CIMS3
Ciudades inteligentes: Modelado y simulación de sociedades sustentable

Gestión de Flota y Planificación de Servicios de Transporte Público

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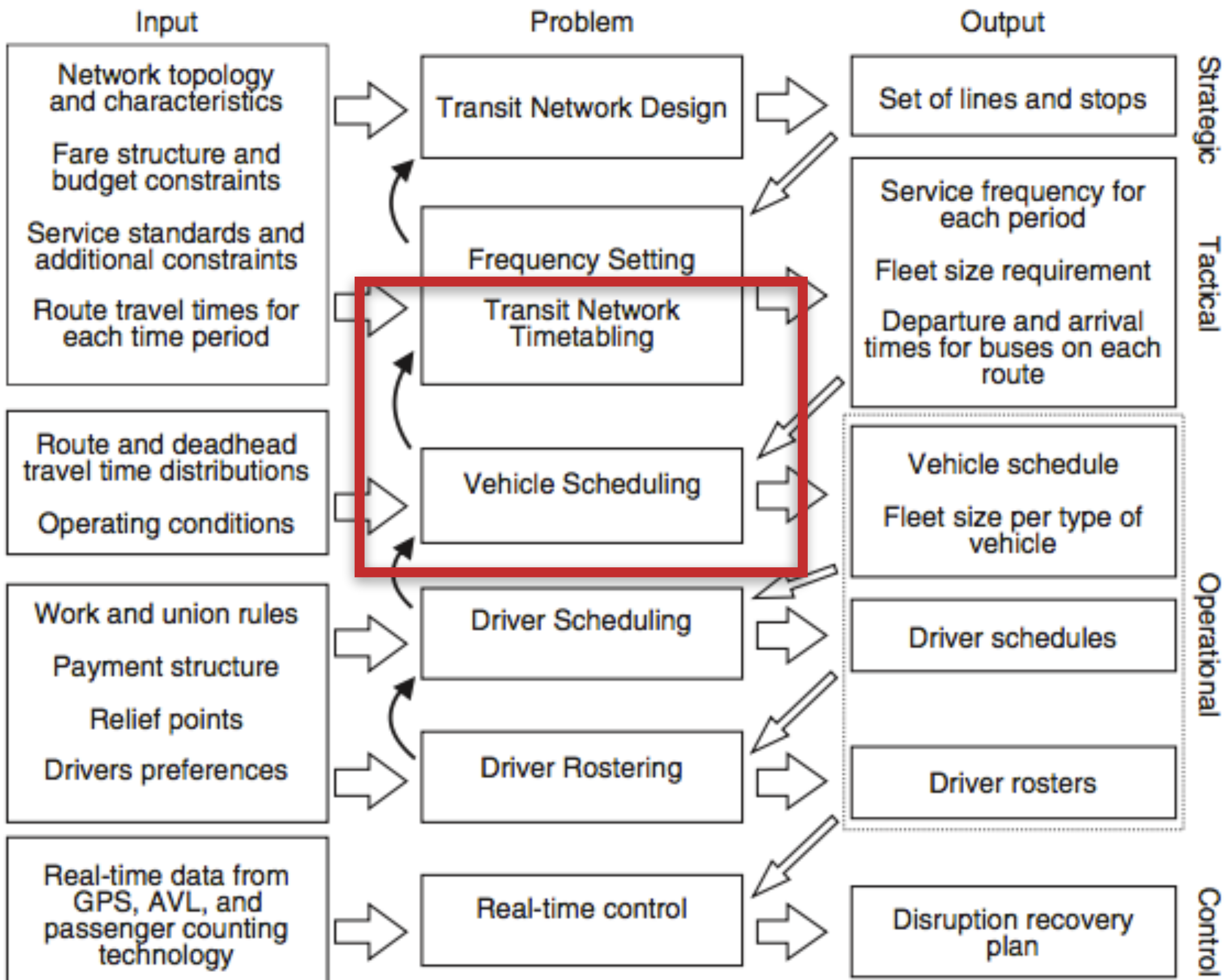
Outline

- Planning, Operation and Control of Public Transport Systems
- Integrated Timetabling - Vehicle Scheduling model: STP Santiago application.
- Timetabling model for night transit services: Transantiago collaboration.
- Mesoscopic-microscopic simulation scheme for transit operations to verify feasibility of operations plans provided by PT companies.

