Across Latitudes and Cultures
Bus Rapid Transit Centre of Excellence

Juan Carlos Muñoz
Pontificia Universidad Católica de Chile
Northwestern University; April 7, 2011
CoE ALC-BRT

- Who we are
- Objectives
- Selected projects
Who we are

- Headquarters: Department of Transport Engineering and Logistics at the Pontificia Universidad Católica de Chile
- Instituto Superior Técnico from the Lisbon Technical University
- Institute of Transport and Logistics Studies from the University of Sydney
- Massachusetts Institute of Technology
- EMBARQ Network from The World Resources Institute Centre for Sustainable Transport
Our Vision

BRT systems are a feasible instrument to make metropolitan areas more sustainable from the economic, financial, social, political, technical and environmental perspectives, making them more attractive places to live, work and visit.

We will not be a BRT Advocacy agency. Instead, we will give clear guidelines on when and how BRT projects can effectively enhance mobility and meet accessibility needs.
Our Main Objective

Develop a new framework for the planning, design, financing, implementation, operation and control of BRT.
Our Objectives

• Give clear guidelines to decision makers on when and how BRT projects can effectively enhance mobility and meet accessibility needs.

• Support the successful deployment of BRT, through the identification and effective communication of the conditions necessary for success at the strategic, tactical and operational decision levels.
Two selected research projects

Consider a BRT corridor...

1.- What can we achieve in time savings, reliability and comfort if properly controlled?

2.- What types of services should you operate?
What can we achieve in time savings, reliability and comfort if properly controlled?

Felipe Delgado, Juan Carlos Muñoz, Ricardo Giesen

Depto. Ingeniería de Transporte y Logística, Pontificia Universidad Católica de Chile
Motivation
Motivation
Bus bunching

- Severe problem if not controlled
  - Most passengers wait longer than they should for crowded buses
  - Put pressure in the authority for more buses
  - Reduces reliability affecting passengers and operators
Outline

1. Objective

2. System Characteristics and State Variables

3. Model

4. Experiment

5. Results

6. Conclusions
1. Objective

- Consider a high frequency & capacity-constrained corridor.

- Consider two control strategies:
  - Holding
  - Boarding Limits

- Understand their impact in waiting time, reliability and comfort

- Identify scenarios where they are more useful.
Innovations

1.- Decision variables:
   Holding
   Boarding Limits

   This can be used even when at less than physical capacity in order to increase operating speed.

2.- Bus capacity incorporated without resorting to binary variables
2. System Characteristics

The system is composed by:

One-way loop Transit corridor.

Operated by a single service.

$N$ stops.

$K$ homogeneous buses.
2. State Variables

Real Time information about:

- Bus position.
- Bus loads.
- # of Passengers waiting at each stop.

However, we could work with estimations...
3. Model: Assumptions

Some information about trip destinations.

Dwell time: dominated by boardings.

Buses serve all stops and overtaking is not allowed.
3. Model: Problem definition

Every time a bus reaches a stop:

- How much to hold it?
- Should we prevent some passengers from boarding?

Solve a rolling horizon optimization problem to take those single decisions.
3. Model: Problem definition

Every time a bus reaches a stop:

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3. Model: Problem definition

Every time a bus reaches a stop:

How much to hold it?

Should we prevent some passengers from boarding?

Solve a rolling horizon optimization problem to take those single decisions
3. Model: Objective Function

1. Waiting time experienced by passengers as they wait for the first bus to arrive, \( W_{\text{first}} \)

\[
\sum_{k=1}^{K} \sum_{n=e_{k}+1}^{e_{k+1}} \left\{ \frac{\lambda_n}{2} \cdot (td_{kn} - t_0)^2 + c_n \cdot (td_{kn} - t_0) \right\} + \sum_{k=2}^{K} \sum_{n=e_{k-1}+1}^{e_k} \left\{ \frac{\lambda_n}{2} \cdot (td_{kn} - td_{k-1n})^2 \right\} + \sum_{n=e_K+1}^{e_1} \left\{ \frac{\lambda_n}{2} \cdot (td_{1n} - td_{kN})^2 \right\}
\]

2. In-vehicle waiting time for passengers aboard a bus being held, \( W_{\text{in-veh}} \)

\[
\sum_{k=1}^{K} \sum_{n=2}^{N} mt_{kn} \cdot h_{kn-1} + \sum_{k=1}^{K} mt_{k1} \cdot h_{kN}
\]
3. Model: Objective Function

