Design of a mixed freights/people transportation system in the Physical Internet era

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## Outline

1. Introduction
2. The shared transportation system
3. The optimal matching problem
4. MILP Formulation
5. Case study
6. Conclusions
Introduction

Ride Sharing mobility service and the Physical Internet paradigm are considered together with the aim of better exploiting the supply capacity, thus reducing the number of travels and, consequently, users’ costs and also the environmental impact on the territory.
3 actors: drivers, riders, and logistic providers

- **drivers** can provide travel solutions to other users
- **riders** want to travel with drivers
- **logistic providers** need to move goods and parcels from one node to another of the network

Centralized approach

- A **supply manager** receives all the travel proposals and requests of drivers, riders, and logistic providers, builds shared travels by solving an optimal matching problem, and provides the solution to the users

Optimal matching problem

- MILP formalization
- Determination of the **optimal paths** of drivers, the **optimal pairings** drivers-riders and drivers-freight deliveries, and the **optimal arrival and departure times** of the various users of the system
The shared transportation system – Drivers & Riders

- **Drivers**
  - travel with their own cars (alone or with passengers)
  - agree to share their trip with some riders and to carry some parcels
  - agree to slightly anticipate or postpone their departure or arrival
  - agree to follow a path different from the shortest one
  - accept all shared travels proposed by the SM

- **Riders**
  - travel alone
  - can reach their own destination by means of multiple consecutive trips
The shared transportation system – **Freight deliveries**

The SM investigates the possibility of delivering the goods by means of the cars that belong to the drivers, in order to prevent the use of further vehicles (light trucks) in the network

- a single delivery, which is made of some boxes and parcels, can be split and assigned to multiple drivers
  
  *(Physical Internet principle)*

- goods (either split or not) can reach their destination by means of multiple consecutive trips
The shared transportation system – **Freight deliveries**

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- goods (either split or not) can reach their destination by means of multiple consecutive trips
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The SM investigates the possibility of delivering the goods by means of the cars that belong to the drivers, in order to prevent the use of further vehicles (light trucks) in the network:

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The shared transportation system – **Freight deliveries**

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- A single delivery, which is made of some boxes and parcels, can be split and assigned to multiple drivers

  *(Physical Internet principle)*

- Goods (either split or not) can reach their destination by means of multiple consecutive trips
The optimal matching problem

- Graph representation of the transportation network (origins and destinations of trips located at nodes)

- **Main decision variables:**
  - assignments of drivers, riders, and freight deliveries on arcs
  - matchings between drivers-riders and drivers-freight deliveries
  - actual departure times and actual arrival times

- **Main parameters:**
  - travel times on arcs
  - desired departure times and desired arrival times
  - delayed/anticipated departure/arrival gaps
The optimal matching problem

■ **sub-riders**
  - riders are “virtually decomposed” into sub-riders that can be matched, if necessary, with different drivers
  - the path followed by each sub-riders is suitably constrained so that the actual path of a rider consists of the chain of the relevant sub-riders

■ **partial freight deliveries and sub-deliveries**
  - each single box to be delivered represents a “partial freight delivery” to be suitable assigned to one or more drivers
  - each partial freight delivery can be multi-trip and therefore can be divided into some sub-deliveries (associated with different drivers)

■ **virtual drivers**
  - pair composed of a driver and a sub-ride (or a sub-delivery)
  - are used to compute arrival and departure times of drivers, riders, and freight deliveries at the various nodes of the transportation network
The optimal matching problem

- **Objectives**

  - finding the minimum deviation between the optimal computed departure and arrival times of drivers and riders with respect to the desired ones, thus determining solutions that are perceived as nearly optimal by users

\[
Q^d = \sum_{i \in D} \left[ f_i^d(d_i, \delta_i) + f_i^a(a_i, \alpha_i) \right] + \sum_{j \in R} \left[ f_j^d(d_j, \delta_j, 1) + f_j^a(a_j, \alpha_j, S_j) \right]
\]

\[
f^d(d_i, \delta_i) = \max \left\{ 0, \delta_i - (d_i + r_i^{dd}) \right\} + \max \left\{ 0, (d_i - r_i^{ad}) - \delta_i \right\}
\]

\[
f^a(a_i, \alpha_i) = \max \left\{ 0, \alpha_i - (a_i + r_i^{da}) \right\} + \max \left\{ 0, (a_i - r_i^{aa}) - \alpha_i \right\}
\]

\[
f^d(d_j, \delta_j, 1) = \max \left\{ 0, \delta_j, 1 - (d_j + r_j^{dd}) \right\} + \max \left\{ 0, (d_j - r_j^{ad}) - \delta_j, 1 \right\}
\]

\[
f^a(a_j, \alpha_j, S_j) = \max \left\{ 0, \alpha_j, S_j - (a_j + r_j^{da}) \right\} + \max \left\{ 0, (a_j - r_j^{aa}) - \alpha_j, S_j \right\}
\]
The optimal matching problem

