Modelling competition in demand-based optimization models

Stefano Bortolomiol
Virginie Lurkin  Michel Bierlaire

Transport and Mobility Laboratory (TRANSP-OR)
École Polytechnique Fédérale de Lausanne

Swiss Operations Research Days

Bern, 12 June 2018
Outline

1. Motivation
2. Modelling the problem
3. Current status of the research
Motivation

Modelling the problem

Current status of the research
Competition in transportation

- Competition is often present in the form of oligopolies (regulations, limited capacity of the infrastructure, barriers to entry, etc.).

- Deregulation often led to oligopolistic markets.
  - Airlines
  - Railways
  - Buses
Motivation

Trending topic

TRANSPORTS FlixBus ET EuRoBUS s'Allient pour Desservir la Suisse

Les deux compagnies de bus FlixBus et EuRoBUS se sont mises d'accord pour démarrer le cabotage en Suisse à partir du 10 juin. C'est une concurrence accrue pour les CFF.

PAR PASCAL SCHMUCK ZURICH 05.06.2018

ARTICLES EN RELATION
• Gros succès de FlixBus en Suisse
• FlixBus épingle pour cabotage

FlixBus s'implante en Suisse. A partir du 10 juin, la compagnie allemande de bus desservira les trajets St-Gall-Aéroport de Genève, Coire-Sion, Coire-Aéroport de Zurich et Bâle EuroAirport-Lugano. Elles'associe avec EuRoBUS, la plus grande entreprise de bus en Suisse, révèle le Blick.

Réforme de la SNCF : à quoi va ressembler la suite après le vote du ...
LCI - 5 hours ago
Après son vote par l'Assemblée en avril, puis par le Sénat le 5 juin, le projet de loi de réforme de la SNCF doit faire l'objet d'une commission ...

Réforme de la SNCF. Faut-il vous préparer à une poursuite de la ...
Ouest-France - 6 Jun 2018

Contre la réforme ferroviaire, les cheminots envahissent le siège de la ...
Le HuffPost - 5 Jun 2018

SNCF : le Sénat a voté le projet de réforme ferroviaire
Franceinfo - 6 Jun 2018
Vote au Sénat de la réforme de la SNCF : la grève n'est pas finie
In-Depth - La Tribune.fr - 6 Jun 2018
Le Sénat vote la réforme de la SNCF
In-Depth - Le Figaro - 5 Jun 2018
How to study competitive transport markets?

- Modelling demand
- Modelling supply
- Modelling competition
Modelling demand

- Each customer chooses the alternative that maximizes his/her utility.
- Customers have different tastes and socioeconomic characteristics that influence their choice.
Motivation

Modelling supply

- Operators take decisions that optimize their objective function (e.g. revenue maximization).
- Decisions can be related to pricing, capacity, frequency, availability ...
- Decisions are influenced by:
  - The preferences of the customers
  - The decisions of the competitors
Modelling competition

- We consider non-cooperative games.

- We aim at understanding the Nash equilibrium solutions of such games, i.e. stationary states of the system in which no competitor has an incentive to change its decisions.
1 Motivation

2 Modelling the problem

3 Current status of the research
Modelling the problem

Starting point:
MILP for the demand-based optimization problem for one operator (Pacheco et al. (2017)).

The goal:
MILP that models the non-cooperative multi-leader-follower game played by operators and customers.
The framework

Three-level framework: customers, operators and market.

1. **Customer level**: discrete choice models take into account preference heterogeneity and model individual decisions. These can be integrated in a MILP by relying on simulation to draw from the distribution of the error term of the utility function.
The framework

Three-level framework: customers, operators and market.

1. **Customer level**: discrete choice models take into account preference heterogeneity and model individual decisions. These can be integrated in a MILP by relying on simulation to draw from the distribution of the error term of the utility function.

2. **Operators level**: a mixed integer linear program can maximize any relevant objective function.
The framework

Three-level framework: customers, operators and market.