3. Extra waiting time for passengers prevented from boarding a bus, \( W_{\text{extra}} \)

\[
\sum_{k=1}^{K-1} \sum_{n=e_{(k-1)}+1}^{e_k} w_{kn-1} \cdot (td_{kn} - td_{k-1n}) + \sum_{n=e_K+1}^{e_t} w_{Kn} \cdot (td_{1n} - td_{Kn})
\]

4. Penalty for passengers left behind if there is available capacity, \( PE \)

\[
\sum_{k=1}^{K} \sum_{n=2}^{N} w_{kn-1} \cdot S_{kn} + \sum_{k=1}^{K} w_{kN} \cdot S_{k1}
\]
3. Model: Objective Function

\[
\min_{h_{kn}, w_{kn}} \theta_1 \cdot W_{\text{first}} + \theta_2 \cdot W_{\text{in-veh}} + \theta_3 \cdot W_{\text{extra}} + \theta_4 \cdot PE
\]
# 3. Model: Constraints

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ td_{kn} = t_0 + \frac{r_{n-1} - d_k}{v_{n-1}} + f_{kn} + h_{kn} ]</td>
<td>Departure times from stop &lt;br&gt;∀ k: n = e_k + 1 (1)</td>
</tr>
<tr>
<td>[ td_{kn} = td_{kn-1} + \frac{r_{n-1}}{v_{n-1}} + f_{kn} + h_{kn} ]</td>
<td>∀ k: n = e_k + 2, ..., N (2)</td>
</tr>
<tr>
<td>[ m_{kin} = b_{ki} \cdot (1 - \sum_{j=i+1}^{n-1} p_{kj}) ]</td>
<td>Bus loads &lt;br&gt;∀ k: n = e_k + 2, ..., N+1; i=1,2,...,n-2 (3)</td>
</tr>
<tr>
<td>[ m_{kin} = b_{ki} ]</td>
<td>∀ k: n = e_k + 2, ..., N+1; i=n-1 (4)</td>
</tr>
<tr>
<td>[ mt_{kn} = \sum_{j=1}^{n-1} m_{kin} ]</td>
<td>Available bus capacity &lt;br&gt;∀ k: n = e_k + 1, ..., N+1 (5)</td>
</tr>
<tr>
<td>[ s_{kn} = cap - mt_{kn} ]</td>
<td>Potential passenger demand</td>
</tr>
<tr>
<td>[ dp_{kn} = c_{kn} + \lambda_n \cdot (td_{kn} - t_n) ]</td>
<td>Number of passengers alighting a bus at a stop &lt;br&gt;∀ k: n = e_k + 1, ..., e_{(k-1)} (7)</td>
</tr>
<tr>
<td>[ dp_{kn} = w_{k-n} + \lambda_n \cdot (td_{kn} - td_{k-n}) ]</td>
<td>Passengers prevented from boarding &lt;br&gt;∀ k: n = e_k + 1, ..., N (9)</td>
</tr>
<tr>
<td>[ a_{kn} = \sum_{j=1}^{n-1} b_{kj} ]</td>
<td>Passengers allowed to board &lt;br&gt;∀ k: n = e_k + 1, ..., N (12)</td>
</tr>
<tr>
<td>[ w_{kn} \geq dp_{kn} - s_{kn} - a_{kn} ]</td>
<td>Dwell time &lt;br&gt;∀ k: n = e_k + 1, ..., N (10)</td>
</tr>
<tr>
<td>[ w_{kn} \geq 0 ]</td>
<td>Buses can not overtake &lt;br&gt;∀ k ≠ 1; n = e_k + 1, ..., N (14)</td>
</tr>
<tr>
<td>[ b_{kn} = dp_{kn} - w_{kn} ]</td>
<td>∀ k: n = e_k + 1, ..., N (12)</td>
</tr>
<tr>
<td>[ f_{kn} = b_{kn} \cdot t_b ]</td>
<td>&lt;br&gt;∀ k: n = e_k + 1, ..., N (13)</td>
</tr>
<tr>
<td>[ td_{kn} - td_{k-n} \geq 0 ]</td>
<td>&lt;br&gt;Buses can not overtake (14)</td>
</tr>
<tr>
<td>[ l_n - td_{Kn} \geq 0 ]</td>
<td>&lt;br&gt;∀ k: n = e_k + 1, ..., N (15)</td>
</tr>
</tbody>
</table>
4. Experiment: Simulation Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Bus capacity is reached</th>
<th>Service frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>High</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>High</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>Medium</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>Medium</td>
</tr>
</tbody>
</table>
4. Experiment: Simulated control strategies

No control

Spontaneous evolution of the system.