- **Objectives**
  - finding the minimum deviation between the optimal computed departure and arrival times of drivers and riders with respect to the desired ones, thus determining solutions that are perceived as nearly optimal by users
  - minimizing the completion times of freight deliveries

\[ Q^c = \sum_{k \in L} \max(\alpha_k, 1, S_k, \ldots, \alpha_k, b_k, S_k) \]
The optimal matching problem

- **Objectives**
  - finding the minimum deviation between the optimal computed departure and arrival times of drivers and riders with respect to the desired ones, thus determining solutions that are perceived as nearly optimal by users
  - minimizing the completion times of freight deliveries
  - maximizing the number of matches

\[
Q^m = \sum_{j \in R} \left( 1 - \sum_{i \in D} \max(\theta_{j,1,i}, \ldots, \theta_{j,S_j,i}) \right) + \\
+ \sum_{k \in L} \left( b_k - \sum_{r=1}^{b_k} \sum_{i \in D} \max(\omega_{k,r,1,i}, \ldots, \omega_{k,r,S_k,i}) \right)
\]
The optimal matching problem

- **Objectives**

  - finding the minimum deviation between the optimal computed departure and arrival times of drivers and riders with respect to the desired ones, thus determining solutions that are perceived as nearly optimal by users
  - minimizing the completion times of freight deliveries
  - maximizing the number of matches
  - minimizing the number of sub-trips, again to improve the perceived utility of the proposed solution which decreases with the number of changes during the trip

\[ Q^s = \sum_{j \in \mathcal{R}} \sum_{s=1}^{S_j} \sum_{i \in \mathcal{D}} \theta_{j,s,i} + \sum_{k \in \mathcal{L}} \sum_{r=1}^{b_k} \sum_{s=1}^{S_k} \sum_{i \in \mathcal{D}} \omega_{k,r,s,i} \]
The optimal matching problem

- **Objectives**
  - finding the minimum deviation between the optimal computed departure and arrival times of drivers and riders with respect to the desired ones, thus determining solutions that are perceived as nearly optimal by users
  - minimizing the completion times of freight deliveries
  - maximizing the number of matches
  - minimizing the number of sub-trips, again to improve the perceived utility of the proposed solution which decreases with the number of changes during the trip
  - minimizing the splitting of freight deliveries

\[ Q^p = \sum_{k \in L}^{S_k} \sum_{s=1}^{D} \sum_{i \in D} \sum_{(r,v) \in B} \max \{0, \omega_{k,r,s,i} - \omega_{k,v,s,i}\} + \max \{0, \omega_{k,v,s,i} - \omega_{k,r,s,i}\} \]
MILP Formulation

\[
\min \quad w^d \tilde{Q}^d + w^c \tilde{Q}^c + w^m \tilde{Q}^m + w^s Q^s + w^p \tilde{Q}^p
\]

subject to:

- \ldots
- 63 sets of constraints
- \ldots

very large formulation!
MILP Formulation

\[
\mathcal{Q}^c + w^m \mathcal{Q}^m + w^s \mathcal{Q}^s + w^p \mathcal{Q}^p
\]

large formulation!
MILP Formulation

\[
\text{minimize } w_d \tilde{Q}_d + w_c \tilde{Q}_c + w_m \tilde{Q}_m + w_s Q_s + w_p \tilde{Q}_p \\
\text{subject to:}
\]

63 sets of constraints

**very large formulation**!
**MILP Formulation**

With each variable, it is possible to determine variables $\gamma_{d,s}$ and $\gamma_{c,p}$ by imposing the following conditions:

\[
\begin{align*}
\sum_{d \in D_s} \gamma_{d,s} & \leq A_s + \frac{1}{w_d} \sum_{d \in D_s} (1 - \delta_{d,s}) - A_s \quad \text{in } D_s \cap R_s \cap W = \emptyset, \ldots, \emptyset_2 \quad (3) \\
\sum_{c \in C_p} \gamma_{c,p} & \leq A_p + \frac{1}{w_c} \sum_{c \in C_p} (1 - \delta_{c,p}) - A_p \quad \text{in } W \cap C_p \cap V = \emptyset, \ldots, \emptyset_2 \quad (4) \\
\gamma_{d,s} & \geq A_s + \frac{1}{w_d} \sum_{d \in D_s} (1 - \delta_{d,s}) - A_s \quad \text{in } W \cap D_s \cap R_s \cap W = \emptyset, \ldots, \emptyset_2 \quad (5) \\
\gamma_{c,p} & \geq A_p + \frac{1}{w_c} \sum_{c \in C_p} (1 - \delta_{c,p}) - A_p \quad \text{in } W \cap C_p \cap V = \emptyset, \ldots, \emptyset_2 \quad (6)
\end{align*}
\]