Planning, Operation and Control of Public Transport Systems

- Transit Network Planning (TNP) process can be split in subproblems at strategic, tactical and operational levels:
- Process stages:
  - **Transit Network Design (TND)**
  - **Frequency Setting (FS)**
  - **Transit Network Timetabling (TNT)**
  - **Vehicle Scheduling Problem (VSP)**
  - **Driver Scheduling Problem (DSP)**
  - **Driver Rostering Problem (DRP)**
  - **Real-time Control Problem (RCP)**
- Urban context where operations happen is dynamic and difficult to predict: key elements such as demand and travel times follow time-dependent pattern with stochastic features.
- Main trade-off in planning tasks is between level of service (users) and operational costs of operators and agencies.

Interaction among stages of a planning process as well as real-time control strategies for fleet management (source Ibarra-Rojas et al., 2015)



Some models used in the literature to solve timetabling and vehicle scheduling

- Generation of trips: *timetabling* (Ceder and Tal, 2001; Wu et al, 2016)
- Timetabling depends on demand. Objective mostly related to synchronization of services (Ceder et al., 2001; Eranki, 2004; Ibarra-Rojas, Rios-Solis, 2012).
- Vehicle scheduling: *multiple depot vehicle scheduling problem MDVSP* (Forbes et al. 1994; Lobel, 1998; Haghani and Banihashemi, 2002; Kliewer et al., 2006; Wei et al., 2013)
- In general, the timetabling and vehicle scheduling stages are treated separately.
- For the case of buses, vehicle scheduling processes were studied more intensively than timetabling.
- Some authors studied in an integrated way the vehicle and crew scheduling stages (Kliewer et al., 2010)

Models for stage 2: Timetabling

Ceder et al. (2001).

Optimization model maximizing synchronization

- Transit network and the set of services are already defined
- The model maximizes the number pairs of simultaneous arrivals of buses to nodes in the network (bus stops).

Models for stage 2: Timetabling

Ceder et al. (2001).

$$\max \sum_{k=1}^{M-1} \sum_{q=k+1}^{M} Y_{kq}, \qquad (2.1)$$

s.a.

$$X_{1k} \leq Hmax_k \qquad 1 \leq k \leq M, (2.2)$$

$$X_{F_k k} \leq T \qquad 1 \leq k \leq M, (2.3)$$

$$Hmin_k \leq X_{(i+1)k} - X_{ik} \leq Hmax_k \qquad 1 \leq k \leq M, 1 \leq i \leq F_k - 1, (2.4)$$

$$B \cdot D_{nijkq} \geq X_{ik} + T_{kn} - (X_{jq} + T_{qn}), \quad \forall\, k \in M, \forall\, n \in \bar{N}, \forall\, q \in M, i \leq F_k, j \leq F_q, (2.5)$$

$$B \cdot D_{nijkq} \geq X_{jq} + T_{qn} - (X_{ik} + T_{kn}), \quad \forall\, k \in M, \forall\, n \in \bar{N}, \forall\, q \in M, i \leq F_k, j \leq F_q, (2.6)$$

$$Y_{kq} \leq \sum_{n \in A_{kq}} \sum_{i=1}^{F_k} \sum_{j=1}^{F_q} (1 - D_{nijkq}) \qquad 1 \leq k \leq M, 1 \leq q \leq M, q \neq k, (2.7)$$

$$X_{ik} \in [0, T], Y_{kq} \in \mathbb{Z}^+, D_{nijkq} \in \{0, 1\} \qquad (2.8)$$

Stage 3: Vehicle scheduling

- MDVSRTC is often solved by heuristics methods due to its complexity and big size
- The objective function usually is one of:
  - Minimize the total number of vehicles (fixed cost associated with vehicles)
  - Minimize time or costs related to *deadheading* trips
  - A combination of both costs
- Forbes (1994) uses a basic idea, later extended by other researchers

