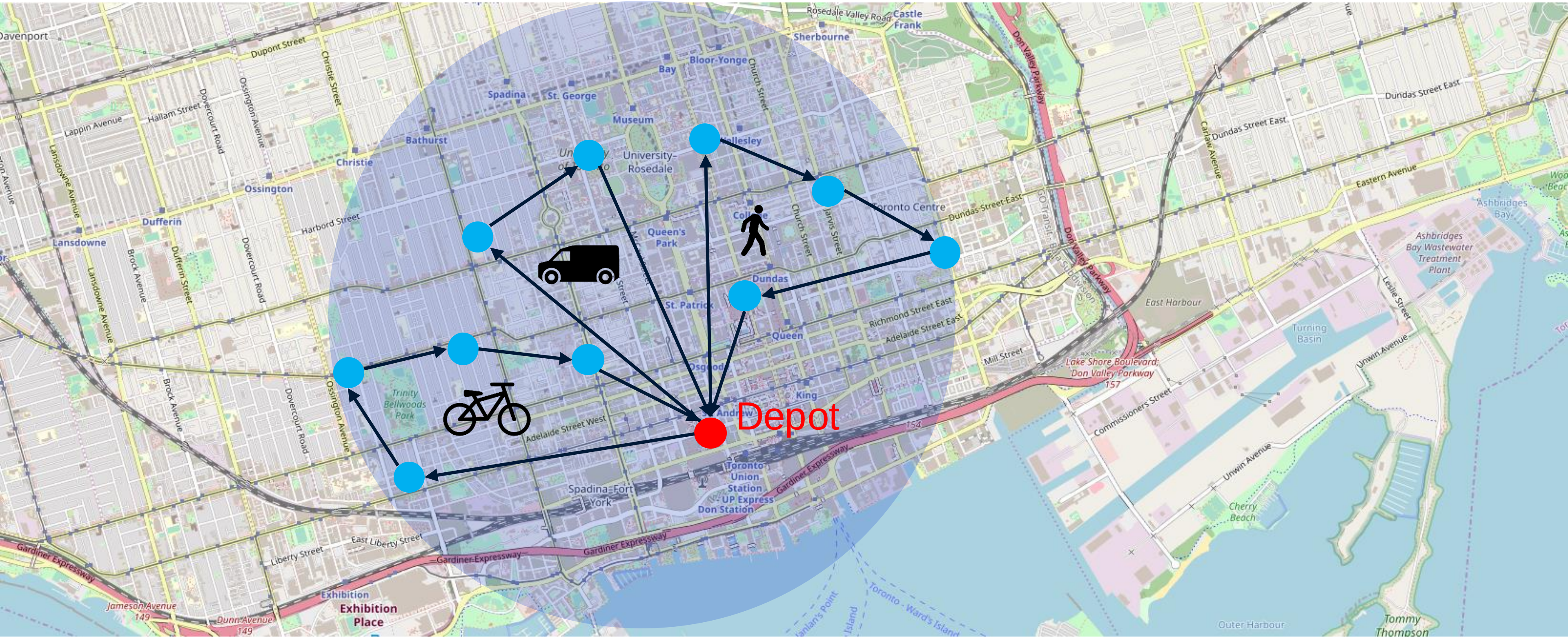
IMPLEMENTATION IN THEORY

- **V**ehicle **R**outing **P**roblem with **M**ultiple **V**ehicle **T**ypes and **T**ime **W**indows **(VRPMVTTW)**

1.1 Introduction

THIS PROJECT

- Development of a VRPMVTTW heuristic solver
- Application to Toronto Case Study



2.0 Research Context

- **The Vehicle Routing Problem**
- **VRPMVTTW**
- **Cargo Bike Technologies**

2.1 Research Context

THE VEHICLE ROUTING PROBLEM

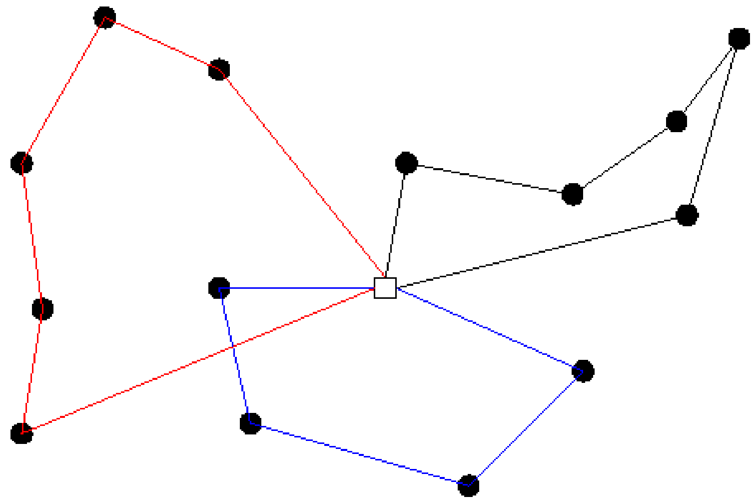


Figure 2. Graphical Representation of the Vehicle Routing Problem (NEO, 2018)

2.1 Research Context

THE VEHICLE ROUTING PROBLEM

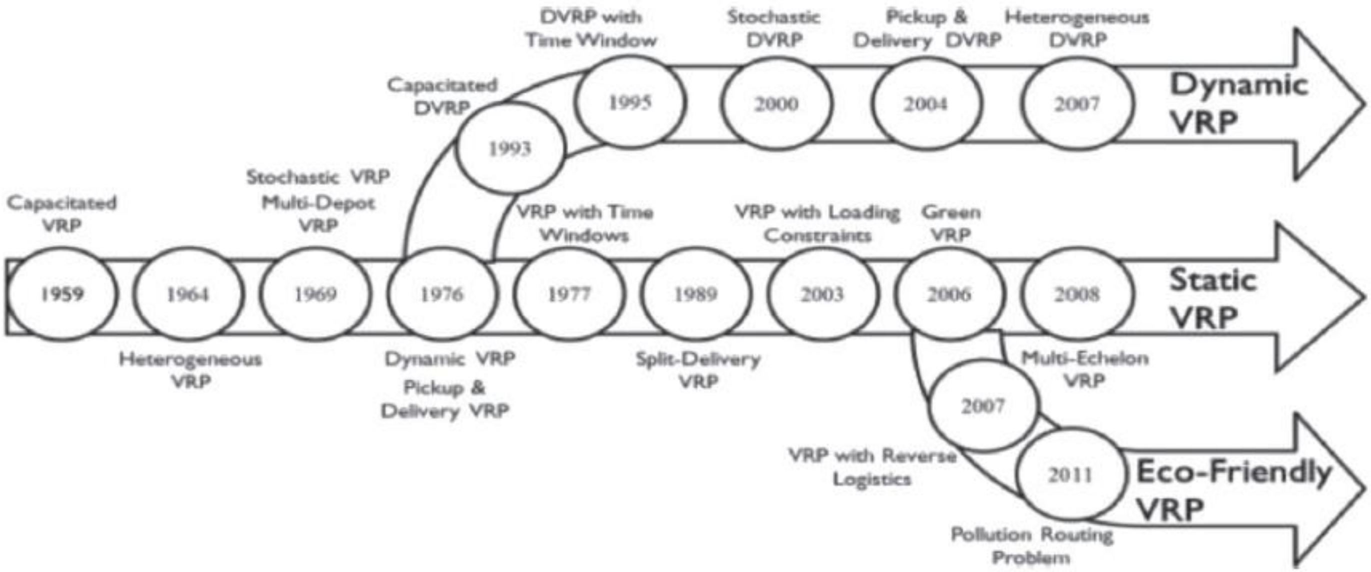


Figure 3. Historical progression of vehicle routing research (Kim et al., 2015)