1. **Customer level**: discrete choice models take into account preference heterogeneity and model individual decisions. These can be integrated in a MILP by relying on simulation to draw from the distribution of the error term of the utility function.

2. **Operators level**: a mixed integer linear program can maximize any relevant objective function.

3. **Market level**: Nash equilibrium solutions are found by enforcing best response constraints.
The framework: customer level

- For all customers \( n \in N \) and all alternatives \( i \in I \), \( R \) draws are extracted from the error term distribution, each corresponding to a different behavioral scenario. For each \( r \in R \) we have:

\[
U_{inr} = \beta_{in}p_{in} + q_{in} + \xi_{inr}
\]

where \( p_{in} \) is a variable endogenous to the optimization model, \( \beta_{in} \) is the corresponding parameter, \( q_{in} \) is the exogenous term and \( \xi_{inr} \) is the error term.

- In each scenario, customers choose the alternative with the highest utility:

\[
w_{inr} = 1 \text{ if } U_{inr} = \max_{j \in I} U_{jnr}, \text{ and } w_{inr} = 0 \text{ otherwise}
\]

- Over multiple scenarios, the probability of \( n \in N \) choosing \( i \in I \) is given by:

\[
P_{in} = \frac{\sum_{r \in R} w_{inr}}{R}
\]
The framework: operators level

- We assume that an operator $k \in K$ can decide on price $p_{in}$ and availability $y_{in}$ of each alternative $i \in C_k$ for all customers $n \in N$.

- Stackelberg game: the operator (the leader) knows the best response of the customers (“collective” follower) to all strategies.

- Objective function to be maximized by operator $k$:

$$V_k = \frac{1}{R} \sum_{i \in C_k} \sum_{n \in N} \sum_{r \in R} p_{in} w_{inr}$$
The framework: market level

- The payoff of an operator also depends on the strategies of the competitors
- Let’s define as $X_k$ the set of strategies that can be played by operator $k \in K$
- Condition for Nash equilibrium (best response constraints):
  $$V_k = V_k^* = \max_{x_k} V_k(x_k, x_{K\{k\}}) \quad \forall k \in K$$
- Nash (1951) proves that every finite game has at least one mixed strategy equilibrium solution
A fixed-point iteration method

- Sequential algorithm to find Nash equilibrium solutions of a two-player game:
  - Initialization: one player selects an initial feasible strategy.
  - Iterative phase: operators take turns and each plays its best response pure strategy to the last strategy played by the competitor.
  - Termination criterion: either a Nash equilibrium or a cyclic equilibrium is reached.
A fixed-point iteration method

- The algorithm reproduces the behavior of two or more operators that do not know the competitors’ objective function.

- Different initial strategies can lead to different equilibria.

- There is no guarantee that a pure strategy Nash equilibrium exists or that it is unique.
MILP formulations

Pure strategies:

- Each operator $k \in K$ chooses a pure strategy from a finite set $S_k$.
- Number of pure strategy solutions of the game: $|S| = \prod_{k \in K} S_k$.
- For each solution $s \in S$ we can derive a payoff function $V_{ks}$ for each operator $k \in K$.
- If $s \in S$ includes only best response strategies for all operators, then it is a pure strategy Nash equilibrium for the finite game.

Mixed strategies:

- Operator $k$ chooses a mixed strategy from the finite set $S_k$, i.e. a vector of probabilities $p_{sk}$ associated to all pure strategies $s_k$ in $S_k$, such that $\sum_{s_k \in S_k} p_{sk} = 1$. 

