Planning for local delivery using sidewalk robots

Comparing optimized mothership vans methods

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Research Question and Agenda

1. Introduction
   1. Past Research/Literature
   2. Vehicle Characteristics

2. Methodology
   1. Overview
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   3. Analytical Results

3. Default Design Case Study
   1. Case Study Results
   2. Sensitivity Analysis
   3. Closed Form Results

4. Optimized Design
   1. Design Variables
   2. Changes and Impacts
   3. Example

5. Conclusions

**Research Question:** What different ways can Sidewalk Robots be deployed from Motherships?

**Research Question:** How can we estimate the travel distances on road and on sidewalks?

**Research Question:** How does the proposed Mercedes-Benz design compare with a conventional truck?

**Research Question:** Is the default design the cheapest way to implement the MS?
Introduction
Past Works, Terminology Contributions
SADR = Sidewalk Autonomous Delivery Robot

Vehicles of pedestrian scale, either fully autonomous or ‘human-in-the-loop’, that deliver light packages via a sidewalk network.

Also known as a “Person Delivery Device”.

MS = MotherShip Van

Vehicles capable of carrying one or more SADR plus additional packages for replenishment. Travels via the road network. May be autonomous or driven by a human.
## Sept 2016: Mercedes-Benz and Starship Technologies released Mothership concept (*video in appendix*)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Classification of Strategy</th>
<th>MS Banned from Delivery</th>
<th>SADR Capacity</th>
<th>Methodology</th>
<th>Author's Problem Terminology</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Boysen et al., 2018)</td>
<td>MS Series</td>
<td>Yes</td>
<td>1</td>
<td>Mixed-Integer Program</td>
<td>Truck-based Robot Delivery (TBRD)</td>
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<tr>
<td>(Jennings &amp; Figliozzi, 2019)</td>
<td>MS Series</td>
<td>Yes</td>
<td>1</td>
<td>Continuum Approximation</td>
<td>No terminology provided</td>
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<tr>
<td>(Deng et al., 2020)</td>
<td>MS Tandem</td>
<td>No</td>
<td>1 - 25</td>
<td>Exact MIP and a Genetic Algorithm</td>
<td>Vehicle Routing Problem with Movement Synchronization (VRPMS)</td>
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<tr>
<td>(Simoni et al., 2020)</td>
<td>MS Tandem</td>
<td>No</td>
<td>1 - 3</td>
<td>Dynamic Program of Integer Program</td>
<td>Weighted Interval Scheduling Problem (WISP) of Traveling Salesman Problem with Robot (TSP-R)</td>
</tr>
<tr>
<td>(Yu et al., 2020)</td>
<td>MS Parallel</td>
<td>Yes</td>
<td>1 – 50</td>
<td>MILP, hybrid multi-start metaheuristic including destroy and repair operators together with a backtracking component</td>
<td>Two-Echelon Location Routing Problem (2E-LRP)</td>
</tr>
<tr>
<td>(Chen, Demir, &amp; Huang, 2021)</td>
<td>MS Parallel</td>
<td>No</td>
<td>10kg</td>
<td>Adaptive Large Neighborhood Search heuristic algorithm</td>
<td>Vehicle Routing Problem with Time Windows and Delivery Robots (VRPTWDR)</td>
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<tr>
<td>(Chen, Demir, Huang, et al., 2021)</td>
<td>MS Parallel</td>
<td>No</td>
<td>1</td>
<td>Meta-heuristic of Mixed-Integer Linear Program</td>
<td>Vehicle Routing Problem with Time Windows and Delivery Robots (VRPTWDR)</td>
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<tr>
<td>(Ostermeier et al., 2022)</td>
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<td>1</td>
<td>Computational Heuristics and Algorithms</td>
<td>No terminology provided</td>
</tr>
<tr>
<td>(Yu et al., 2022)</td>
<td>MS Tandem and MS Parallel</td>
<td>No</td>
<td>1 – 50</td>
<td>MILP solved with an adaptive large neighborhood search algorithm</td>
<td>Two-Echelon, Van-based Robot Hybrid Pickup and Deliveries (2E-VRHPD); Parallel Van and Robot Scheduling Problem with Hybrid Pickup and Delivery operations (PVRSP-HPD); a Two-Echelon Vehicle Routing Problem with Hybrid Pickup and Delivery operations (2E-VRP-HPD)</td>
</tr>
</tbody>
</table>
Introduction – Strategy Terminology

**MS Series**
(Boysen et al., 2018)

Name describes the ‘order’ that the SADRs are deployed in.