2.2 Research Context
VRPMVTTW

- **Ferland & Michelon (1988)**
  - Formulate and define the problem
  - Propose three heuristic methods:
    1. Discrete approximation of time windows
    2. Iterative generation and improvement upon feasible solutions
    3. Division of problem into subsets
- **Liu & Shen (1999)**
  - Comparison of heuristic method performance
  - Proposed Heuristic:
    - Sequential insertion of demand points into trip chains

2.3 Research Context

CARGO BIKE TECHNOLOGIES

- Address last-mile challenges
- Suitable for downtown operation
- Applicable when depot is close to demand

Figure 4. Cargo bicycle from The Drop Distribution in Toronto (The Drop, 2019)

3.0 Methods

- **Selection of VRPMVTTW Heuristic**
- **VRPMVTTW Solver Implementation**
- **Problem Formulation**
- **Case Study Application**

3.1 Methods

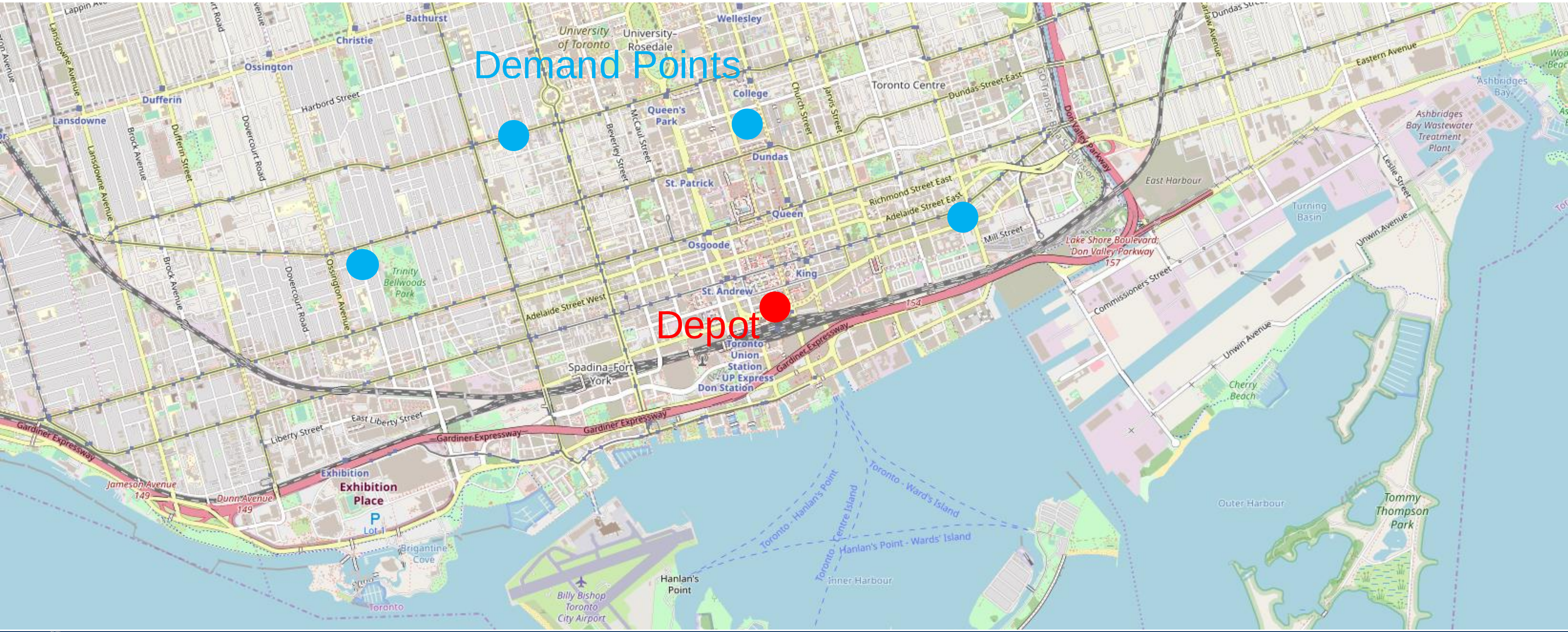
SELECTION OF VRPMVTTW HEURISTIC

- Basis: Liu & Shen (1999)
- Modifications:
  - Waiting costs
  - Service time costs
  - Consideration of all modes
  - Revised time window and service time feasibility constraints

