On the evaluation of autonomous delivery robots in the food industry

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First of all: Why should we evaluate the operation of ADRs?

**Answer:** To better understand the capabilities, benefits, and unintended consequences of these systems as an alternative to mitigate the externalities of freight transportation

**Background:**

- ADRs are an environmentally-friendly alternative since they do not produce tail-pipe emissions. They are considered as a replacement for ICE vans in the delivery of parcels.
- ADRs have proven to be a cost-efficient alternative to transport cargo in indoors environments.
- In theory, new technological developments have made ADRs a versatile and cost-efficient alternative for outdoor last-mile deliveries.
- More than 60% of merchants’ customers live within 3 miles of the store location. (FedEx research).
- Traffic incidents involving ADRs have been more common in recent years.
Our ADR: bot! by KiwiCampus

Bot 3.0 series features:

- Dual 4G LTE integrated GPS (communication system)
- 6 FOV 120° Cameras 1920*1080P: 3 frontals, 2 laterals, and 1 rear.
- 7 Benewakes (LIDAR): 5 frontals, 2 rear
- 1 AI computing module Jetson TX2
- Digital face: 9’’ LCD Screen
- Spot-lights UV 200
- Swappable lithium-ion batteries
- Payload capacity: one order
- Top speed: 10 mph.
- Pneumatic cargo compartment with remote opening/closing function.
The hybrid delivery system: bicycle + ADR

System description:
1. Customers order online
2. Restaurants have agreements with operator, facilitating the logistic process
3. Kiwers (biker) pick-up orders from restaurants
4. ADRs wait in strategic clusters to reduce the distance travelled
5. Kiwers load food to ADRs
6. ADRs deliver food to customers
7. ADRs & Kiwers reposition
Methodology

1. Field observation: descriptive analysis
2. Operation data analysis
3. Simulation and sensitivity analysis
4. Design of strategies to improve the system
Safety, mobility, and potential road conflicts
Safe sidewalk operation and crossing intersections; a big challenge

**Relevant factors:**

- Technological limitations, e.g., limited object recognition
- High network latency, i.e., delays in data reception
- Long reaction time by supervisors
- People’s curiosity
- Required human intervention, i.e., offline devices, stuck wheels
- Sidewalk topology and geometry
- Traffic conditions
Analysis of intersection delays

Pole Line and 5th Street: A complex intersection

- There were delays in 43% of the trials
- 10% of the delays range between 5 and 10.7 seconds
- 43% of the delays range between 1 and 5 seconds
- 47% of the delays range between 0 and 1 seconds
Operation data analysis
Semi-autonomous food delivery

How can we deliver on-time using kiwers and bots?

• Distribution network design
• Bikers schedule and bots’ fleet size
• Resource allocation to time-slots
• Queuing & repositioning
• Automation limitations
Data analysis

Weekly Operation Statistics

Ratio between delivery route distance and client-restaurant distance
Semi-autonomous food delivery

- Raw data: ~16,000 orders
- Total delivery
  - Avg. time ~45 mins
- Restaurant preparation
  - Avg. time ~19 mins (42%)
  - From when an order is placed in the app until the kiwer receives the order
- Kiwer delivery
  - Avg. time ~11 mins (24%)
- ADR delivery
  - Avg. time ~10 mins (22%)
- ADR waiting for the client
  - Avg. time ~5 mins (11%)
Scalability & Operations

• Delivery distance has an important effect on the system

• ADRs can travel faster but speeds are limited to avoid incidents and for better control
Simulation Model
## Results of Monte-Carlo Simulation