Buses are dispatched from the terminal as soon as they arrive or until they reach the designed headway.

No other control action is taken along the route.

Threshold control

Myopic rule of regularization of headways between buses.

At each stop a bus is held if the headway with the previous bus is less than the designed headway.

Dispatched immediately in other case
4. Experiment: Simulated control strategies

**Holding & Boarding Limits (HBL)**
- Solve the rolling horizon optimization model
- No penalty for passengers left behind

**Holding (H)**
- Solve the rolling horizon optimization model
- Very high penalty so boarding limits are never used.
- Holding is the only decision variable.
5. Results

30 runs for every combination of strategies and scenarios

Each run represents 2 hours of bus operation.

15 minutes “warm-up” period.

Variability is introduced in the simulation experiment.
5. Results: Simulation Framework
5. Results: High frequency scenario
## 5. Results: High frequency scenario

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>No control</td>
<td>Threshold control</td>
</tr>
<tr>
<td>Wfirst</td>
<td>4552.10</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>459.78</td>
</tr>
<tr>
<td>% reduction</td>
<td>-73.19</td>
</tr>
<tr>
<td>Wextra</td>
<td>1107.37</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>577.01</td>
</tr>
<tr>
<td>% reduction</td>
<td>-40.25</td>
</tr>
<tr>
<td>Win-veh</td>
<td>270.57</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>36.00</td>
</tr>
<tr>
<td>% reduction</td>
<td>2317.74</td>
</tr>
<tr>
<td>Tot</td>
<td>5930.03</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>863.80</td>
</tr>
<tr>
<td>% reduction</td>
<td>42.05</td>
</tr>
</tbody>
</table>

*22-04-2011*
## 5. Results: Medium frequency scenarios

<table>
<thead>
<tr>
<th></th>
<th>Scenario 3</th>
<th></th>
<th></th>
<th>Scenario 4</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No control</td>
<td>Threshold control</td>
<td>H</td>
<td>HBL</td>
<td>No control</td>
<td>Threshold control</td>
</tr>
<tr>
<td>Wfirst</td>
<td>3654.20</td>
<td>667.14</td>
<td>280.38</td>
<td>73.06</td>
<td>1178.27</td>
<td>59.47</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>1196.42</td>
<td>738.44</td>
<td>276.27</td>
<td>188.96</td>
<td>874.95</td>
<td>175.22</td>
</tr>
<tr>
<td>% reduction</td>
<td>-81.74</td>
<td>-92.33</td>
<td>-98.00</td>
<td>-94.95</td>
<td>-98.28</td>
<td>-97.88</td>
</tr>
<tr>
<td>Wextra</td>
<td>777.65</td>
<td>379.24</td>
<td>11.68</td>
<td>343.60</td>
<td>12.64</td>
<td>0.58</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>784.90</td>
<td>608.44</td>
<td>15.77</td>
<td>120.95</td>
<td>19.41</td>
<td>2.21</td>
</tr>
<tr>
<td>% reduction</td>
<td>-51.23</td>
<td>-98.50</td>
<td>-55.82</td>
<td>-95.41</td>
<td>-52.92</td>
<td>-41.27</td>
</tr>
<tr>
<td>Win-veh</td>
<td>156.52</td>
<td>2004.85</td>
<td>1201.92</td>
<td>1020.95</td>
<td>74.58</td>
<td>667.83</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>68.80</td>
<td>669.44</td>
<td>159.17</td>
<td>110.13</td>
<td>23.31</td>
<td>163.34</td>
</tr>
<tr>
<td>% reduction</td>
<td>1180.87</td>
<td>667.89</td>
<td>552.27</td>
<td>795.43</td>
<td>601.13</td>
<td>597.60</td>
</tr>
<tr>
<td>Tot</td>
<td>4588.37</td>
<td>3051.22</td>
<td>1493.99</td>
<td>1437.61</td>
<td>1265.49</td>
<td>727.88</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>1920.05</td>
<td>1966.02</td>
<td>426.32</td>
<td>320.08</td>
<td>891.72</td>
<td>324.81</td>
</tr>
<tr>
<td>% reduction</td>
<td>-33.50</td>
<td>-67.44</td>
<td>-68.67</td>
<td>-42.48</td>
<td>-56.60</td>
<td>-56.33</td>
</tr>
</tbody>
</table>
5. Results: **Trajectories Scenario 1**  
(Capacity reached & high frequency)
5. Results: **Trajectories Scenario 1**
(Capacity reached & high frequency)
5. Results: **Bus Loads** Scenario 1
(Capacity reached & high frequency)