Customer level

Customer constraints:

\[ \sum_{i \in I} w_{inrs} = 1 \quad (1) \]

\[ w_{inrs} \leq y_{inrs} \quad (2) \]

\[ y_{inrs} \leq y_{ins} \quad (3) \]

\[ y_{ins} = 0 \quad (4) \]

\[ \sum_{n \in N} w_{inrs} \leq C_i \quad (5) \]

\[ C_i(y_{ins} - y_{inrs}) \leq \sum_{m \in N : L_{im} < L_{in}} w_{imrs} \quad (6) \]

\[ \sum_{m \in N : L_{im} < L_{in}} w_{imrs} \leq (C_i - 1)y_{inrs} + (n - 1)(1 - y_{inrs}) \quad (7) \]

\[ U_{inrs} = \beta_{inpins} + q_{in}^d + \xi_{inr} \quad (8) \]

\[ lbU_{nr} \leq z_{inrs} \leq lbU_{nr} + M_{Unr} y_{inrs} \quad (9) \]

\[ U_{inrs} - M_{Unr}(1 - y_{inrs}) \leq z_{inrs} \leq U_{inrs} \quad (10) \]

\[ z_{inrs} \leq U_{nr} \quad (11) \]

\[ U_{nr} \leq z_{inrs} + M_{Unr}(1 - w_{inrs}) \quad (12) \]
Operator and market level (Pure strategies)

Find \( s \in S \) such that \( e_s = 1 \)

\[
s.t.
\]

Equilibrium constraints:

\[
e_s \geq \sum_{k \in K} x_{ks} - (|K| - 1) \quad \forall s \in S \tag{13}
\]

\[
e_s \leq x_{ks} \quad \forall k \in K, \forall s \in S \tag{14}
\]

Operator constraints:

\[
V_{ks} = \frac{1}{R} \sum_{i \in C_k} \sum_{n \in N} \sum_{r \in R} p_{ins} w_{inrs} \quad \forall k \in K, \forall s \in S \tag{15}
\]

\[
V_{ks} \leq V_{kt}^{\text{max}} \quad \forall k \in K, \forall s \in S_k, \forall t \in S^C_k \tag{16}
\]

\[
V_{kt}^{\text{max}} \leq V_{ks} + M_r (1 - x_{ks}) \quad \forall k \in K, \forall s \in S_k, \forall t \in S^C_k \tag{17}
\]

\[
\sum_{s \in S} x_{ks} = |S^C_k| \quad \forall k \in K \tag{18}
\]
Modelling the problem

Operator and market level (Mixed strategies)

Find $p_{s_k}$, $b_{s_k}$, $r_{s_k}$, $V_{s_k}$, $V_k$ such that... or $\max \sum_{k \in K} V_k$ or...

s.t.

MILP mixed-strategy Nash:

$$\sum_{s_k \in S_k} p_{s_k} = 1 \quad \forall k \in K$$  \hspace{1cm} (19)

$$V_{s_k} = \sum_{s_k^C \in S_k^C} p_{s_k^C} V_k(s_k, s_k^C) \quad \forall k \in K, \forall s_k \in S_k$$  \hspace{1cm} (20)

$$V_k \geq V_{s_k} \quad \forall k \in K, \forall s_k \in S_k$$  \hspace{1cm} (21)

$$r_{s_k} = V_k - V_{s_k} \quad \forall k \in K, \forall s_k \in S_k$$  \hspace{1cm} (22)

$$p_{s_k} \leq 1 - b_{s_k} \quad \forall k \in K, \forall s_k \in S_k$$  \hspace{1cm} (23)

$$r_{s_k} \leq M b_{s_k} \quad \forall k \in K, \forall s_k \in S_k$$  \hspace{1cm} (24)

Pure strategy payoffs:

$$V_k(s_k, s_k^C) = \frac{1}{R} \sum_{i \in C_k} \sum_{n \in N} \sum_{r \in R} p_{ins} w_{inrs} \quad \forall k \in K, \forall (s_k, s_k^C) \in S$$  \hspace{1cm} (25)
### Numerical example: pure strategy equilibria