In (3) and (4), $M$ is a suitably chosen constant ("big number") which ensures that, when $\gamma_{d,s} = 0$, the optimal value of the objective function $L$ is set to the value $\gamma_{d,s}$ which minimizes the related virtual driver willingness $v_s$. This is achieved by virtue of the right-hand side of (3) (and, similarly, $A_s + \frac{1}{w_d} \sum_{d \in D_s} (1 - \delta_{d,s}) - A_s$) instead, when $\gamma_{d,s} = 0$, is not constrained by the virtual driver driver $w_{d,s}$ and it is always satisfied. Analogous considerations hold for what concerns virtual courier and constraint (7) and (8).

In conclusion, it is worth saying that the introduction of virtual drivers allows determining, by means of linear equations, the number of virtual drivers instead the number of virtual couriers. Nevertheless, with this formulation, the number of variables and constraints increases significantly.

### Cost terms

The optimal matching problem has the objectives of:

1. finding the minimum deviation between the optimal cost of the system and of the system in the actual case, thus determining solutions that are perceived as nearly identical by users;
2. maximizing the completion times of freight deliveries;
3. minimizing the number of virtual drivers;
4. maximizing the number of virtual couriers, again in order to improve the predictive ability of the proposed solution which decreases with the number of changes during the trip;
5. minimizing the switching of freight deliveries.

The first cost term is defined as:

\[
\begin{align*}
\sum_{d \in D_s} \left[ a_{d,s} \gamma_{d,s} + \sum_{c \in C_p} b_{c,s} \gamma_{c,p} \right] + \\
\sum_{c \in C_p} \left[ a_{c,p} \gamma_{c,p} + \sum_{d \in D_s} b_{d,c} \gamma_{d,s} \right]
\end{align*}
\]

with

\[
\begin{align*}
\gamma_{d,s} & = \min \left( \delta_{d,s} - A_s, (a_s - c_s)^2 \right) + \\
\gamma_{c,p} & = \min \left( \delta_{c,p} - A_p, (a_p - c_p)^2 \right)
\end{align*}
\]

\[\vdots\]

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**Design of a mixed freights/people transportation system in the PL era**
With each variable it is possible to determine variables $y_{ij}$ and $y_{jk}$ by imposing the following conditions:

$$
\begin{align*}
\sum_{i \in A} x_{ij} & \leq A_j + \sum_{i \in A} \epsilon_{ij} a_{ij} + M (1 - \delta_{ij}) \quad \forall j \in R, y_{ij} = 1, \ldots, S_j, \quad (3)

\sum_{j \in R} x_{ij} & \leq A_i + \sum_{j \in R} \epsilon_{ij} a_{ij} + M (1 - \delta_{ij}) \quad \forall i \in C, \quad (4)

\sum_{i \in C} x_{ij} & \leq C_j + \sum_{i \in C} \epsilon_{ij} a_{ij} + M (1 - \delta_{ij}) \quad \forall j \in R, y_{ij} = 1, \ldots, S_j, \quad (5)

\sum_{j \in R} x_{ij} & \leq C_i + \sum_{j \in R} \epsilon_{ij} a_{ij} + M (1 - \delta_{ij}) \quad \forall i \in C, \quad (6)

\end{align*}
$$

In (5) and (6), $M$ is a suitably chosen constant ("big M") such that $y_{ij}$ is set to be the smallest solution of the linear program $\epsilon_{ij} a_{ij}$ subject to the right-hand side (RHS) constraint $y_{ij} = 1, \ldots, S_j$. Instead, when $y_{ij} = 0$, $\epsilon_{ij} a_{ij}$ is not considered in the considered diagnosis $x_{ij}$ and $y_{ij}$ are always satisfied. Analogous considerations hold for what concerns the decision variables and constraints (1) and (2).

In conclusion, it is worth noting that the introduction of virtual drivers allows determining, by means of linear programming, the number of virtual drivers and the number and composition of the mixed freight/regular sub-delivery. Nevertheless, with this formulation, the number of variables and constraints increase significantly.

5 Cost Terms

The optimal matching problem has the objective of:

1. finding the minimum deviation between the optimal computed departure and arrival times of drivers and trucks with respect to the actual times, thus determining solutions that are perceived as nearly optimal by the customers;
2. minimizing the completion time of freight delivery;
3. minimizing the number of subtrips, again to improve the pre-ordained ability of the proposed solution which decreases with the number of changes during the trip;
4. minimizing the frights delivery.