3.3 Methods

VRPMVTTW SOLVER IMPLEMENTATION

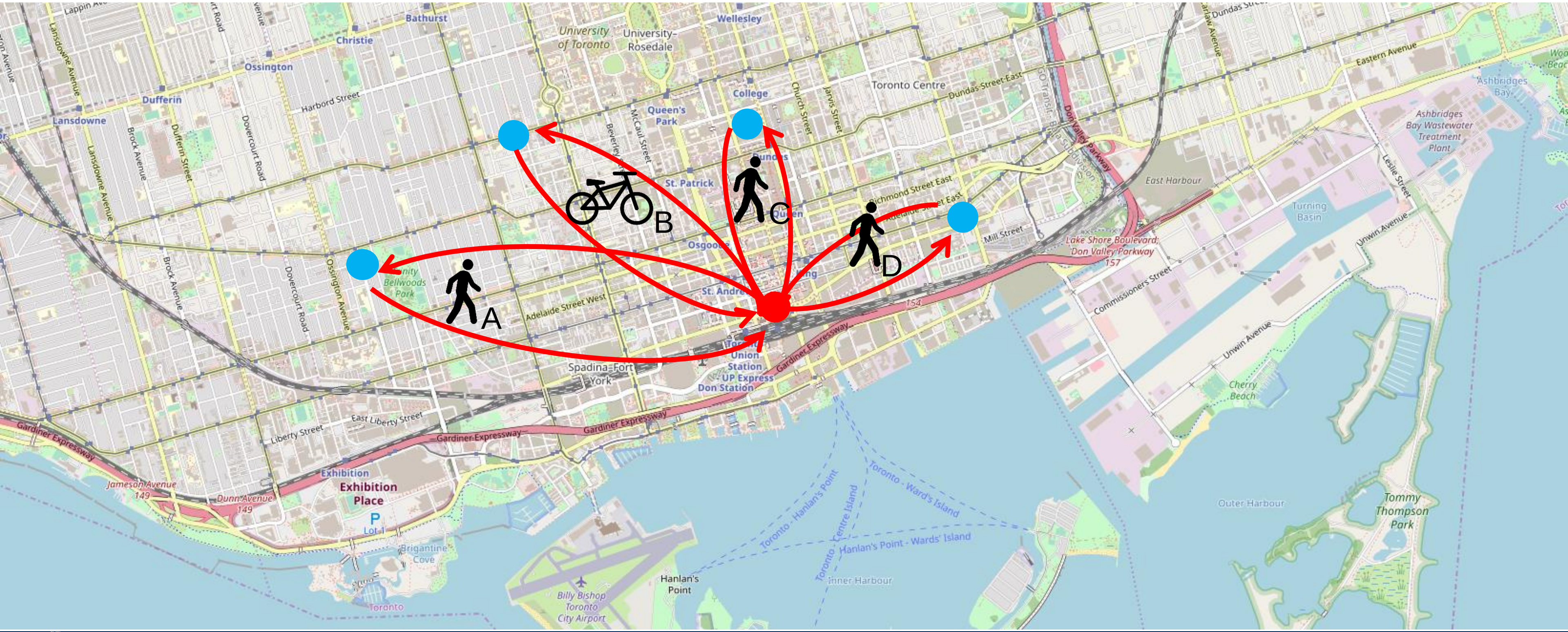
- Identify depot and demand points



3.3 Methods

VRPMVTTW SOLVER IMPLEMENTATION

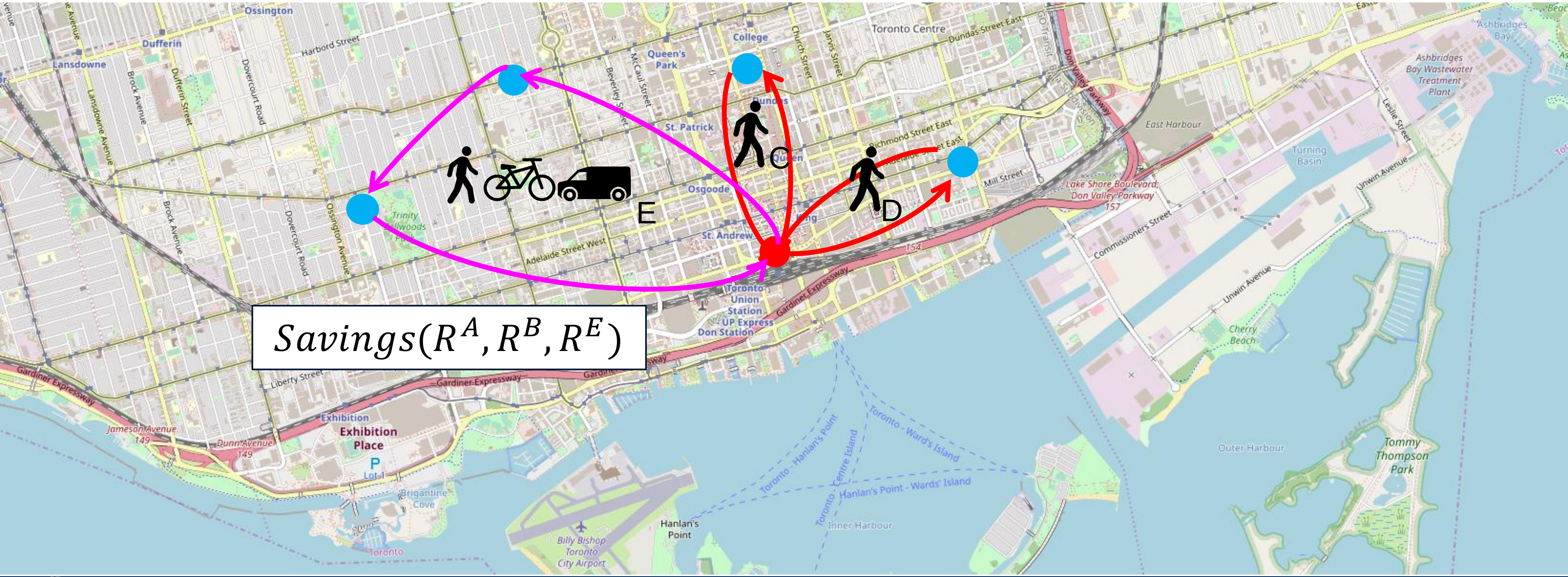
- Initiate all routes $[0, i, 0]$ with smallest feasible vehicle



3.3 Methods

VRPMVTTW SOLVER IMPLEMENTATION

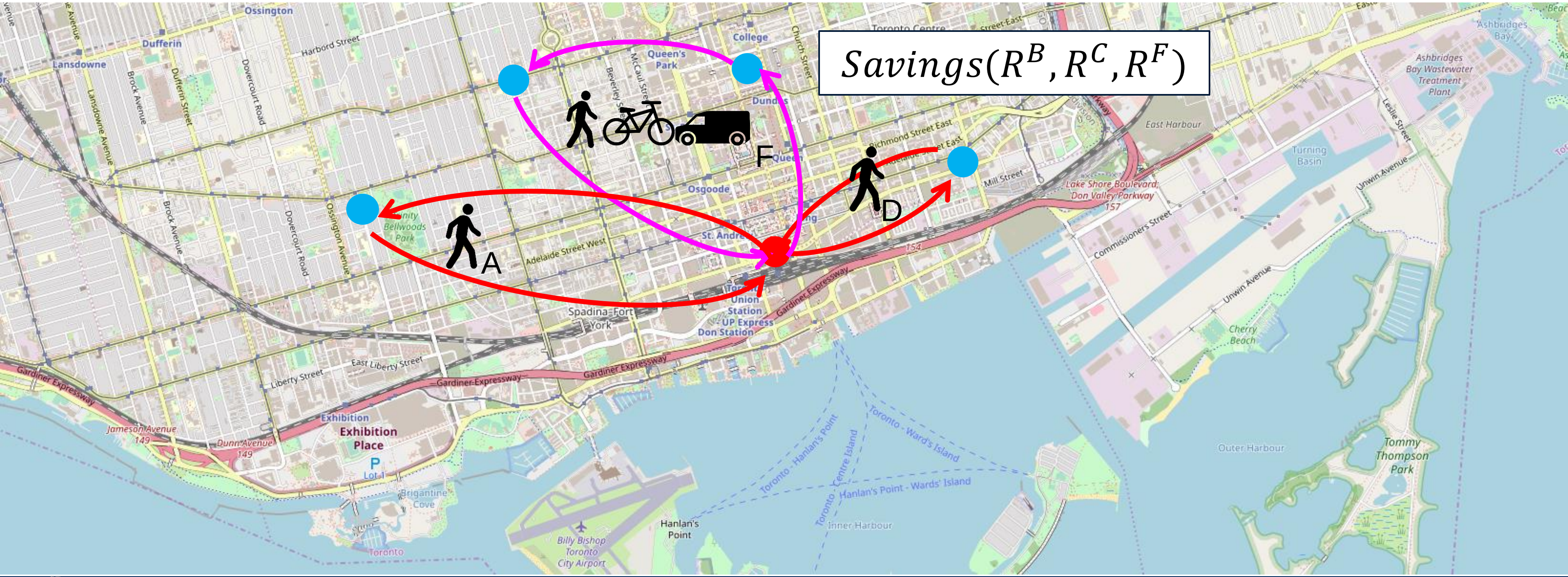
- Route Insertion:
  - Feasibility check and savings calculation (for all potential combinations)



3.3 Methods

VRPMVTTW SOLVER IMPLEMENTATION

- Savings Calculation:
- Consider travel cost, upfront cost, departure times, value of excess capacity



