Modeling and Optimizing Paratransit in the Age of TNCs

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6 Faculty in Transportation Group
- Traffic operations and control
- Public transportation
- Systems analysis
- Transportation safety
- Human factors
- Air traffic modeling and control

UMass Amherst Transportation Center
- Regional Traveler Information Center (RTIC)
- Local Technical Assistance Program (LTAP)
- Transportation Training Institute (TTI)
- Cooperative Research Program
- UMass Traffic Research Safety Program (UMassSafe)
- Aviation Center
How can transportation systems be designed and managed to respond to users’ needs?

• Simple models of system operations provide useful insights for providing efficient service.

• Taxis (and TNCs) have the potential to serve some trips at lower cost.

• Future systems may exploit benefits of multiple services operating together to serve diverse demand.
Outline

1. Demand Responsive Transit: ADA Paratransit
2. Modeling Paratransit Operations
3. Operation and Demand Strategies
4. Coordination with Taxis and TNCs
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ADA Paratransit
DRT includes modes of transportation that serve the public, which adapt to passenger demands by changing routes, stops, and/or departure times.

**How Much Route and Schedule can Change**

**LOW FLEXIBILITY**
- Heavy Rail
- Fixed-Route Bus
- Special Line Bus
- Deviated Fixed-Route Bus

**FULL FLEXIBILITY**
- Paratransit / Dial-a-Ride
- Taxi / TNC
- Individual Mode
Required Service for People with Disabilities

- Required by Americans with Disabilities Act of 1990
- Required for agencies to receive federal funding
- Customers who are unable to navigate public bus system, or are unable to access the system are eligible
- Transit operators must provide paratransit service to destinations with 3/4 mile of fixed routes, same hours of operation.
Requirements

• Trips are reserved at least 24 hours in advance

• Scheduled pick-up is within 1 hour of requested pick-up; Actual pick-up is within 20 minutes of scheduled pick-up

• Travel time is within $1.5 \times$, and fare within $2 \times$ conventional mode
New Jersey Transit: Access Link

Statewide Paratransit Service

- Annual Trips: 951,000 trips/yr
- Service Region: 18,000 km²
- Vehicle Fleet: 372 veh
- Urban core areas provide contiguous coverage
- ¾ mile buffers provide service around outlying bus routes

Legend
- Urban Core Areas
- Extended Buffer (1/4 Mile)
- 3/4 Mile Buffer
- MCD IV Residential Property Location
- County Boundary
- Municipal Boundary

160 miles
250 km
New Jersey Transit: Access Link

Statewide Paratransit Service

• State is divided into 6 overlapping service regions

• Trips are served without transfer within each region. Travel between regions requires a transfer.

• Service in each region is operated under a separate contract, with separate fleet and facilities
Growing Demand for ADA Paratransit

National Trends

• Demand increased by 41% from 2000 to 2010.

• Paratransit customers are 5-7% of demand, but 20-25% of operating costs. (National Transit Database)

• Aging population will cause this increase to continue.
The average American lives in a neighborhood with 2,440 people/km$^2$.

Source: http://www.citylab.com/housing/2012/10/americas-truly-densest-metros/3450/
Demand is very peaked at certain times of day. Vehicles and drivers are costly when only used for a short time period.
Modeling Paratransit Operations
Data Sources

**Records of All Trips**
October 2010 – September 2012: ~2 million trips

- Pick-up/Drop-off Locations
- Pick-up/Drop-off Times
- Passenger ID
- Vehicle ID

**Average Vehicle Speeds (min/mile)**
Continuous Approximation Model

Continuous approximation is a technique to treat integer variables (e.g., number of vehicles, number of passengers, etc.) as continuous values so that simple equations can define general relationships.

For each region $i$, and each time period $j$:

**Data Inputs**
- Region Area
- Demand
- Time-Window Constraint for Pick-up
- Travel Time Constraints

**Data Outputs**
- Total Vehicle Miles
- Total Vehicle Hours
- Required Fleet Size
Continuous Approximation Model

Specific origin-destination demands and corresponding routes vary from day to day. For planning purposes, a **continuous approximation** model is useful for modeling aggregate operations and costs.