**Payoff matrix of player 1**

<table>
<thead>
<tr>
<th></th>
<th>S1 0.70</th>
<th>S1 0.73</th>
<th>S1 0.76</th>
<th>S1 0.79</th>
<th>S1 0.82</th>
<th>S1 0.85</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2 0.50</td>
<td>10.00</td>
<td>10.00</td>
<td>10.00</td>
<td>10.00</td>
<td>10.00</td>
<td>10.00</td>
</tr>
<tr>
<td>S2 0.53</td>
<td>10.49</td>
<td>10.60</td>
<td>10.60</td>
<td>10.60</td>
<td>10.60</td>
<td>10.60</td>
</tr>
<tr>
<td>S2 0.56</td>
<td>10.53</td>
<td>10.42</td>
<td>10.53</td>
<td><strong>10.86</strong></td>
<td>11.20</td>
<td>11.20</td>
</tr>
<tr>
<td>S2 0.59</td>
<td>10.27</td>
<td>10.03</td>
<td>9.80</td>
<td>9.91</td>
<td>10.62</td>
<td><strong>11.45</strong></td>
</tr>
<tr>
<td>S2 0.65</td>
<td>9.62</td>
<td>9.36</td>
<td>8.84</td>
<td>8.45</td>
<td>8.71</td>
<td>8.58</td>
</tr>
</tbody>
</table>

**Payoff matrix of player 2**

<table>
<thead>
<tr>
<th></th>
<th>S1 0.70</th>
<th>S1 0.73</th>
<th>S1 0.76</th>
<th>S1 0.79</th>
<th>S1 0.82</th>
<th>S1 0.85</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2 0.50</td>
<td>14.00</td>
<td>14.45</td>
<td>14.74</td>
<td>14.69</td>
<td><strong>14.76</strong></td>
<td>14.62</td>
</tr>
<tr>
<td>S2 0.53</td>
<td>14.00</td>
<td>14.45</td>
<td>14.74</td>
<td><strong>15.01</strong></td>
<td>14.60</td>
<td>14.45</td>
</tr>
<tr>
<td>S2 0.56</td>
<td>14.00</td>
<td>14.60</td>
<td>14.74</td>
<td><strong>14.85</strong></td>
<td>14.76</td>
<td>14.28</td>
</tr>
<tr>
<td>S2 0.59</td>
<td>14.00</td>
<td>14.60</td>
<td>15.05</td>
<td><strong>15.48</strong></td>
<td>15.09</td>
<td>14.45</td>
</tr>
<tr>
<td>S2 0.62</td>
<td>14.00</td>
<td>14.60</td>
<td>15.20</td>
<td>15.48</td>
<td><strong>15.91</strong></td>
<td>15.81</td>
</tr>
<tr>
<td>S2 0.65</td>
<td>14.00</td>
<td>14.60</td>
<td>15.20</td>
<td>15.80</td>
<td>15.91</td>
<td><strong>16.32</strong></td>
</tr>
</tbody>
</table>

(a) Game with 1 pure strategy Nash equilibrium

(b) Game with no pure strategy Nash equilibrium

Payoff matrices for two games with different support strategies. Best response payoffs are in bold. Equilibrium payoffs are in blue.
### Numerical example: mixed strategy equilibria