3.3 Methods

VRPMVTTW SOLVER IMPLEMENTATION

- Savings Calculation:
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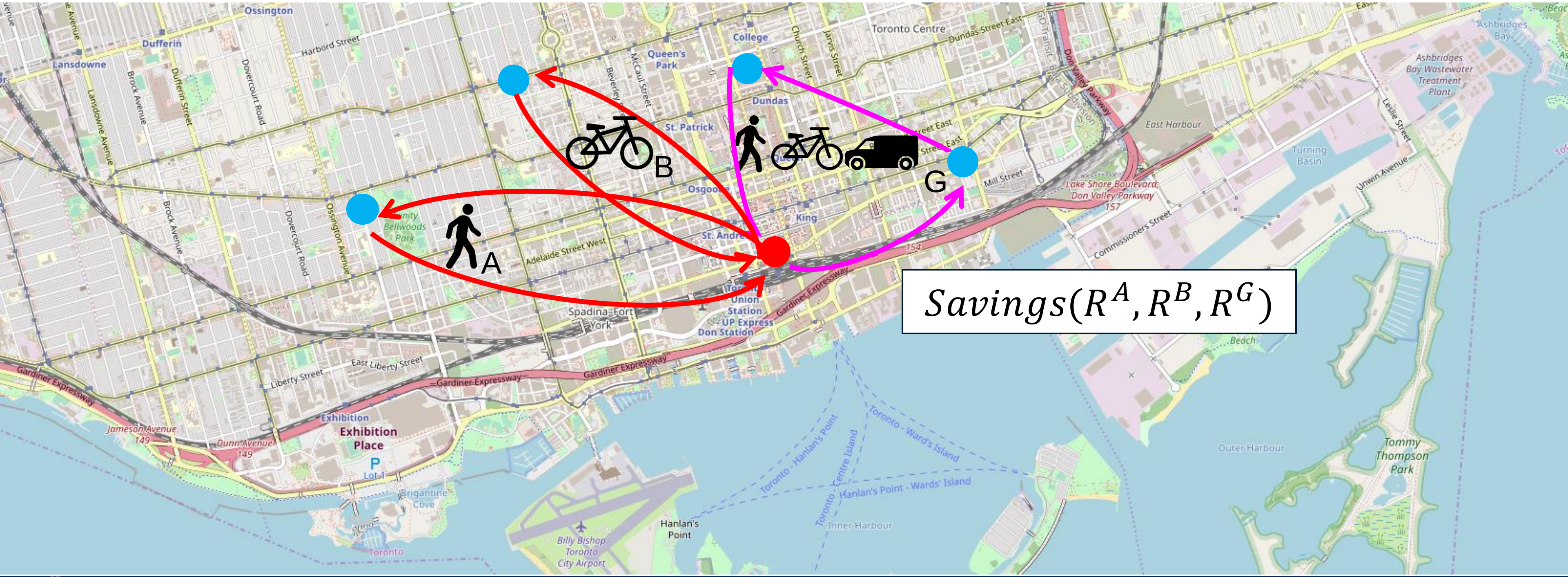
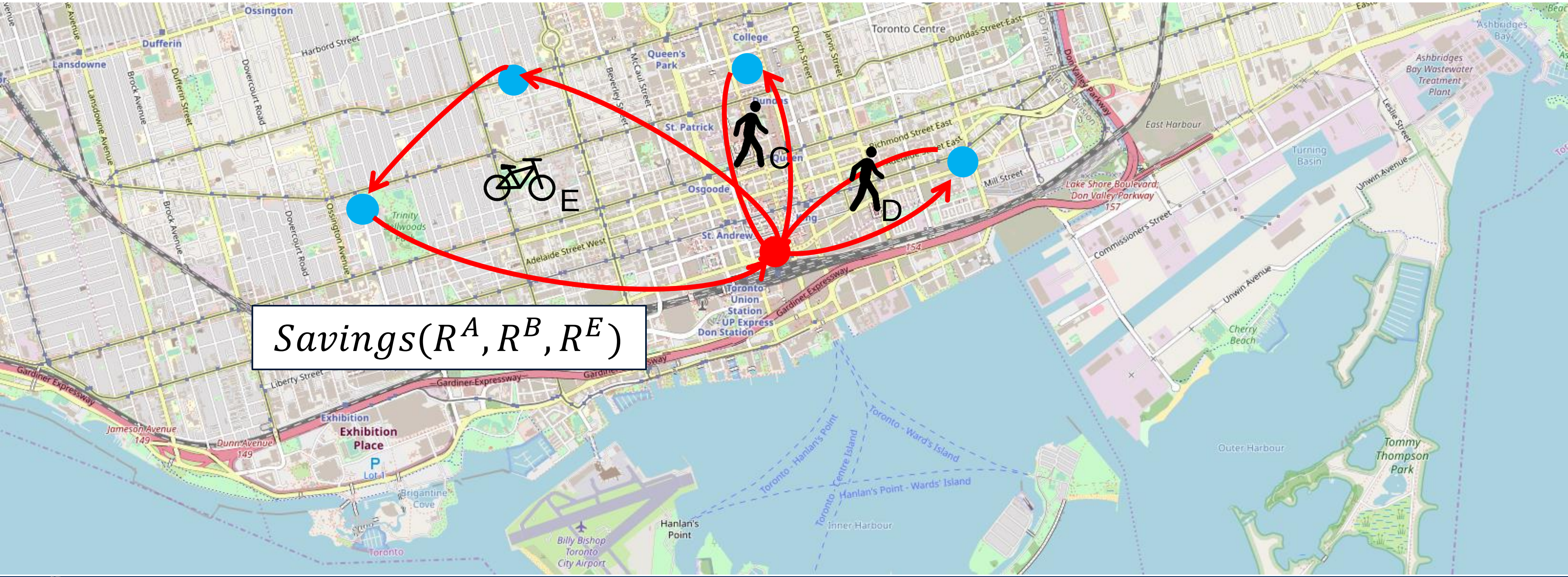


3.3 Methods

VRPMVTTW SOLVER IMPLEMENTATION

- Route Insertion:
  - According to maximum savings combination



3.1 Methods

PROBLEM FORMULATION: OBJECTIVE

Cost Function = Cost of Travel + Waiting Time Cost + Service Time Cost + Upfront Vehicle Cost

- Adapted from Munari, Dollevoet, Spillet (2017)
- Demand points numerated i, j
- Vehicle types numerated k
- Costs: $\boldsymbol{C_{ij}^k}, \boldsymbol{W^k}, \boldsymbol{S^k}, \boldsymbol{F^k}$
- Wait time: w^k
- Nodes serviced by vehicle type k: c^k
- Vehicles of type k: u^k

3.2 Methods

PROBLEM FORMULATION: OBJECTIVE

$$\min \sum_{k=1}^{K} \left(\sum_{(i,j)\in\mathcal{E}} (C_{ij}^k x_{ij}^k) + W^k \sum_{i=1}^{n} w_i^k + S^k c^k + F^k u^k \right)$$

- Adapted from Munari, Dollevoet, Spillet (2017)
- Demand points numerated i, j
- Vehicle types numerated k
- Costs: $\boldsymbol{C_{ij}^k}, \boldsymbol{W^k}, \boldsymbol{S^k}, \boldsymbol{F^k}$
- Wait time: w^k
- Nodes serviced by vehicle type k: c^k
- Vehicles of type k: u^k

3.2 Methods

PROBLEM FORMULATION: CONSTRAINTS

- Each customer serviced once
- Flow of vehicles internally consistent
- Capacity constraints
- Time window constraint

3.2 Methods

SAVINGS FUNCTION

- Consider: travel cost, upfront cost, departure times, value of excess capacity
- Function Parameters: α and β
  - α: trade off between cost savings and departure time
  - β: preference for sequential construction

3.4 Methods

CASE STUDY APPLICATION

- Application to downtown Toronto express courier operations
- Last mile delivery operations

3.4 Methods

CASE STUDY: VEHICLE CHARACTERISTICS

Vehicle Type	Avg. Speed (km/h)	Volume Capacity (m^3)	Operating Cost ($/min)	Waiting/ Service Cost ($/min)	Service Time (min)
Delivery Van	24.0 km/h	6.787 m^3	$1.129	$1.017	4.16 min
Cargo Bike	17.7 km/h	2.000 m^3	$0.720	$0.720	3.33 min
Walking	5.0 km/h	0.085 m^3	$0.635	$0.635	2.75 min