**Operation Model**
- \( \lambda \) Demand Rate
- \( T \) Time Window
- \( A \) Service Area
- \( v \) Traffic Speed
- \( n \) Vehicle Occupancy
- \( b \) Duration of Stop

**Cost Model**
- \( VMT \) Vehicle Miles
- \( M \) Fleet Size
- \( VHT \) Vehicle Hours

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda )</td>
<td>Demand Rate</td>
<td></td>
</tr>
<tr>
<td>( T )</td>
<td>Time Window</td>
<td></td>
</tr>
<tr>
<td>( A )</td>
<td>Service Area</td>
<td></td>
</tr>
<tr>
<td>( v )</td>
<td>Traffic Speed</td>
<td></td>
</tr>
<tr>
<td>( n )</td>
<td>Vehicle Occupancy</td>
<td></td>
</tr>
<tr>
<td>( b )</td>
<td>Duration of Stop</td>
<td></td>
</tr>
<tr>
<td>( VMT )</td>
<td>Vehicle Miles</td>
<td>Vehicle Miles</td>
</tr>
<tr>
<td>( M )</td>
<td>Fleet Size</td>
<td></td>
</tr>
<tr>
<td>( VHT )</td>
<td>Vehicle Hours</td>
<td>Vehicle Hours</td>
</tr>
</tbody>
</table>

- Cost per Pick-up
- Total Annual Cost

Rahimi and Gonzales (2015)
Operation and Cost Model

Vehicle Miles Traveled (VMT)

\[ VMT = r_1 \frac{\lambda \sqrt{A}}{2} \left( \frac{1}{\sqrt{\lambda T}} + \frac{1}{\sqrt{n}} \right) \]

Vehicle Hours (VHT) and Fleet Size (M)

\[ VHT = M t_p = \lambda t_p \left( b + r_2 \frac{\sqrt{A}}{2v} \left( \frac{1}{\sqrt{\lambda T}} + \frac{1}{\sqrt{n}} \right) \right) \]

- \( \lambda \)  Demand Rate [pick-ups/time]
- \( A \)  Area of Service Coverage [dist^2]
- \( T \)  Time Window (maximum difference from schedule) [time]
- \( n \)  Vehicle Occupancy [passengers]
- \( t_p \)  Duration of Time Period [time]
- \( b \)  Average Boarding & Alighting Time [time]
- \( v \)  Average Traffic Speed [dist/time]
Operation Model: Vehicle Miles Traveled (\(VMT\))

Region 5
The slope is \(r_1\)

\[ y = 0.80x \]
\[ R^2 = 0.97 \]
Operation Model: Vehicle Hours Traveled ($VHT$)

Region 5
The slope is $r_2$

$M - \lambda b$

Required Number of Vehicles in Network

Required Number of Vehicles for Straight-line Distances Between ODs

\[
\frac{\sqrt{A}}{2v} \left( \frac{1}{\sqrt{\lambda T}} + \frac{1}{\sqrt{n}} \right)
\]

$y = 1.43x$

$R^2 = 0.86$
Comparing Efficiency in Service Regions

The $r$ factors provide an indication of how efficiently resources are used. The VHT value will always be greater than VMT because extra waiting time in the schedule increases its value.