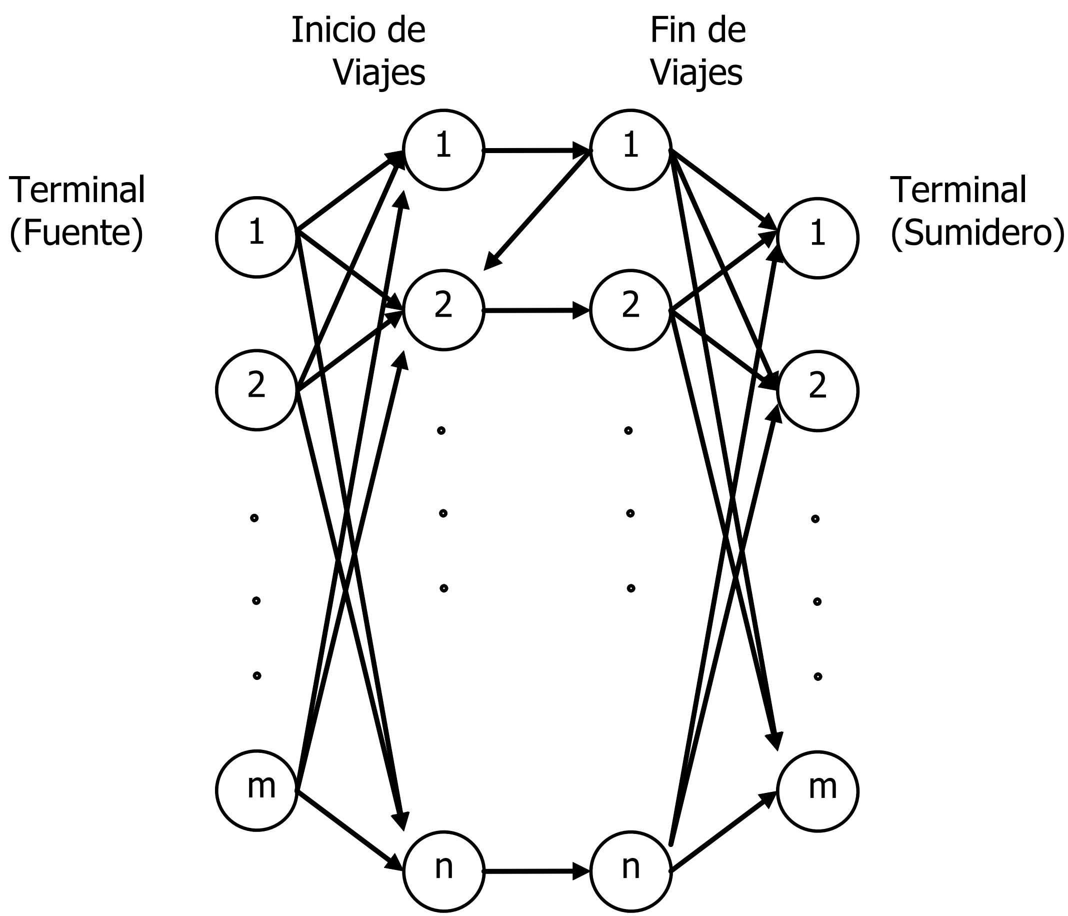
Modelos de la literatura: Etapa 3

Forbes et al. (1994) - Variables

Variable	Tipo	Definición
A_{di}	Binario	Igual a 1 si el viaje i es el primer viaje ejecutado por un vehículo del depósito d; igual 0, en otro caso.
X_{ijd}	Binario	Igual a 1 si los viajes compatibles i y j son ejecutados consecutivamente por un vehículo del depósito d; igual 0, en otro caso.
B_{id}	Binario	Igual a 1 si el viaje i es el último viaje ejecutado por un vehículo del depósito d; igual a 0, en otro caso.
w_{id}	Binario	Igual a 1 si el viaje i es ejecutado por un vehículo del depósito d; igual a 0, en otro caso.

Modelos de la literatura: Etapa 3

Forbes et al. (1994) – Red de la formulación



Modelos de la literatura: Etapa 3

Forbes et al. (1994) - Parámetros

Parámetro	**Definición**
a_{di}	costo del viaje entre el depósito d y el punto de inicio del viaje i más el (Costo Fijo)/2.
c_{ijd}	costo del viaje i más el tiempo entre el inicio del viaje j y el tiempo de fin del viaje i (si viajar al depósito d no es factible en el tiempo entre 2 viajes); Min. de lo anterior y el costo total de viaje i más el costo del viajar desde el viaje i al *depot* d y desdo el *depot* d al viaje j (si viajar al *depot* d es factible en el tiempo entre 2 viajes).
b_{id}	costo de viajar desde el punto de término del viaje i a el depósito d más el tiempo del viaje i más el (Costo Fijo)/2.
r_d	Número de vehículos en el déposito d.