Figure 5. Case study vehicle characteristics

3.4 Methods

CASE STUDY: DEMAND DISTRIBUTION

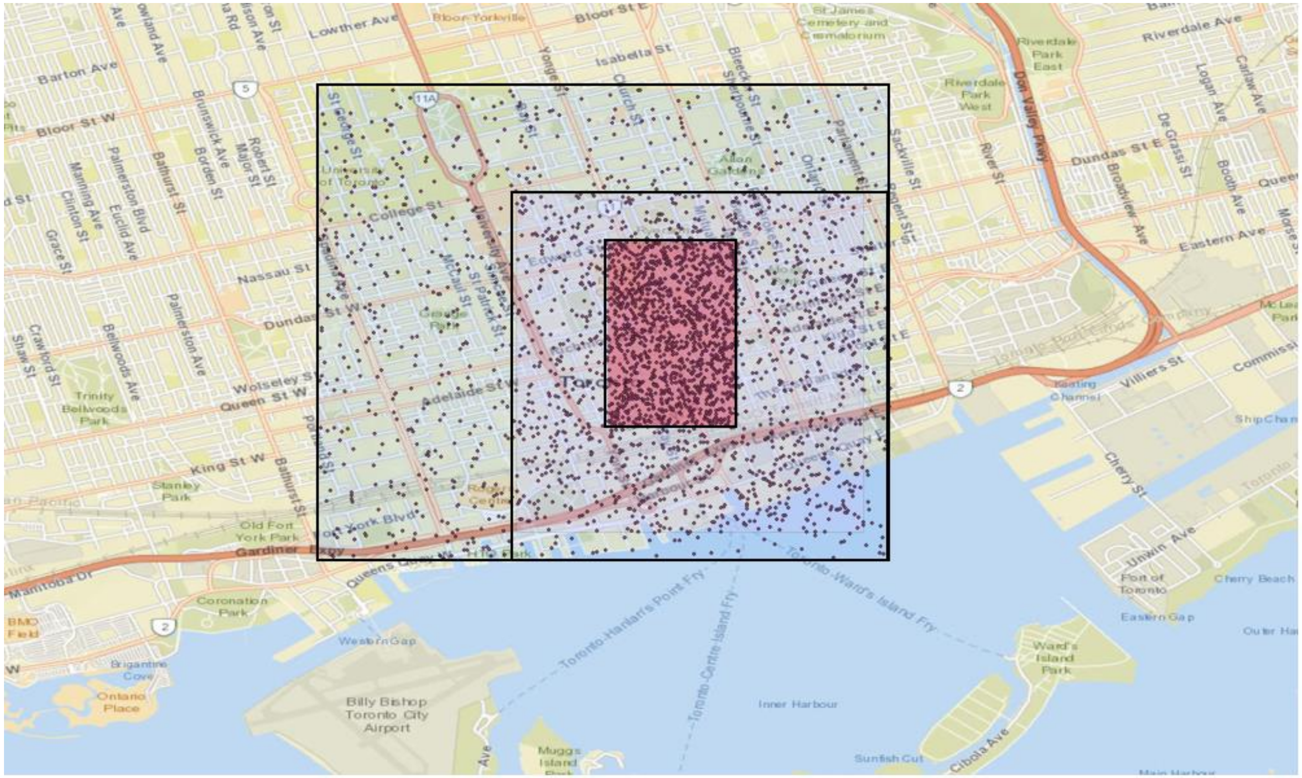


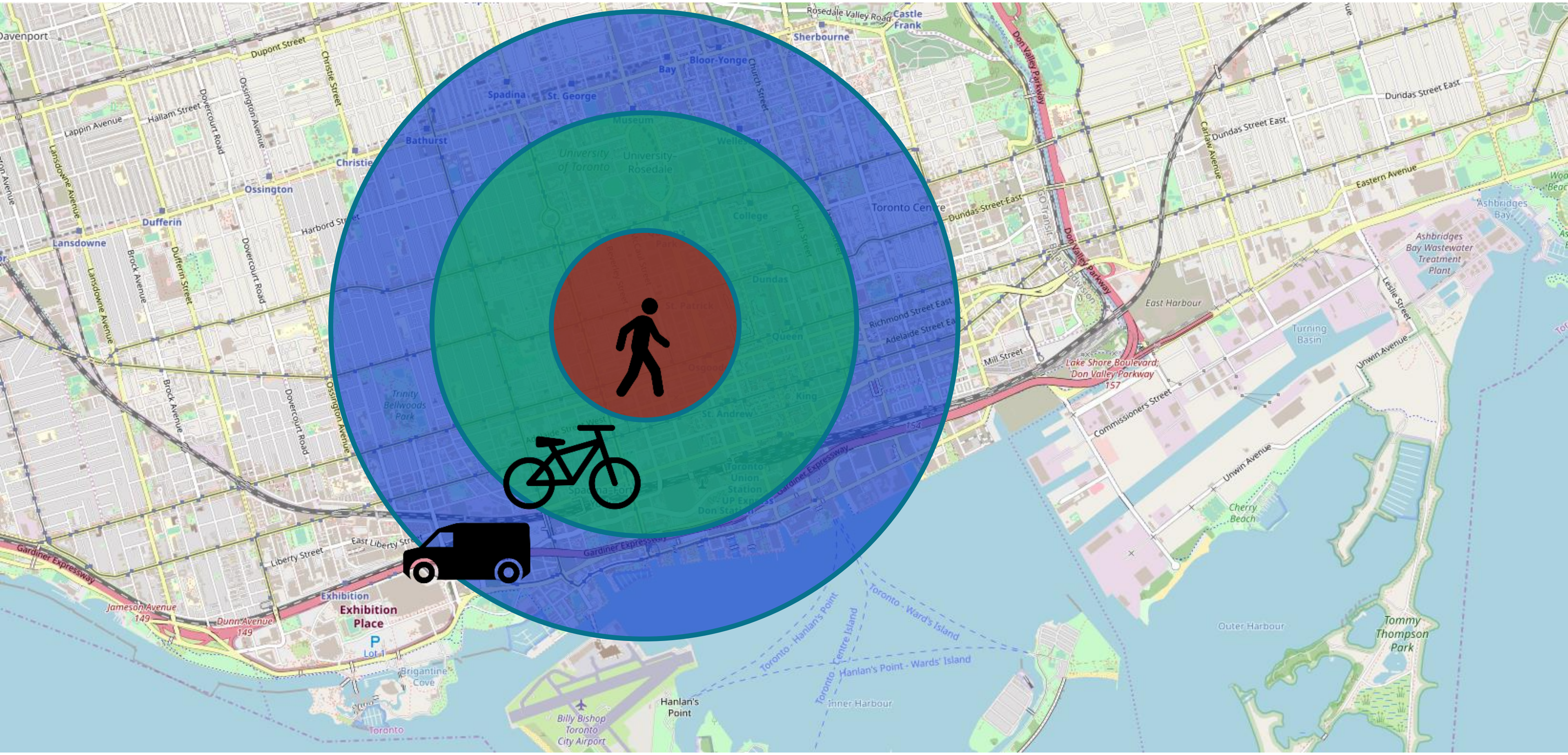
Figure 6. Distribution of demand points in downtown Toronto