<table>
<thead>
<tr>
<th>Region</th>
<th>$r_{VMT}$</th>
<th>$r_{VHT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.86</td>
<td>1.65</td>
</tr>
<tr>
<td>3</td>
<td>1.19</td>
<td>2.22</td>
</tr>
<tr>
<td>4E</td>
<td>0.99</td>
<td>1.58</td>
</tr>
<tr>
<td>4W</td>
<td>1.25</td>
<td>4.08</td>
</tr>
<tr>
<td>5</td>
<td>0.80</td>
<td>1.43</td>
</tr>
<tr>
<td>6</td>
<td>0.95</td>
<td>1.61</td>
</tr>
</tbody>
</table>
Operation and Cost Model

Vehicle Miles Traveled ($VMT$)  

\[
VMT = r_1 \frac{\lambda \sqrt{A}}{2} \left( \frac{1}{\sqrt{\lambda T}} + \frac{1}{\sqrt{n}} \right)
\]

Vehicle Hours ($VHT$) and Fleet Size ($M$)  

\[
VHT = M t_p = \lambda t_p \left( b + r_2 \frac{\sqrt{A}}{2v} \left( \frac{1}{\sqrt{\lambda T}} + \frac{1}{\sqrt{n}} \right) \right)
\]

Total Cost of Paratransit ($TC$)  

\[
TC(\lambda) = \alpha_0 + \alpha_1 \frac{r_1 \lambda \sqrt{A}}{2} \left( \frac{1}{\sqrt{\lambda T}} + \frac{1}{\sqrt{n}} \right) + (\alpha_2 t_p + \alpha_3) \left[ b \lambda + \frac{r_2 \lambda \sqrt{A}}{2v} \left( \frac{1}{\sqrt{\lambda T}} + \frac{1}{\sqrt{n}} \right) \right]
\]

- $\lambda$  Demand Rate [pick-ups/time]
- $A$  Area of Service Coverage [dist$^2$]
- $T$  Time Window (maximum difference from schedule) [time]
- $n$  Vehicle Occupancy [passengers]
- $t_p$  Duration of Time Period [time]
- $b$  Average Boarding & Alighting Time [time]
- $v$  Average Traffic Speed [dist/time]
## Model for Access Link Region 5

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Fit ($R^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of Service Coverage, $A$</td>
<td>559 mi&lt;sup&gt;2&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Travel Demand, $\lambda$</td>
<td>381,049 pax/yr</td>
<td></td>
</tr>
<tr>
<td>Vehicle Occupancy, $n$</td>
<td>1.26 pax/veh</td>
<td></td>
</tr>
<tr>
<td>Average Traffic Speed, $v$</td>
<td>23.6 mi/hr</td>
<td></td>
</tr>
<tr>
<td>Fleet Size, $M$</td>
<td>99 veh</td>
<td></td>
</tr>
<tr>
<td>Boarding &amp; Alighting Time, $b$</td>
<td>4.0 min</td>
<td></td>
</tr>
<tr>
<td>Travel Distance Parameter, $r_1$</td>
<td>0.80</td>
<td>0.97</td>
</tr>
<tr>
<td>Travel Time Parameter, $r_2$</td>
<td>1.43</td>
<td>0.86</td>
</tr>
<tr>
<td>Fixed Annual Cost, $\alpha_0$</td>
<td>1,780,000 $</td>
<td></td>
</tr>
<tr>
<td>Cost per Vehicle Mile, $\alpha_1$</td>
<td>0.46 $/\text{veh-mile}$</td>
<td>0.91</td>
</tr>
<tr>
<td>Cost per Vehicle Hour, $\alpha_2$</td>
<td>14.35 $/\text{veh-hr}$</td>
<td>0.92</td>
</tr>
<tr>
<td>Annual Cost per Vehicle, $\alpha_3$</td>
<td>37,879 $/\text{veh}$</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Characteristics of Total Annual Operating Cost

Annual operating cost increases with demand and with coverage area. Growing demand means increasing costs for agencies.