[Graphs showing bus loads for 'No Control' and 'Threshold' scenarios, with load and stop axes labeled.]
5. Results: **Bus Loads**  Scenario 1  
(Capacity reached & high frequency)
5. Results: **Cycle Time**  
Scenario 1  
(Capacity reached & high frequency)

![Histograms showing cycle times](image)

- **No Control**
  - Mean = 33.64
  - Std. Dev. = 3.51

- **Threshold**
  - Mean = 35.62
  - Std. Dev. = 1.38

22-04-2011
5. Results: **Cycle Time**  Scenario 1
(Capacity reached & high frequency)
### 5. Results: Waiting time Distribution Scenario 1 (Capacity reached & high frequency)

<table>
<thead>
<tr>
<th></th>
<th>Period 15-25</th>
<th></th>
<th></th>
<th>Period 25-120</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-2 min</td>
<td>2-4 min</td>
<td>&gt; 4 min</td>
<td>0-2 min</td>
<td>2-4 min</td>
<td>&gt; 4 min</td>
</tr>
<tr>
<td><strong>No Control</strong></td>
<td>57.76</td>
<td>29.60</td>
<td>12.64</td>
<td>63.46</td>
<td>27.68</td>
<td>8.86</td>
</tr>
<tr>
<td><strong>Threshold Control</strong></td>
<td>78.15</td>
<td>20.64</td>
<td>1.21</td>
<td>82.52</td>
<td>16.46</td>
<td>1.02</td>
</tr>
<tr>
<td><strong>H</strong></td>
<td>79.24</td>
<td>20.29</td>
<td>0.47</td>
<td>87.30</td>
<td>12.62</td>
<td>0.08</td>
</tr>
<tr>
<td><strong>HBL</strong></td>
<td>78.47</td>
<td>21.33</td>
<td>0.20</td>
<td>89.40</td>
<td>10.59</td>
<td>0.01</td>
</tr>
</tbody>
</table>
5. Results: **Computational time Scenario 1**  
(Capacity reached & high frequency)

Problem solved using MINOS in an Intel Core2 Duo @ 2.66 GHz

Confidence Interval 95%

(n=1403)
6. Conclusions

Developed a tool for Holding and Boarding limits strategy.

Boarding Limits only attractive in high demand and high frequency scenarios.

Savings up to 68% in waiting times are obtained.

Severely impacts in comfort and reliability

The tool is fast enough for real time applications.
Choosing the Right Express Services for a Bus Corridor with Capacity Constraints

Carola Leiva, Homero Larrain, Juan Carlos Muñoz and Ricardo Giesen
### Introduction

<table>
<thead>
<tr>
<th>All stop services</th>
<th>Limited stop services*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher in-vehicle travel time.</td>
<td>Lower in-vehicle travel time.</td>
</tr>
<tr>
<td>Similar waiting times for different O/D pairs.</td>
<td>Most waiting times increase, some decrease.</td>
</tr>
<tr>
<td>No transfers.</td>
<td>May force some transfers.</td>
</tr>
<tr>
<td>Higher operation costs, in terms of $/Km.</td>
<td>Lower operation costs, in terms of $/Km.</td>
</tr>
<tr>
<td>Other aspects: capacity, comfort, accessibility, etc.</td>
<td></td>
</tr>
</tbody>
</table>

*Jointly operated with all stop services, assuming a constant fleet size.
Objective

• Formulate a model that allows to choose which combination of services to provide on a corridor, and their optimal frequencies.

• Determine opportunities for express services (or limited stop) on a corridor based on its demand characteristics.
The Problem
The Problem

- Different operation schemes.