4.0 Results

- **Overall Findings**
- **VRPMVTTW Sample Output**
- **Grid Search Results**

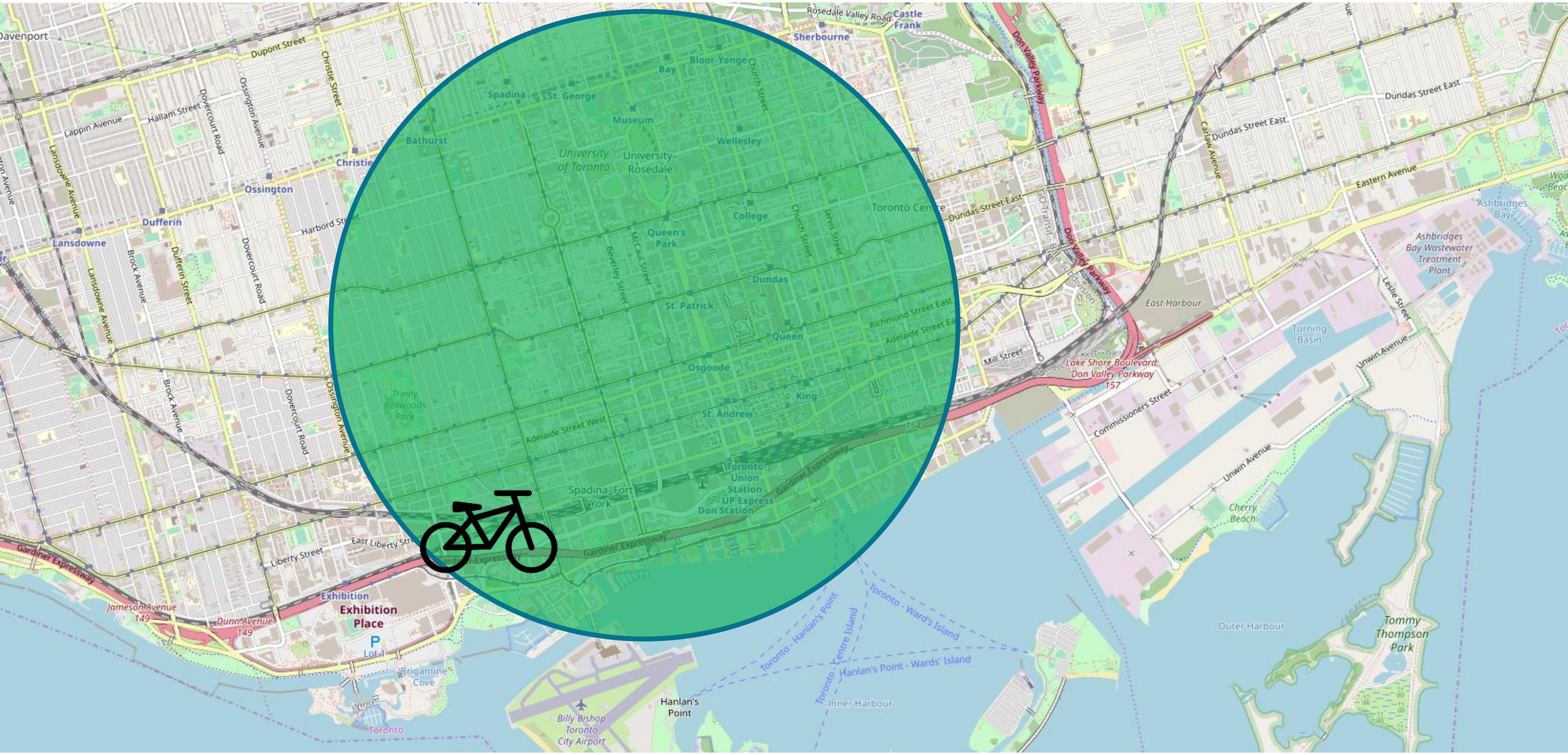
1.1 Introduction

- Expected Result: service areas



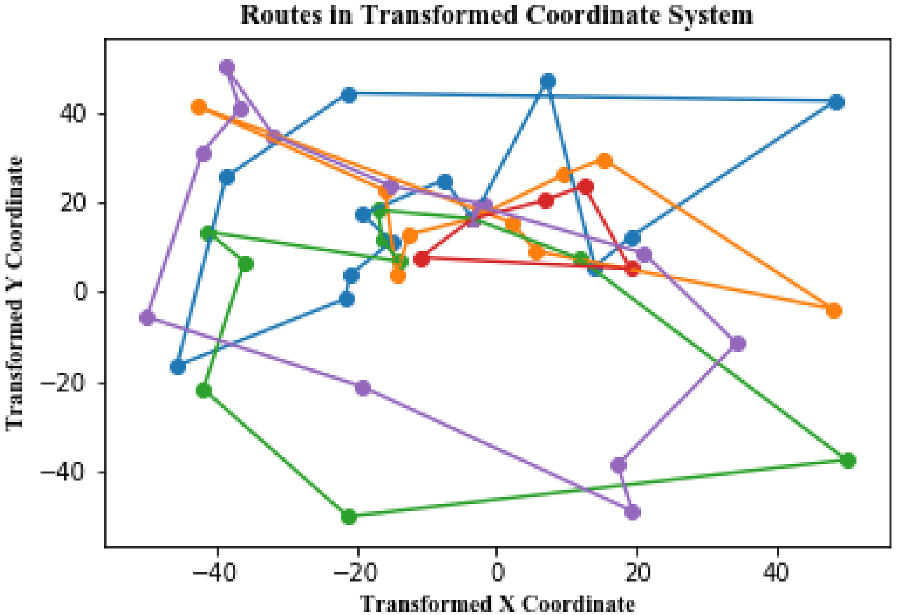
1.1 Introduction

- Actual Result: dominant mode in urban context



4.1 Results

VRPMVTTW SAMPLE OUTPUT



Route	Vehicle	Total Travel Time (min)	Cost per day
[0, 68, 65, 40, 58, 0]	Bike	85.6	$ 24.09
[0, 47, 75, 84, 12, 0]	Bike	69.8	$ 20.14
[0, 53, 77, 18, 63, 11, 0]	Bike	87.3	$ 24.50

Figure 7. Top: Sample plot of five routes generated; Bottom: Sample solver output

4.2 Results

GRID SEARCH RESULTS

- **α=1.00** → prefer route savings over avoiding pushing back departure times
- **β>1.00** → prefer sequential construction

$\alpha \backslash \beta$	0.5	1.0	1.5	2.0
0.25	1344	1344	1479	1345
0.50	589	589	589	589
0.75	480	480	478	478
1.00	464	461	**456**	**456**