Annual Cost Contours (Million $)
Characteristics of Average Operating Cost per Trip

Average cost per trip increases with area, but decreases with demand. More dense demand makes the system more efficient.
3 Operation and Demand Strategies
Cost Comparison of Zoning Strategies

Operation and Demand Strategies

Symmetric Non-Overlapping

Symmetric Overlapping

Redundant Subzone

Total Annual Agency Cost ($10 Million)

Portion of Region in Overlap ($w$)

- Symmetric Non-Overlapping
- Symmetric Overlapping (Even Split of Overlap Trips)
- Symmetric Overlapping (All Overlap Trips to Zone 1)
- Redundant Subzone (Even Split of Overlap Trips)
- Redundant Subzone (All Overlap Trips to Zone 1)
Many agencies split large operating areas into multiple zones. Travel from one zone to another requires a transfer that delays travelers and requires an extra vehicle trip.

\[ t_{od} = md_{od} + b + w_o \]

Access Link Region 5
Single Region

Access Link Region 5
2 Zones

\[ t_{od} = md_{od} + b + w_o + X \]
Transfer Time, \( X = 9.6 \) min
Operation and Demand Strategies

Time-Dependent Pricing to Spread Demand

(Amirgholy and Gonzales, 2015)

The capacity of DRT service depends on the number of waiting customers. Adaptation of bottleneck pricing optimizes operations.

Optimizing Capacity Without Pricing

Optimizing Capacity With Pricing
4 Coordination with Taxis and TNCs
Regional Paratransit Service

- Annual Trips: 215,000 trips/yr
- Service Region: 630 mi²
- Average Operating Cost: $28.66 per trip
Regional Paratransit Service

- Annual Trips: 215,000 trips/yr
- Service Region: 630 mi²
- Average Operating Cost: $28.66 per trip

Records of All Trips
June 2015 – June 2017: 432,830 trips

- Pick-up/Drop-off Locations
- Pick-up/Drop-off Times
- Passenger ID Type of Disability
- Vehicle ID
- Network Distance Traveled by Paratransit Vehicles
Model of Paratransit

Specific origin-destination demands and corresponding routes vary from day to day. For planning purposes, a continuous approximation model is useful for modeling aggregate operations and costs.

Operation Model

Time Window, $T = 40$ min

Service Area, $A = 627$ mi$^2$

Traffic Speed, $v = 20.5$ mi/hr

Vehicle Occupancy, $n = 1.2$ pax/veh

Duration Loading and Unloading, $b = 10$ min

Vehicle Miles, $VMT$

Fleet Size, $M$

Vehicle Hours, $VHT$
Coordination with Taxis and TNCs

Operation Model

Vehicle Miles Traveled ($VMT$)

$$VMT = r_1 \frac{\lambda \sqrt{A}}{2} \left( \frac{1}{\sqrt{\lambda T}} + \frac{1}{\sqrt{n}} \right)$$

Travel Distance Parameter

$r_1 = 0.82$  \hspace{1cm} (R$^2 = 0.97$)

Vehicle Hours Traveled ($VHT$) and Fleet Size ($M$)

$$VHT = M t_p = \lambda t_p \left( b + r_2 \frac{\sqrt{A}}{2v} \left( \frac{1}{\sqrt{\lambda T}} + \frac{1}{\sqrt{n}} \right) \right)$$

Travel Time Parameter

$r_2 = 0.90$  \hspace{1cm} (R$^2 = 0.96$)

$\lambda$  Demand Rate [pick-ups/time]

$A$  Area of Service Coverage [dist$^2$]

$T$  Time Window (maximum difference from schedule) [time]

$n$  Vehicle Occupancy [passengers]

$t_p$  Duration of Time Period [time]

$b$  Average Boarding & Alighting Time [time]

$v$  Average Traffic Speed [dist/time]
Cost Function for ADA Paratransit Coordination with Taxis and TNCs

Total Cost of Paratransit ($TC_p$)

\[
TC_p(\lambda) = \alpha_0 + \alpha_1 \frac{r_1 \lambda \sqrt{A}}{2} \left( \frac{1}{\sqrt{\lambda T}} + \frac{1}{\sqrt{n}} \right) + (\alpha_2 t_p + \alpha_3) \left[ b \lambda + \frac{r_2 \lambda \sqrt{A}}{2v} \left( \frac{1}{\sqrt{\lambda T}} + \frac{1}{\sqrt{n}} \right) \right]
\]