**MS Parallel**
(Chen et al., 2021)

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Introduction – Vehicle Characteristics

**Assumptions:**
- Cost is modelled via travel distance; We do not consider vehicle speeds.
- Vehicles always used to full capacity. Capacities equal between similar vehicles.
- Operator may be a 3PL or company fleet.
- Routes pre-planned at regional warehouse, and routes are reliable (deterministic).

**MS Capital Cost (α_ms):** $222 per day

**MS Transport Cost (β_ms):** 17¢ per kilometer

*Assumed Gasoline MS Van*

**SADR Capital Cost (α_s):** $3.52 per day

**SADR Transport Cost (β_s):** 1.2¢ per kilometer

*Assumed Electric SADR*
Introduction – Regional Terminology

**Assumptions:**
- Uniform demand density (\( \lambda \))
- Uniform touring constant (\( k = 0.87 \))
- Assumed Euclidean paths
- Sufficient MS fleet size (\( m \))
- Sufficient SADR fleet size (\( s \))
- Sufficient deployment locations (\( P \))
- Sufficient time to conduct deliveries.
Methodology

Overview, Example Application,
“Analytical Rules of Thumb” Table Summary
Methodology - Overview

• Goal: Determine analytical expressions for on-road and on-sidewalk travel distance for each system (MS Series, MS Parallel, Conventional Truck [CT]).

• Method: Apply the following equations* and adapt as necessary.

For one vehicle in a multi-vehicle routing problem, the tour distance estimate is:

\[ l(c, n, a, d) = 2.\ d + \frac{k.\ \sqrt{a.\ (c - 1)}}{\sqrt{n}} \]

- \( l \) = distance per vehicle
- \( c \) = vehicle capacity
- \( a \) = service area
- \( k \) = touring constant

For the fleet of vehicles in a multi-vehicle routing problem, the tour distance estimate is:

\[ l_t(c, n, a, d) = 2.\ \frac{n}{c}.\ d + \frac{k.\ \sqrt{n.\ a.\ (c - 1)}}{c} \]

- \( l_t \) = distance for fleet
- \( n \) = number of delivery points
- \( d \) = logistical sprawl (add more)

Reminder: Vehicles always used to full capacity. Capacities equal between similar vehicles.

*Equations adapted from Daganzo (2005) and Figliozzi (2008),
Methodology – Application Example MS Series

Distance per SADR \((D_{S1})\)

\[ l_t (c, n, a, d) = 2 \cdot \frac{n}{c} \cdot d + \frac{k \cdot \sqrt{n \cdot a} \cdot (c - 1)}{c} \]

\[ c = C_s \]
\[ n = \theta \cdot C_s \]
\[ a = A_{S1} = \frac{n}{\lambda} = \frac{\theta \cdot C_s}{\lambda} \]
\[ d = \frac{2 \cdot r}{3} = \frac{2 \cdot \sqrt{\theta \cdot C_s}}{3 \cdot \sqrt{\pi \cdot \lambda}} \]

\[ D_{S1} = \frac{4 \cdot \sqrt{\theta^3 \cdot C_s}}{3 \cdot \sqrt{\pi \cdot \lambda}} + k \cdot \theta \cdot (C_s - 1) \]
Methodology - Results

System 1: MS-Series

\[ T_{D1} = \frac{4 \cdot A \cdot \sqrt{\lambda} \cdot \theta}{3 \cdot \pi \cdot C_s} + \frac{k \cdot A \cdot \sqrt{\lambda} \cdot (C_s - 1)}{C_s} \]

System 2: MS-Parallel

\[ T_{D2} = \frac{4 \cdot A \cdot \sqrt{\lambda} \cdot C_c}{3 \cdot C_s \cdot \pi \cdot \theta} + \frac{k \cdot A \cdot \sqrt{\lambda} \cdot (C_s - 1)}{C_s} \]