- Validation of simulation results for key parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\frac{1}{n} \sum x_n$</th>
<th>$\mu$</th>
<th>Rel. Error</th>
<th>P-Value*</th>
<th>Dist. Fit</th>
<th>Parameters</th>
<th>Log-Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Biker Speed</td>
<td>3.416</td>
<td>3.420</td>
<td>-0.132%</td>
<td>0.471</td>
<td>Gamma</td>
<td>K=2.352, θ=1.453</td>
<td>-6.686E+05</td>
</tr>
<tr>
<td>Avg Bot Speed</td>
<td>0.985</td>
<td>1.020</td>
<td>-3.431%</td>
<td>1.22E-08</td>
<td>Triangular</td>
<td>a=0.052, c=0.821, d=0.239</td>
<td>-6.146E+05</td>
</tr>
<tr>
<td>Avg Bot Proportion</td>
<td>0.306</td>
<td>0.307</td>
<td>-0.520%</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Avg Bot Delivery Time</td>
<td>10.202</td>
<td>10.221</td>
<td>-0.188%</td>
<td>0.408</td>
<td>Gamma</td>
<td>K=1.514, θ=6.749</td>
<td>-1.048E+06</td>
</tr>
<tr>
<td>Avg Biker Delivery Time</td>
<td>10.815</td>
<td>10.807</td>
<td>0.077%</td>
<td>0.741</td>
<td>Gamma</td>
<td>K=1.501, θ=7.196</td>
<td>-1.066E+06</td>
</tr>
<tr>
<td>Avg Restaurant Prep. Time</td>
<td>19.142</td>
<td>19.079</td>
<td>0.329%</td>
<td>0.071</td>
<td>Gamma</td>
<td>K=2.338, θ=8.157</td>
<td>-1.210E+06</td>
</tr>
<tr>
<td>Avg Waiting for client Time</td>
<td>4.317</td>
<td>4.330</td>
<td>-0.300%</td>
<td>0.375</td>
<td>Gamma</td>
<td>K=0.700, θ=6.180</td>
<td>-7.728E+05</td>
</tr>
<tr>
<td>Avg Delivery Time</td>
<td>44.476</td>
<td>44.438</td>
<td>0.086%</td>
<td>0.446</td>
<td>Gamma</td>
<td>K=6.218, θ=7.146</td>
<td>-1.356E+06</td>
</tr>
</tbody>
</table>

* Z-test P-Value; k: Shape; θ: Scale; a=lower bound; c=mode; d=upper bound.
Impact of demand levels on delivery times

Policy: Wait for 3 order(s)/Lambda = 1

- Total Delivery Time (min)
- Bots Number
- Kiwers Number
Impact of demand levels on productivity
Impact of automation on the system performance

- Required Person-Hours includes labor of Kiwers (bikers) + supervisors
- Robots capable of making a greater number of correct decisions require a higher level of automation
- Supervisors must reason decisions in situations that are unknown to the ADRs.
- Full automation may not be cost-efficient; supervise more than 6 robots reduce less than 6% of labor
Strategies to improve the system: Dispatch policies
Decision support plots for different Wait-for policies

<table>
<thead>
<tr>
<th>Wait-for Policy</th>
<th>BDS Person-Min/Ord</th>
<th>HDS Person-Min/Ord</th>
<th>BDS ADT/Ord</th>
<th>HDS ADT/Ord</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>21.8</td>
<td>29.73</td>
<td>36.09</td>
<td>39.6</td>
</tr>
<tr>
<td>W2</td>
<td>18.45</td>
<td>22.56</td>
<td>25.82</td>
<td>27.41</td>
</tr>
<tr>
<td>W3</td>
<td>17.4</td>
<td>20.08</td>
<td>22.1</td>
<td>23.42</td>
</tr>
<tr>
<td>W4</td>
<td>16.78</td>
<td>18.91</td>
<td>20.7</td>
<td>21.25</td>
</tr>
<tr>
<td>W5</td>
<td>16.35</td>
<td>18.12</td>
<td>19.67</td>
<td>20.15</td>
</tr>
<tr>
<td>W6</td>
<td>16.53</td>
<td>17.79</td>
<td>18.78</td>
<td>19.3</td>
</tr>
<tr>
<td>W7</td>
<td>16.31</td>
<td>17.4</td>
<td>18.45</td>
<td>18.73</td>
</tr>
<tr>
<td>W8</td>
<td>16.07</td>
<td>17.34</td>
<td>17.98</td>
<td>18.41</td>
</tr>
<tr>
<td>W9</td>
<td>15.9</td>
<td>16.91</td>
<td>17.66</td>
<td>18</td>
</tr>
<tr>
<td>W10</td>
<td>16.04</td>
<td>16.73</td>
<td>17.54</td>
<td>17.57</td>
</tr>
</tbody>
</table>