Marginal Cost of Paratransit ($MC_p$)

\[
MC_p(\lambda) = \alpha_0 + \alpha_1 \frac{r_1 \sqrt{A}}{2} \left( \frac{1}{2\sqrt{\lambda T}} + \frac{1}{\sqrt{n}} \right) + (\alpha_2 t_p + \alpha_3) \left[ b + \frac{r_2 \sqrt{A}}{2v} \left( \frac{1}{2\sqrt{\lambda T}} + \frac{1}{\sqrt{n}} \right) \right]
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Fit ($R^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Annual Cost, $\alpha_0$</td>
<td>135,135 $</td>
<td></td>
</tr>
<tr>
<td>Cost per Vehicle Mile, $\alpha_1$</td>
<td>0.518 $/\text{veh-mile}$</td>
<td>0.80</td>
</tr>
<tr>
<td>Cost per Vehicle Hour, $\alpha_2$</td>
<td>19.89 $/\text{veh-hr}$</td>
<td>0.86</td>
</tr>
<tr>
<td>Annual Cost per Vehicle, $\alpha_3$</td>
<td>55,044 $/\text{veh}$</td>
<td>0.93</td>
</tr>
</tbody>
</table>
The cost of taxi, by comparison, is governed by a meter rate that depends on distance and travel time.

\[ AC_t = \beta_0 + \beta_1 l + \beta_2 d \]

- \( l \) distance traveled [dist]
- \( d \) delay (time exceeding travel at 25 mph) [time]

### Parameter Value

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Cost, ( \beta_0 )</td>
<td>2.40 $/trip</td>
</tr>
<tr>
<td>Cost per Distance, ( \beta_1 )</td>
<td>2.50 $/mile</td>
</tr>
<tr>
<td>Cost per Delay Time, ( \beta_2 )</td>
<td>21.00 $/hr</td>
</tr>
</tbody>
</table>

Source: Yellow Cab of Springfield
Identifying Opportunities to Reduce Cost

Coordination with Taxis and TNCs

Average Trip Length

Estimated Average Taxi Fare

Which trips should be incentivized to switch to taxi or TNC to minimize total cost of paratransit operations and subsidies?
System cost is minimized by transferring trips that can be served by taxi at less than the marginal cost of paratransit.

1) Sort trips from lowest to highest expected taxi trip cost

2) Plot against marginal cost of paratransit trips in order of decreasing demand

3) Identify threshold cab fare which matches marginal cost of paratransit; all lower fares would be more cost on taxi

Suppose customers can be incentivized to switch to taxi by offering a subsidized fare.
Coordination with Taxis and TNCs

Case 1: All Customers Potentially Use Taxi

Consider the whole day as a single time period

![Graph showing cost per trip and annual combined cost as functions of annual demand shifted to taxis, λₜ. The graph includes lines for average paratransit cost, marginal paratransit cost, and taxi fare.](image-url)
Case 2: Only Ambulatory Customers Can Use Taxi

75% of PVTA’s customers are ambulatory (not in wheelchair)
### Comparing Existing and Coordinated Systems

<table>
<thead>
<tr>
<th>Case</th>
<th>Threshold Price</th>
<th>Taxi Demand</th>
<th>Paratransit Demand</th>
<th>Annual Cost*</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Paratransit</td>
<td>0</td>
<td>206,100</td>
<td>0</td>
<td>$6,163,000</td>
</tr>
<tr>
<td>All Taxi</td>
<td>206,100</td>
<td>0</td>
<td>0</td>
<td>$4,537,000</td>
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<tr>
<td>Case 1</td>
<td>$28.09</td>
<td>162,700</td>
<td>43,400</td>
<td>$4,182,000</td>
</tr>
<tr>
<td>Case 2</td>
<td>$27.13</td>
<td>105,400</td>
<td>100,700</td>
<td>$5,074,000</td>
</tr>
</tbody>
</table>

*Considering the whole day as a single time period

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**Percent of trips shifted to taxi**

- 0% - 25%
- 25% - 50%
- 50% - 75%
- 75% - 100%

**Case 1**

**Case 2**
Case 3: Consider Varying Demand by Time of Day

The marginal cost varies by time of day, because demand varies by time of day.