The first cost terms is defined as:

$$
\text{Cost} = \sum_{i \in A} \left[ p_i \left( d_i - f_i(a_{ij}) \right) + f_{ij} (a_{ij}) \right] \quad (7)
$$

with

$$
f_{ij} (a_{ij}) = \max \left( \min \left( a_{ij}, 0 \right), a_{ij} - a_i \right) \quad (8)
$$

$$
a_i = \frac{d_i}{1 - k_i} - \sum_{j \in R} y_{ij} \quad (9)
$$

$$
a_i \geq \min \left( a_i - a_i, 0 \right) \quad (10)
$$

$$
a_i \geq a_i - a_i \quad (11)
$$

$$
a_i \geq a_i - a_i \quad (12)
$$

$$
a_i \geq a_i - a_i \quad (13)
$$

$$
a_i \geq a_i - a_i \quad (14)
$$

$$
a_i \geq a_i - a_i \quad (15)
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a_i \geq a_i - a_i \quad (16)
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a_i \geq a_i - a_i \quad (17)
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a_i \geq a_i - a_i \quad (20)
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a_i \geq a_i - a_i \quad (35)
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$$
a_i \geq a_i - a_i \quad (36)
$$

$$
a_i \geq a_i - a_i \quad (37)
$$

$$
a_i \geq a_i - a_i \quad (38)
$$

5.1 Case study

In this section, the results of the application of the proposed model to a certain road are presented. In particular, the optimal matching and the relevant polices obtained for different instances of the problem in sections 4.1 and 4.2 are analyzed. To this aim, a route of the Italian city of Genova covering an area of about 50 km² is considered. The relevant road transportation network can be represented by means of a graph with 121 nodes and 172 edges, each edge having length, travel time, and cost.

- two drivers that travel from node 3 to node 46, once a light truck that can carry up to 2 trucks, the second, which travels from node 4 to node 46, once a van with 3 available tons or less;
- two trucks that needs to go from node 16 to node 41, the first, which travels from node 4 to node 46, the second, which travels from node 4 to node 46, once a van with 3 available tons or less.

As a general overview of the problem solution, a Branch-and-Bound (B&B) method has been applied using the IBM ILOG CPLEX 12.8 and GAMS (general algebraic modeling system) as optimization tool. The computational times are found reasonable, with the solution found in a few seconds in the cases discussed in this section, however, they can be reasonably improved by means of the branch bound technique, in particular, by selecting an automated initial solution for the B&B and adding a good lower bound.
Case study

CITY OF GENOVA
area covering about 20 km²
52 nodes - 80 arcs
Case study

DRIVER 1

travels from node 3 to node 46

can carry up to 5 boxes
Case study

**DRIVER 2**
travels from node 4 to node 43
3 available seats or box space
RIDER 1
needs to go from node 16 to node 41
Case study

RIDER 2
needs to go from node 39 to node 16
Case study

FREIGHT DELIVERY
6 boxes stored in node 3
to be delivered to node 46
Case study

- Branch-\&-Bound approach with the MILP solver IBM-ILOG Cplex
- Intel-Xeon E3-1240, 3.40 GHz processor, 8Gb RAM
- Computational times: around 1.5 hour
  - Possibility of reducing computational times by fixing an admissible initial solution for the B&B and finding a good lower bound (the relaxation of the capacity constraints provides good bounds)
  - Heuristic algorithms are in any case welcomed
Case study

Optimal solution:

- Rider 1 is assigned to Driver 2
- Rider 2 is not assigned
- 5 out of 6 boxes are assigned to Driver 1
- 1 out of 6 boxes are assigned to Driver 2
- Optimal paths are also determined
- Driver 1 uses his/her shortest route
- Driver 2 worsens his/her shortest route of about 7 minutes (the difference is “compensated” by the fares paid by the matched rider and box)
Case study

OPTIMAL PATH OF DRIVER 1
travels from node 3 to node 46
carries 5 boxes
Case study

OPTIMAL PATH OF DRIVER 2

go to node 3 to pick up the sixth box
then go to node 16 to pick up Rider 1
then go to node 41 to drop off Rider 1
then go to node 46 to drop off the sixth box
finally go to his/her final destination (node 43)
Conclusions

- The problem of optimizing urban mobility by optimally matching drivers’ proposals with riders’ and logistic providers’ requests has been addressed in this work.

- The proposed formalization exploits the paradigm of the Physical Internet which promotes the delivery of goods – possibly fractionated into smaller boxes and parcels – by using existing networks and providers, within a highly shared environment.
  - Logistic providers can exploit the traffic network travelled by drivers that are willing to share their trip (as they belong to a ride sharing system and can get a revenue for the service).

- Major future research direction:
  - Definition of a heuristic algorithm able to find a near-optimal solution in acceptable time.
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THANK YOU FOR YOUR ATTENTION !!!

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