Payoff matrices of player 1 and player 2

<table>
<thead>
<tr>
<th></th>
<th>$S_1$ \ $S_2$</th>
<th>0.75</th>
<th>0.77</th>
<th>0.79</th>
<th>0.81</th>
<th>0.83</th>
<th>0.85</th>
<th>$p_1$</th>
<th>$V_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>10.00</td>
<td>10.00</td>
<td>10.00</td>
<td>10.00</td>
<td>10.00</td>
<td>10.00</td>
<td>10.00</td>
<td>0.00</td>
<td>10.00</td>
</tr>
<tr>
<td>0.52</td>
<td>10.40</td>
<td>10.40</td>
<td>10.40</td>
<td>10.40</td>
<td>10.40</td>
<td>10.40</td>
<td>10.40</td>
<td>0.00</td>
<td>10.40</td>
</tr>
<tr>
<td>0.54</td>
<td>10.80</td>
<td>10.80</td>
<td>10.80</td>
<td>10.80</td>
<td>10.80</td>
<td>10.80</td>
<td>10.80</td>
<td>0.27</td>
<td>10.80</td>
</tr>
<tr>
<td>0.56</td>
<td>10.42</td>
<td>10.53</td>
<td>10.86</td>
<td>11.09</td>
<td>11.20</td>
<td>11.20</td>
<td>0.73</td>
<td>10.80</td>
<td></td>
</tr>
<tr>
<td>0.58</td>
<td>9.74</td>
<td>9.86</td>
<td>10.09</td>
<td>10.44</td>
<td>10.67</td>
<td>11.37</td>
<td>0.00</td>
<td>10.05</td>
<td></td>
</tr>
<tr>
<td>0.60</td>
<td>9.60</td>
<td>9.60</td>
<td>9.72</td>
<td>10.08</td>
<td>10.44</td>
<td>10.68</td>
<td>0.00</td>
<td>9.70</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$S_1$ \ $S_2$</th>
<th>0.75</th>
<th>0.77</th>
<th>0.79</th>
<th>0.81</th>
<th>0.83</th>
<th>0.85</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>14.70</td>
<td>14.78</td>
<td>14.69</td>
<td>14.74</td>
<td>14.28</td>
<td>14.62</td>
<td></td>
</tr>
<tr>
<td>0.52</td>
<td>14.70</td>
<td>15.09</td>
<td>14.85</td>
<td>14.58</td>
<td>14.61</td>
<td>14.45</td>
<td></td>
</tr>
<tr>
<td>0.54</td>
<td>14.85</td>
<td>14.94</td>
<td>15.17</td>
<td>14.74</td>
<td>14.44</td>
<td>14.45</td>
<td></td>
</tr>
<tr>
<td>0.56</td>
<td>14.85</td>
<td>14.94</td>
<td>14.85</td>
<td>14.90</td>
<td>14.61</td>
<td>14.28</td>
<td></td>
</tr>
<tr>
<td>0.58</td>
<td>15.00</td>
<td>15.09</td>
<td>15.17</td>
<td>15.07</td>
<td>15.11</td>
<td>14.45</td>
<td></td>
</tr>
<tr>
<td>0.60</td>
<td>15.00</td>
<td>15.25</td>
<td>15.48</td>
<td>15.39</td>
<td>15.27</td>
<td>14.30</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$p_2$</th>
<th>0.19</th>
<th>0.81</th>
<th>0.00</th>
<th>0.00</th>
<th>0.00</th>
</tr>
</thead>
</table>

**Figure:** Game with mixed strategy Nash equilibrium
The model requires finite strategy sets (enumeration), therefore the problem is solvable with small solution spaces only.

The assumption of a finite game requires price discretization.

Formulation 1: all pure strategy Nash equilibria of the game can be found, if they exist.

Formulation 2: among the mixed strategy Nash equilibria, it is possible to select one by choosing a relevant objective function, e.g. total welfare maximization.
1 Motivation

2 Modelling the problem

3 Current status of the research
A MILP model for the fixed-point problem

The fixed-point iteration method stops when the same strategies are played in two consecutive iterations.

What if we can write a MILP model to minimize the "difference" in strategies between two consecutive iterations?
A MILP model for the fixed-point problem

- A solution for a two-operator problem: \((x_1, x_2)\)

- Optimization problem for operator 1:

  \[
  x_1^* = \arg \max_{x_1} V_1(x_1, x_2, (x_{cust}))
  \]

- Optimization problem for operator 2:

  \[
  x_2^* = \arg \max_{x_2} V_1(x_1, x_2, (x_{cust}))
  \]

- Fixed-point problem:

  \[
  \min_{x_1, x_2, x_1^*, x_2^*} ||x_1^* - x_1|| + ||x_2^* - x_2||
  \]
Future work

- Implement and test the MILP model for the fixed-point problem.
- Efficient search for equilibria in the solution space.
- Investigation of the concept of Nash equilibrium region for real-life applications.
Questions?

Stefano Bortolomiol

Transport and Mobility Laboratory (TRANSP-OR)
École Polytechnique Fédérale de Lausanne (EPFL)

Email: stefano.bortolomiol(at)epfl.ch