- Separate trip data into time periods reflecting changing demand and traffic congestion
- Marginal cost is greatest during peak demand, when more vehicles would need to be purchased to serve more trips
- During off-peak periods, marginal cost depends only on operating costs of VMT and VHT (not fleet acquisition).
## Optimizing Paratransit and Taxis

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Threshold Price</th>
<th>Taxi Demand</th>
<th>Paratransit Demand</th>
<th>Required Fleet Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>6am – 9am</td>
<td>$19.51</td>
<td>14,503</td>
<td>30,662</td>
<td>20</td>
</tr>
<tr>
<td>9am – 12pm</td>
<td>$19.51</td>
<td>19,329</td>
<td>24,569</td>
<td>16</td>
</tr>
<tr>
<td>12pm – 3pm</td>
<td>$19.56</td>
<td>17,447</td>
<td>27,027</td>
<td>18</td>
</tr>
<tr>
<td>3pm – 6pm</td>
<td>$31.35</td>
<td>42,826</td>
<td>29,733</td>
<td>20</td>
</tr>
<tr>
<td>All Trips Served by ADA Paratransit</td>
<td></td>
<td></td>
<td>$6,760,000 per year</td>
<td></td>
</tr>
</tbody>
</table>

- **Optimized Taxi and Paratransit (Case 3)**
  - 6am – 9am: $19.51, 14,503, 30,662, 20
  - 9am – 12pm: $19.51, 19,329, 24,569, 16
  - 12pm – 3pm: $19.56, 17,447, 27,027, 18
  - 3pm – 6pm: $31.35, 42,826, 29,733, 20
  - **$4,890,000 per year**
Insights and Observations

- Extensive data about demand and operations allows demand responsive transit services to be optimized.

- There are large opportunities to reduce costs through strategic partnerships with taxis and TNCs (~28% based on analysis of time-varying demand).

- In Springfield, incentivized trips to divert to taxi are typically in the urban core (i.e., divert shorter trips).
Regional Paratransit Service

- Annual Trips: 2,188,000 trips/yr
- Service Region: 630 mi²
- Average Operating Cost: $46.62 per trip

Fare to customers: $3.15
October 2016  400 initial participants allocated 20 trips/month
Customer pays $2; MBTA pays the next $13

January 2017  Trip allocation assigned based on previous usage:
2, 20, 25 trips/mo

March 2017  Opened to all The Ride customers
Customer pays $1 on UberPool

June 2017  Allocation tiers adjusted to
2, 10, 20, 30, 40 trips/month

October 2017  MBTA subsidy increased to $40 limit per trip
Initial Developments

Support for the Pilot
• Allows faster, cheaper, same-day service → Customers are pleased with improved service
• Political support and momentum from as high as Governor Baker.

Risks and Challenges
• Customers make more 43% more trips on TNCs, undercutting savings; currently pilot reduces costs by about 1% per customer.
  – ADA does not allow limiting trips or restricting purpose
• Uber and Lyft are platforms not operators
  – Not enough Wheelchair-Accessible Vehicles (WAV)
  – Lower levels of driver screening and training
Coordination with Taxis and TNCs

Coordinating Paratransit and Other Services

Dense, stable demand is most efficient for paratransit.

Alternative providers are best suited for serving:

- **Spatial Fringe**
- **Temporal Fringe & Peaks**

![Graph showing demand rate over time with peaks during certain hours.]
Coordination with Taxis and TNCs

Research Questions

• How do TNCs (same-day service) affect demand?
  – Who is using these services?
  – How many trips are they making?
  – Where are they going?

• How should the remaining van service be organized, if it continues to operate at all?

• What changes in regulation or incentive policies should be made to utilize current and emerging technologies?
Related Publications