Figure 8. Parameter grid search results

5.0 Discussion

- **Sensitivity Analysis**
- **Cargo Bicycle Effectiveness**
- **Limitations**

5.1 Discussion

SENSITIVITY ANALYSIS: BIKE CAPACITY

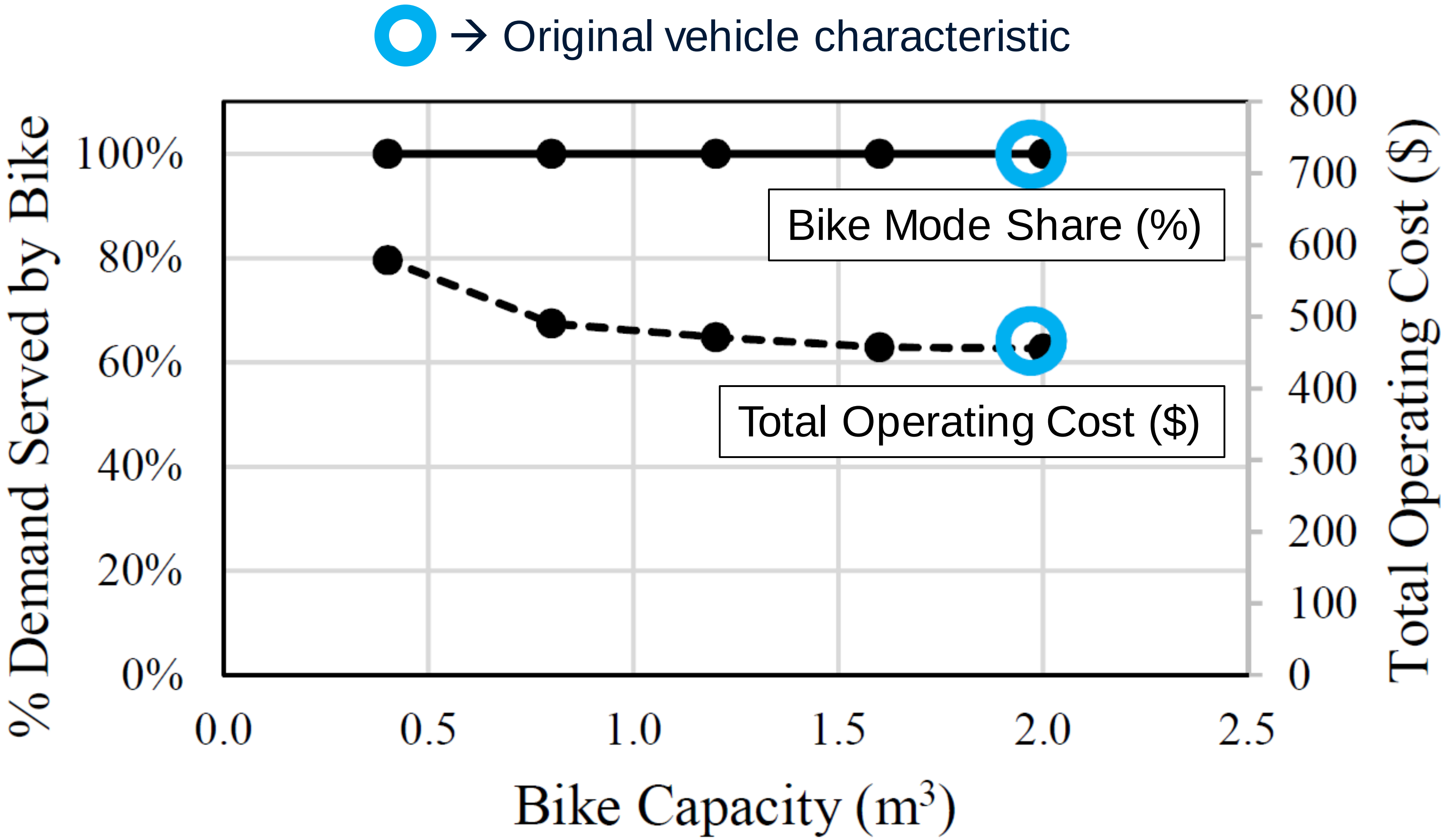


Figure 9. Sensitivity analysis results, altering bike capacity

5.1 Discussion

SENSITIVITY ANALYSIS: BIKE UNIT COST

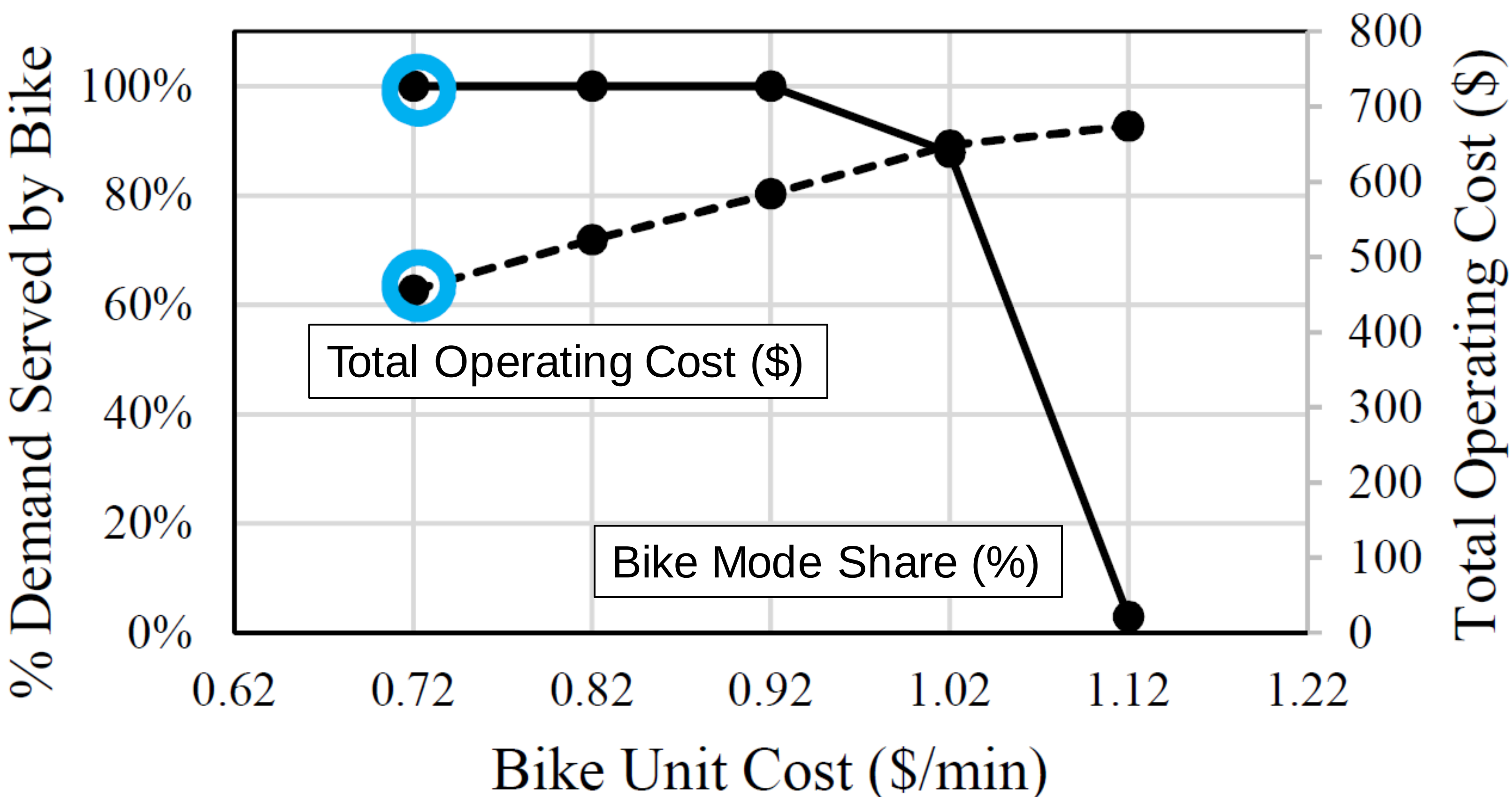


Figure 10. Sensitivity analysis results, altering bike unit cost

5.1 Discussion

SENSITIVITY ANALYSIS: BIKE SPEED

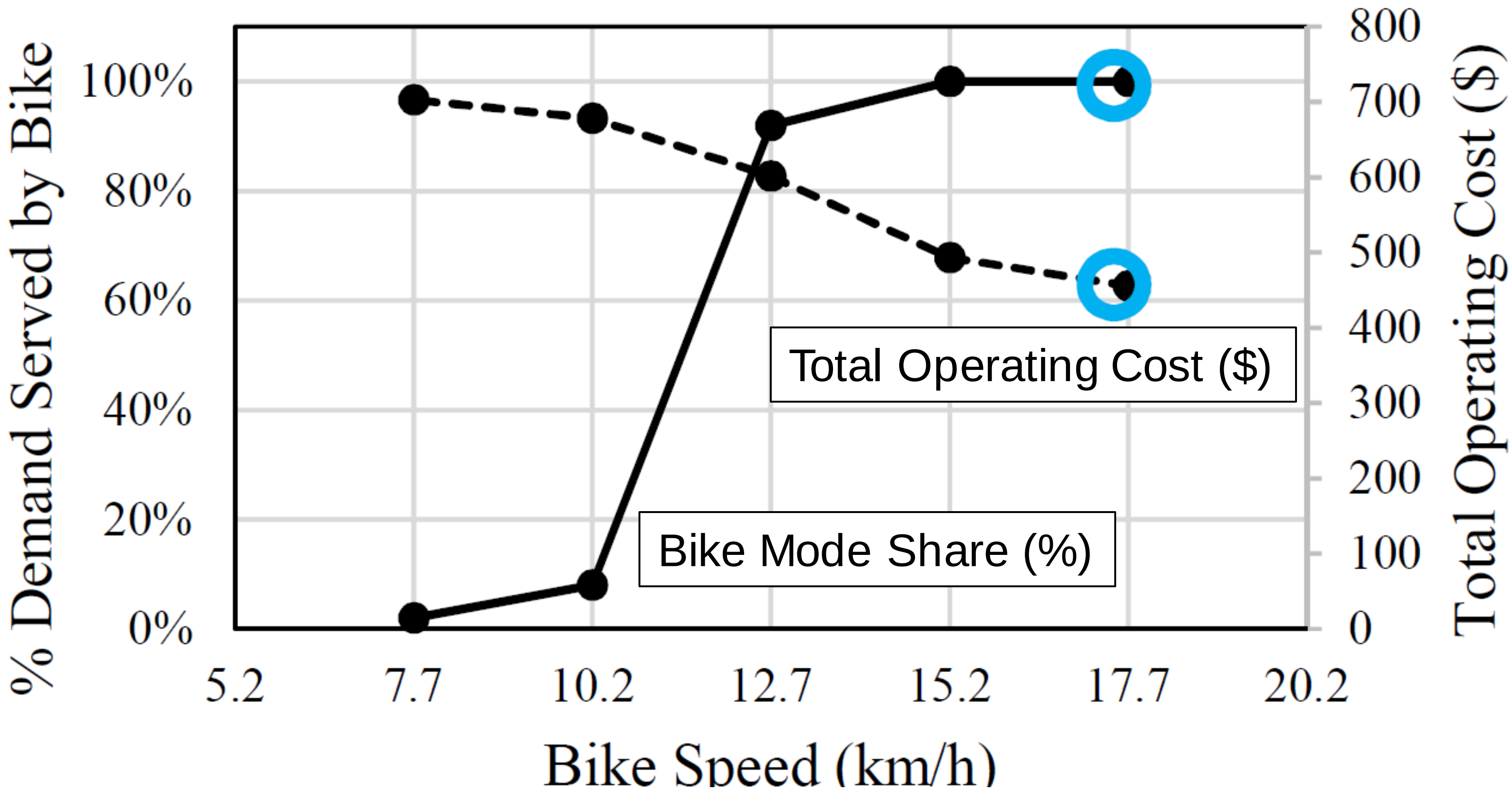


Figure 11. Sensitivity analysis results, altering bike speed

5.1 Discussion

SENSITIVITY ANALYSIS: VAN UNIT COST

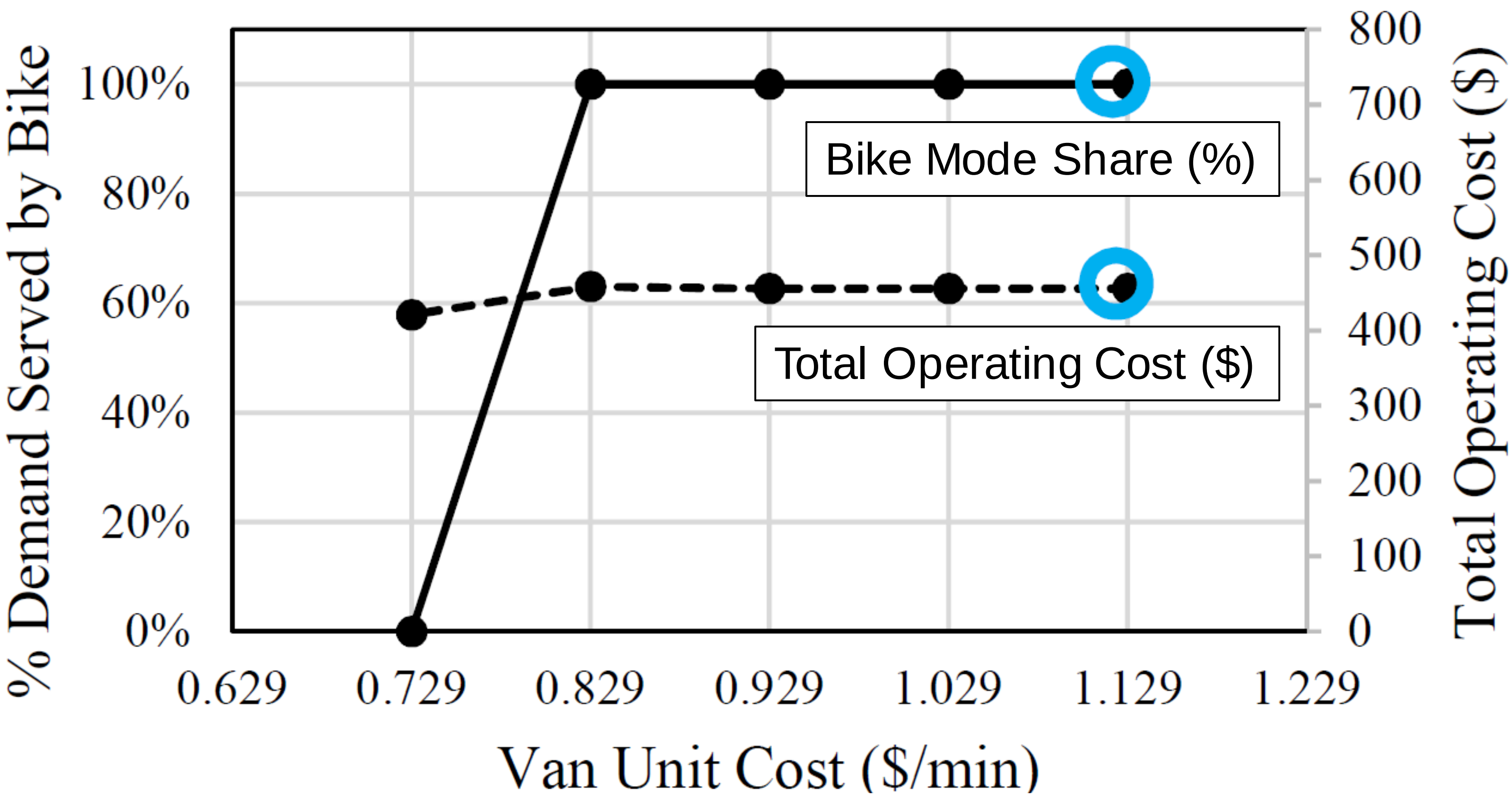


Figure 12. Sensitivity analysis results, altering van unit cost

5.2 Discussion

EFFECTIVENESS OF CARGO BICYCLES

- Most cost-effective mode
- Justifies potential for downtown operations
- Out-perform walking trips in capacity and speed, with marginal cost increases

5.3 Discussion

SOLVER LIMITATIONS

- Restricted to downtown area, with depot downtown (no stem time)
- Deterministic travel times (no reliability representation)