The goal is to find which services to offer, and their optimal frequencies.
Related Works

- Furth and Day (1985) discussed different planning strategies for high demand corridors, including:
  - Short turn (Furth, 1987).
  - Express services.
- Transit modeling:
  - User behavior: Chriqui & Robillard (1975)
The Model

• The goal of this model is to find the set of services that minimize social costs:
  – Operator costs: will depend on what services are provided, and their frequencies.
  – User costs:
    • In-vehicle travel time.
    • Wait time.
    • Transfers.
The Model: Assumptions

- Given transit corridor, with a given set of stops.
- Corridor OD matrix is known for a certain period.
- Set of potential lines
- Random arrival of passengers at constant average rate.
- Passengers minimize their expected travel times.
- Fares are constant for a full trip.
The Model: Notation

- **Notation:**

- $T_{(2,n)}$: Demand for an O/D pair $w$.
- $f_i$: frequency of line $l$
- $V^w_s$: Passenger flow in leg $s$ traveling on pair $w$. 

---

**Diagram:**

- $p_1$, $p_2$, ..., $p_n$
- $l_1, f_1$
- $l_2, f_2$
- $V^{(2,n)}_{(2,1)}$
- $V^{(2,n)}_{(1,n)}$
The Model: Operator Costs

- Assumption: the costs from operating a given service are proportional to it’s frequency.

\[ C_{Op} = \sum_{l \in L} c^l_o f_l \]
The Model: User Costs

- Travel time:
  \[ TT_s = \frac{\sum_{l \in L} tt^s_l \cdot f^s_l}{\sum_{l \in L} f^s_l} \]
  \[ C_{tt} = c_{travel} \sum_{w \in W} \sum_{s \in S} V^w_s \cdot TT_s \]

- Wait time:
  \[ WT_s = \frac{\lambda}{\sum_{l} f^s_l} \]
  \[ C_{wt} = c_{wait} \sum_{w \in W} \sum_{s \in S} V^w_s \cdot WT_s \]

- Transfers:
  \[ C_{tr} = c_{transfer} \left( \sum_{w \in W} \sum_{s \in S} V^w_s - \sum_{w \in W} T^w_w \right) \]
The Model: Formulation

Minimize social costs:

$$\min_{\{f_l, f_l^s, V_s^w\}} (C_{Op} + C_{tt} + C_{wt} + C_{tr})$$

Subject to:

$$\sum_{s \in S_i^+} V_s^w - \sum_{s \in S_i^-} V_s^w = \begin{cases} T_w & \text{if } i = O \\ -T_w & \text{if } i = D \\ 0 & \text{otherwise.} \end{cases} \quad \forall i \in \{1, \ldots, n\}, \forall w \in W$$
The Model: Key Elements

• Capacity & User behavior:
  – If capacity levels are not reached, the optimization will be consistent with a user equilibrium
  – However, when capacity is taken into account, the results may not be consistent with user equilibrium.

• $T_{AB}, T_{AC}$
• Line 1 is faster but much more expensive than line 2
• What will our model select?
The Model: Key Elements

• Capacity & User behavior:
  – If capacity levels are not reached, the optimization will be consistent with a user equilibrium.
  – However, when capacity is taken into account, the results may not be consistent with user equilibrium.
  – An iterative method was designed where the frequencies of lines were increased until they met requirements.
  – The solution obtained by this method satisfies capacity constraints and user behavior.
We used the methodology to understand what factors make express services more appealing
The Experiment: Scenario Definition

- **Load Profile**
  - 3 scenarios

- **Demand Level**
  - x1.2
  - x1
  - x0.8

- **Unbalance Level**
  - x0.5
  - x0.2

- **Avg. Trip Length**
  - Long
  - Mid
  - Short

Total scenarios = 3 * 3 * 3 * 3 = 81 scenarios

$T_w$ (O/D matrix)
Dispersion v/s Concentration

• Disperse O/D trips:
  – Trips are spread among available O/D pairs.
Dispersion v/s Concentration

- Concentrated O/D trips:
  - Some O/D pairs attract a big proportion of the total trips.

Express services should work better in this scenario.
Final remarks

• Express services reduces significantly social costs (up to 10%).

• Limited stop services are more promising in these situations:
  – The longer the average trip length.
  – When the load profile decreases along the corridor.
  – When the demand is mostly concentrated into a few O/D pairs.

• OD matrices will change once express services are implemented.
  – Trip concentration will tend to increase!
Final remarks

• Further research:
  – Modeling the effect of access costs and bus stop election.
  – Studying how travel and detention times, corridor length, and bus stop density affect on limited stop schemes design.
    • Generate a compact indicator for how appealing express services would be
  – Extending to a network configuration.
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www.caspt.org
Questions...
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April 7, 2011 Northwestern University