System 3: Conventional Truck

\[ T_{D3} = 0 \]

\[ T_{DR1} = \frac{2 \cdot d \cdot A \cdot \lambda}{C_c} + \frac{(\theta + 1) \cdot k \cdot A \cdot \sqrt{\lambda}}{\sqrt{\theta} \cdot C_s} \]

\[ T_{DR2} = \frac{2 \cdot d \cdot A \cdot \lambda}{C_c} + \frac{k \cdot A \cdot \sqrt{\lambda} \cdot (\theta - 1)}{\sqrt{C_c} \cdot \theta} \]

\[ T_{DR3} = \frac{2 \cdot d \cdot A \cdot \lambda}{C_c} + \frac{k \cdot A \cdot \sqrt{\lambda} \cdot (C_c - 1)}{C_c} \]

\[ C_s = \text{SADR Capacity (#packages per SADR)} \]
\[ C_m = \text{MS Capacity (# SADRs per MS)} \]
\[ C_c = \text{Package Capacity (#package per MS)} \]
\[ \theta = \text{Reload Capacity (Reloads of SADRs per MS)} \]
\[ \lambda = \text{Demand Density (Packages per area)} \]
\[ k = \text{touring constant (0.87)} \]
\[ d = \text{Logistical Sprawl (regional warehouse)} \]
\[ R_s = \text{Maximum range of SADR (per charge)} \]

N.B. \( C_c = C_s \cdot C_m \cdot \theta \)
### Analytical Comparison Summary

**To minimize SADR distance use system in column compared to system in row**

<table>
<thead>
<tr>
<th></th>
<th>MS-S</th>
<th>MS-P</th>
<th>CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS-S</td>
<td></td>
<td>When the MS capacity is greater than</td>
<td>CT has no sidewalk distance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>the reload capacity.</td>
<td></td>
</tr>
<tr>
<td>MS-P</td>
<td>When the reload capacity</td>
<td></td>
<td>CT has no sidewalk distance</td>
</tr>
<tr>
<td></td>
<td>is greater than the MS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>capacity.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT</td>
<td>CT has no sidewalk distance</td>
<td></td>
<td>CT has no sidewalk distance</td>
</tr>
</tbody>
</table>

**To minimize on-road (MS or CT) distance use system in column compared to system in row**

<table>
<thead>
<tr>
<th></th>
<th>MS-S</th>
<th>MS-P</th>
<th>CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS-S</td>
<td></td>
<td>Equal distances when MS Capacity is</td>
<td>When Reload Capacity is four</td>
</tr>
<tr>
<td></td>
<td></td>
<td>equal to one.</td>
<td>less than SADR Capacity, at</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>least three less.</td>
</tr>
<tr>
<td>MS-P</td>
<td>When MS Capacity is</td>
<td></td>
<td>MS-P road distance always lower,</td>
</tr>
<tr>
<td></td>
<td>greater than one.</td>
<td></td>
<td>or equal when SADR Capacity and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MS Capacity equal one.</td>
</tr>
<tr>
<td>CT</td>
<td>When SADR Capacity is</td>
<td></td>
<td>MS-P road distance always lower</td>
</tr>
<tr>
<td></td>
<td>up to two greater than</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>the Reload Capacity.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Example of analytical comparison of MS Series vs MS Parallel strategies in slide appendix. Please see upcoming publication for full explanation of each comparison.
Default Design Case Study

Evaluating the Mercedes Benz Mothership and Starship Technologies SADRs
Default Design to Evaluate

- MS Package Capacity ($C_0$) = 54
- Reload Capacity ($\theta$) = 6.75
- SADR Capacity ($C_d$) = 1
- MS Capacity ($C_m$) = 8
Vehicle Parameters
Model Mercedes Mothership and Starship Technologies SADRs.

- **Item Capacity** ($C_c$) = 54 packages
- **SADR Capacity** ($C_s$) = 1 package
- **MS Capacity** ($C_m$) = 8 SADRs
- **Reload Capacity** ($\theta$) = 6.75 reloads

**Unit Costs:**

- **CT Capital Cost** ($\alpha_s$):
  - $222 per day, $80,000 purchase
- **CT Transport Cost** ($\beta_s$):
  - 17¢ per kilometer, $1.38/litre
- **MS Capital Cost** ($\alpha_s$):
  - $222 per day, $80,000 purchase
- **MS Transport Cost** ($\beta_s$):
  - 17¢ per kilometer, $1.38/litre
- **SADR Capital Cost** ($\alpha_s$):
  - $3.52 per day, $2540 purchase
- **SADR Transport Cost** ($\beta_s$):
  - 1.2¢ per kilometer, 6¢/kWh