- No minimum delivery staff shift length
- Does not consider a fixed/constrained fleet
- $O(n^3)$ Complexity, limited set of demand data

6.1 Conclusion

- Built upon previous methods for the VRPMVTTW
- Identify cargo bicycles as a promising option for downtown freight delivery

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  - Mehdi Nourinejad
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- **Yokler**, *The electric cargo bike, expert in environmentally-friendly delivery in that last mile;* 2019.
- **OpenStreetMap,** *Map of downtown Toroonto*; 2019.

Savings Functions

VRPMVTTW SOLVER IMPLEMENTATION

- Modified Combined Savings

$$MCS(R^I, R^{II}, R^{III}) = \alpha(T^I + T^{II} - T^{III}) - (1-\alpha)\left(\frac{D_j^{III} - D_j^I}{cus^{II}}\right) + V^I + V^{II} - V^{III}$$

- Modified Optimistic Opportunity Savings

$$MOOS(R^I, R^{II}, R^{III}) = MCS(R^I, R^{II}, R^{III}) + f(K^{III} - q^{II} - q^I)$$

- Savings Function

$$SAVINGS = MOOS(R^I, R^{II}, R^{III}) + (W^I w^I + W^{II} w^{II} - W^{III} w^{III}) + (S^I N^I + S^{II} N^{II} - S^{III} N^{III})$$