Bin (miles)

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## Summary of Wait-for policies impacts on the HDS

<table>
<thead>
<tr>
<th></th>
<th>10% time/35% labor red.</th>
<th>5% time/30% labor red.</th>
<th>Max. labor red.</th>
<th>Max. time red.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ADT</td>
<td>Avg. Labor</td>
<td>ADT</td>
<td>Avg. Labor</td>
</tr>
<tr>
<td><strong>Net Value</strong></td>
<td>39.84</td>
<td>11.48</td>
<td>42.17</td>
<td>12.46</td>
</tr>
<tr>
<td><strong>% Change</strong></td>
<td>-10.33%</td>
<td>-36.04%</td>
<td>-5.09%</td>
<td>-30.58%</td>
</tr>
</tbody>
</table>

*Relative change with respect to the base case*
Summary of Findings
Findings: efficiencies/inefficiencies

• **Times:**
  – Restaurant preparation time + Client picking/collection time ~53 % of delivery time;
  – Delivery time ~45 minutes within 1.25 miles and 56.29 miles within 2 miles
  – When service time and labor requirements are equally valued, the BDS is 5% faster than the HDS, but
    the latter requires 42% less labor

• **Market coverage:**
  – About a 1 – 1.5 mile radius (times are significantly larger after the 1.5 mile distance)
  – Spatial (dis) aggregation of demand affects resource requirements in 3-4x
  – Kiwers traveling ~2/3 of distances (about double the speed)

• **Human-hours of hybrid model:**
  – Fully ADRs vs. No automation of “DRs” can reduce human-hours requirements by 45-65%
  – Even in low to mid automation levels, remote supervision can bring significant reductions in costs
Any questions? Please contact:

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Impact of dispatching policy on productivity
Potential improvements

• Improvements:
  – Network design (multimodal, hubs)
  – Waiting/dispatch policies
  – Repositioning
  – Cluster evaluation (staging and transfer areas)
  – Decisions on Kiwer/ADR delivery split

• Impacts:
  – Potential traffic delays/conflicts with other curb users
  – Jobs
  – Requires transfer locations
SIMULATION MODEL

Stage 1: Output variables calculation
Input random variables initialize according to their distributions

A Client-Restaurant distance per bin
B Trips per bin
C Bot proportion per bin
D Waiting for client time
E Restaurant preparation time
F Biker average speed per bin
G Bot average speed per bin

H A*B = Total distance traveled per bin
I H*(L-D) = Biker distance traveled per bin
J H*C = Bot distance traveled per bin

K L = Biker delivery time per bin
L I/G = Bot delivery time per bin

Sort Stage 1 output variables

Stage 2: Resources assignment
Set scenario conditions
Set demand rate and interarrival order time
Set bikes/bot availability
Set wait for order policy
Assign bikes/bot to orders from Stage 1
Calculate orders delay
Recalculate delivery time
Calculate scenario system performance
Labor requirement

Definitive delivery time
Resources productivity

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Potential next steps

• Spatial and network modeling
• Multi-objective: Costs, labor, time, emissions, energy consumption, etc.
  – Time windows
  – Cluster locations
  – Backbone design (modes)
  – Dynamic demand/dispatching

• Efficient system deployment and operation methodology

• Traffic and sidewalk operation/policies
  – Intersection and sidewalk conflicts