**Total MS System Cost** = Capital Cost per MS * Number of MS + MS Unit Transport Cost * MS Transport Distance + Capital Cost per SADR * Number of SADRs + SADR Unit Transport Cost * SADR Transport Distance

**Total CT System Cost** = Capital Cost per CT * Number of CT + CT Unit Transport Cost * CT Transport Distance
# Default Design Case Study Sensitivity Analysis

<table>
<thead>
<tr>
<th></th>
<th>Default Value</th>
<th>Value for MS-Series TSC to equal CT TSC (% change)</th>
<th>Value for MS-Parallel TSC to equal CT TSC (% change)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logistical Sprawl</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Demand Density</td>
<td>50</td>
<td>N/A</td>
<td>0.021</td>
</tr>
<tr>
<td>SADR Transport Cost</td>
<td>$0.0126</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>SADR Capital Cost</td>
<td>$3.52</td>
<td>N/A</td>
<td>$0.072 (-98%)</td>
</tr>
<tr>
<td>MS Transport Cost</td>
<td>$0.1725</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>MS Capital Cost</td>
<td>$222.22</td>
<td>$191.57 (-14%)</td>
<td>$194.63 (-12%)</td>
</tr>
<tr>
<td></td>
<td>($22.22 vehicle + $200 labor)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT Package Capacity</td>
<td>54</td>
<td>47 (-13%)</td>
<td>48 (-11%)</td>
</tr>
</tbody>
</table>

**MS Series**

\[
\lambda > \left( \frac{4 \sqrt{C_c}}{3R_g \sqrt{\pi C_m}} + \frac{k_c C_c (C_c - 1)}{R_g C_c C_m} \right)^2
\]

\[
\lambda < \left( \frac{\beta_c k_c (C_c - 1) C_c}{\sqrt{\pi} C_m} - \beta_m k_c \sqrt{\frac{C_m C_c}{3}} + \frac{4 \beta_c \sqrt{C_m C_c} C_c}{3 \sqrt{\pi}} - \beta_c k_c C_c C_m (C_c - 1)}{\alpha_c C_c C_m + 2 \beta_m d C_c C_m + \alpha_c C_c C_m^2 C_c - \alpha_c C_c C_m - 2 \beta_c d C_c C_m} \right)^2
\]

**MS Parallel**

\[
\lambda > \left( \frac{4 \sqrt{C_c}}{3R_g \sqrt{\pi C_m}} + \frac{k_c C_c (C_c - 1)}{C_c C_m R_g} \right)^2
\]

\[
\lambda < \left( \frac{\beta_c k_c (C_c - 1) - \beta_m k_c (C_c - 1)}{\sqrt{\pi} C_m} - \beta_c C_c \left( \frac{4 \sqrt{C_m C_c}}{3 \sqrt{\pi}} + \frac{k_c (C_c - 1)}{C_s} \right) \right)^2
\]

\[
\frac{\alpha_c - \alpha_s}{\alpha_c - \alpha_s + (\beta_m - \beta_c) 2d + \alpha_s C_m}
\]
Default Design Insights from Closed Form

Vehicle Parameters
Model Mercedes Mothership and Starship Technologies SADRs.
- Item Capacity ($C_i$) = 54 packages
- SADR Capacity ($C_s$) = 1 package
- MS Capacity ($C_m$) = 8 SADRs
- Reload Capacity ($\theta$) = 6.75 reloads

Unit Costs:
- CT Capital Cost ($\alpha_s$): $222 per day
- CT Transport Cost ($\beta_s$): 17¢ per kilometer
- MS Capital Cost ($\alpha_s$): $222 per day
- MS Transport Cost ($\beta_s$): 17¢ per kilometer
- SADR Capital Cost ($\alpha_s$): $X per day
- SADR Transport Cost ($\beta_s$): 1.2¢ per kilometer

Demand Density, packages per day per sq.km
- Conventional Truck is cheaper
- SADR battery range not sufficient
- No cross-over range
- MIN = 5.04 packages per sq.km
- MAX = 0.02 packages per sq.km

Conventional Truck is cheaper
- MAX = 8.34 packages per sq.km
- SADR battery range not sufficient
- No cross-over range
- MIN = 5.04 packages per sq.km

SADR Capital Cost ($\alpha_s$): $3.52 per day
SADR Capital Cost ($\alpha_s$): $0.1725 per day
Optimized Design

Evaluating the Mercedes Benz Mothership and Starship Technologies SADRs
Objective: MINIMIZE Total System Cost (depends on MS Strategy).

Method: Integer Program Solver, Excel, Exhaustive Search

Subject to: SADR Range Constraint (depends on MS Strategy).
SADR Capacity, integer between 1 and 8
MS Capacity, integer between 1 and 8
Optimized Design – Changes and Impacts

**Suburban (\( \lambda = 50 \) ~1500 persons per sq.km and assumed demand of 10 packages per person per year)**

- **MS-Series**
  - Fewer, larger SADRs

- **MS-Parallel**
  - Fewer, small SADRs

---

Legend:
- (Solid) Road Distance
- (Hatched) Sidewalk Distance
MS-Series Insights
1. High demand density converges to stationary MS used as local hubs.
   1. Because of SADR Capital Costs
2. High SADR capacity preferred.
   1. Opposite to Mercedes design, with many SADRs with low capacity.

MS-Parallel Insights
1. Current SADR capital costs are too high to justify this strategy.
   1. Only used as our model enforces SADR use.
2. Lower SADR capital cost can mean a larger fleet is worthwhile.
   1. Customer time-window pressure is more likely to push and greater SADR fleet.
Thank you!

For more information or to submit further questions direct to me contact:

Email: Jacob.Banb@ucalgary.ca
IISC: www.createiisc.com
Profile: University Website

or visit:

And await publication in review.
References


“Vans & Robots: Efficient delivery with the mothership concept” (Sep 16, 2016), Mercedes-Benz Vans, https://www.youtube.com/watch?v=yUMOLzCsifs&t=94s
Appendix – Problem

Figure 5. Trends in vehicle numbers in Canada
Data source: Environment and Climate Change Canada


US-based MSs: Starship Robots and Mercedes Benz (top), Digit by Ford (middle), ANYmal by ANYbotics (bottom)
Appendix – Analytical Comparison

When should you use MS Series for the least sidewalk travel?

\[ T_{D_S1} < T_{D_S2} \]

\[
\frac{4. A. \sqrt{\lambda} \ C_s}{3. \sqrt{\pi} \ C_s} + \frac{k. A. \sqrt{C_s} (C_s - 1)}{C_s} < \frac{4. A. \sqrt{\lambda} \ C_c}{3. C_s \sqrt{\pi} \ C_s} + \frac{k. A. \sqrt{C_c} (C_c - 1)}{C_c}
\]

\[
\frac{4. A. \sqrt{\lambda} \ C_c}{3. \sqrt{\pi} \ C_c} < \frac{4. A. \sqrt{\lambda} \ C_s}{3. C_s \sqrt{\pi} \ C_s}
\]

\[
\frac{\sqrt{\theta}}{\sqrt{C_s}} < \frac{\sqrt{C_c}}{C_s \sqrt{\theta}}
\]

\[
\frac{\theta}{\sqrt{C_s}} < \frac{\sqrt{C_c}}{C_s}
\]

\[
\theta < \frac{\sqrt{C_c} \cdot C_m \cdot \theta}{\sqrt{C_s}}
\]

\[
\theta < C_m
\]

When there are more SADRs per MS than reloads per MS.

When C_m equals 1.

\[
\frac{2. d. A. \lambda}{C_c} < \frac{2. d. A. \lambda}{C_c} + \frac{k. A. \sqrt{\lambda} (\theta - 1)}{\sqrt{C_c} \cdot \theta}
\]

\[
\frac{2. d. A. \lambda}{\theta \cdot 1 \cdot C_s} < \frac{2. d. A. \lambda}{\theta \cdot 1 \cdot C_s} + \frac{k. A. \sqrt{\lambda} (\theta - 1)}{\theta \cdot \sqrt{1 \cdot C_s}}
\]

\[
0 < \frac{(\theta - 1)}{\theta}
\]

\[
1 < \theta
\]

When should you use MS Series for the least road travel?

\[ T_{D_R1} < T_{D_R2} \]

\[
\frac{(\theta + 1). k. A. \sqrt{\lambda}}{\sqrt{C_c} \cdot \theta} < \frac{k. A. \sqrt{\lambda} (\theta - 1)}{\sqrt{C_c} \cdot \theta}
\]

\[
\frac{(\theta + 1). k. A. \sqrt{\lambda}}{\sqrt{C_s} \cdot \theta} < \frac{k. A. \sqrt{\lambda} (\theta - 1)}{\sqrt{C_s} \cdot \theta}
\]

\[
\frac{(\theta + 1)}{\sqrt{C_m}} < \frac{1}{\sqrt{C_m}}
\]

\[
\theta \left( \frac{\theta + 1}{\theta - 1} \right)^2 < \frac{1}{C_m}
\]

Road travel is equal when there is only one SADR per MS.
Total MS System Cost = Capital Cost per MS * Number of MS + MS Unit Transport Cost * MS Transport Distance + Capital Cost per SADR * Number of SADRs + SADR Unit Transport Cost * SADR Transport Distance

\[ TSC_{#} = \alpha_{m} \cdot m + \beta_{m} \cdot TD_{R#} + \alpha_{s} \cdot s + \beta_{s} \cdot TD_{S#} \]

\[ TSC_{1} = \alpha_{m} \cdot \frac{A \cdot \lambda}{C_{c}} + \beta_{m} \cdot \left( \frac{2 \cdot d \cdot A \cdot \lambda}{C_{c}} + \frac{(\theta + 1) \cdot k \cdot A \cdot \sqrt{\lambda}}{\sqrt{\theta} \cdot C_{s}} \right) + \alpha_{s} \cdot \frac{A \cdot \lambda}{\theta \cdot C_{s}} + \beta_{s} \cdot \left( \frac{4 \cdot A \cdot \sqrt{\lambda} \cdot \theta}{3 \cdot \sqrt{\pi} \cdot C_{s}} + \frac{A \cdot k \cdot \sqrt{\lambda} \cdot (C_{s} - 1)}{C_{s}} \right) \]

\[ TSC_{2} = \alpha_{m} \cdot \frac{A \cdot \lambda}{C_{c}} + \beta_{m} \cdot \left( \frac{2 \cdot d \cdot A \cdot \lambda}{C_{c}} + \frac{k \cdot A \cdot \sqrt{\lambda} \cdot (\theta - 1)}{\sqrt{C_{c} \cdot \theta}} \right) + \alpha_{s} \cdot \frac{A \cdot \lambda}{\theta \cdot C_{s}} + \beta_{s} \cdot \left( \frac{4 \cdot A \cdot \sqrt{\lambda} \cdot C_{c}}{3 \cdot C_{s} \sqrt{\pi} \cdot \theta} + \frac{k \cdot A \cdot \sqrt{\lambda} \cdot (C_{s} - 1)}{C_{s}} \right) \]

Total CT System Cost = Capital Cost per CT * Number of CT + CT Unit Transport Cost * CT Transport Distance

\[ TSC_{3} = \alpha_{c} \cdot \frac{A \cdot \lambda}{C_{c}} + \beta_{c} \cdot \left( \frac{2 \cdot d \cdot A \cdot \lambda}{C_{c}} + \frac{k \cdot A \cdot \sqrt{\lambda} \cdot (C_{c} - 1)}{C_{c}} \right) \]
### Appendix – Constraint Equations

#### MS Series

<table>
<thead>
<tr>
<th>Constraint Type</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range L.B. Constraint</td>
<td>( \lambda &gt; \left( \frac{4. \sqrt{C_c}}{3. R_S \cdot \sqrt{\pi \cdot C_m}} + \frac{k \cdot C_c \cdot (C_s - 1)}{R_S \cdot C_s \cdot C_m} \right)^2 )</td>
</tr>
</tbody>
</table>

#### MS Parallel

<table>
<thead>
<tr>
<th>Constraint Type</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range L.B. Constraint</td>
<td>( \lambda &gt; \left( \frac{4 \cdot C_c}{3. R_s \cdot \sqrt{\pi \cdot C_m \cdot C_s \cdot C_m}} + \frac{k \cdot C_c \cdot (C_s - 1)}{C_s \cdot C_m \cdot R_s} \right)^2 )</td>
</tr>
</tbody>
</table>
Appendix – Future Work

• Time Windows:
  • May be more appropriate to compare two MS time windows against a longer CT tour.
  • Further investigation of time-window constraints in continuum approximation, (Jennings and Figliozzi, 2019).

• Routing Approximation
  • Develop and validate open vehicle routing approximations so that Tandem SADR deployment systems may be modelled.
  • Develop and validate different routing parameters (k) more appropriate for small capacity vehicles and for small scale pathing, (Choi and Schonfeld, 2021)