Modelos de la literatura: Etapa 3

Forbes et al. (1994) - Formulación

$$\text{mín} \sum_{di} a_{di} A_{di} + \sum_{ijd} c_{ijd} X_{ijd} + \sum_{di} b_{id} B_{id}, \quad (2.14)$$

s.a.

$$\sum_{i} A_{di} \leq r_d \quad \forall d, \quad (2.15)$$

$$A_{di} + \sum_{j} X_{jid} - w_{id} = 0 \quad \forall i, d, \quad (2.16)$$

$$B_{id} + \sum_{j} X_{ijd} - w_{id} = 0 \quad \forall i, d, \quad (2.17)$$

$$\sum_{i} B_{id} \leq r_d \quad \forall d, \quad (2.18)$$

$$\sum_{d} w_{id} = 1 \quad \forall i, \quad (2.19)$$

$$A_{di}, X_{ijd} \text{ y } B_{id} \in \mathbb{Z}^{+} \quad (2.20)$$

Modelos de la literatura: Etapa 3

Haghani y Banihashemi (2002) - Variables

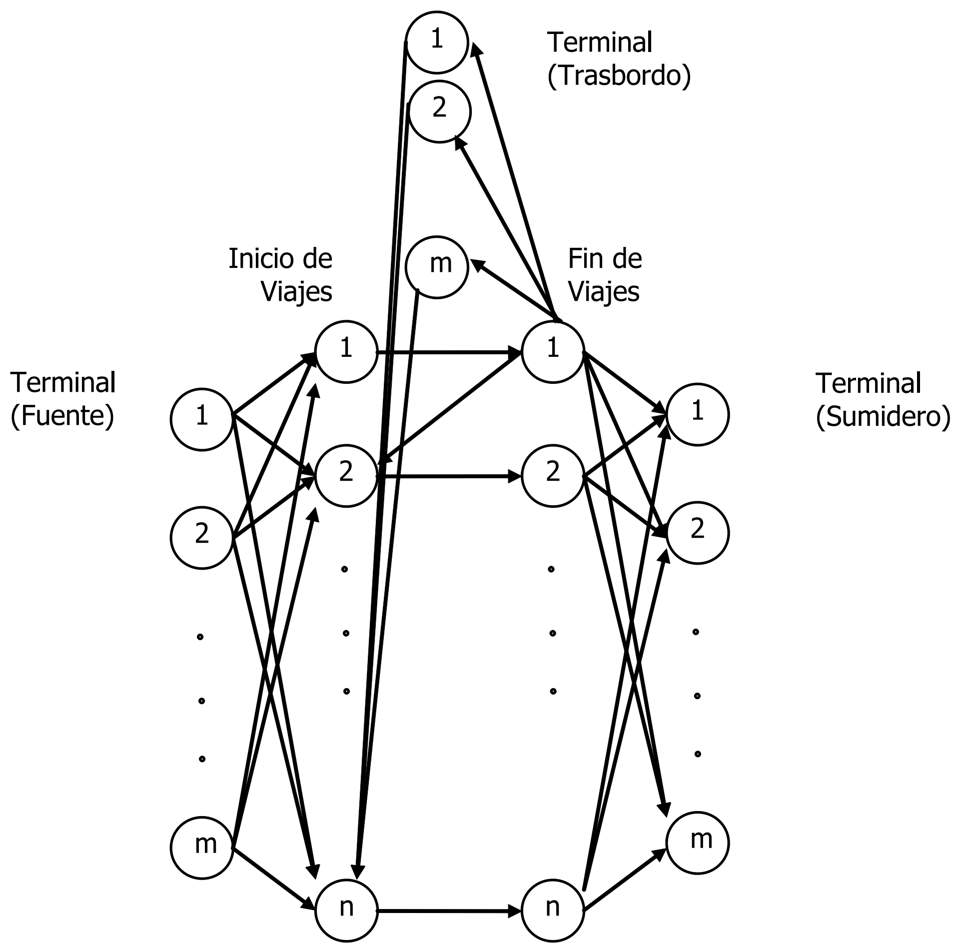
En este trabajo, se dividen los viajes en:

- Viajes compatibles a nivel de terminal.
- Viajes compatibles en las calles.
- Viajes de la mañana, medio día y tarde.

Variable	Tipo	Definición
E_{di}	Binario	Igual a 1 si el viaje i está en el set de los viajes de la tarde y es el primer viaje ejecutado por un vehículo del *depot* d regresando a la calle; 0 en otro caso.
X_{ijd}	Binario	Igual a 1 si los viajes compatibles i y j son ejecutados consecutivamente por un vehículo del *depot* d; 0 en otro caso.
F_{id}	Binario	Igual a 1 si el viaje i está en el set de los viajes de la manaña y es el último viaje ejecutado por un vehículo del *depot* d regresando a la calle; 0 en otro caso.

Modelos de la literatura: Etapa 3

Haghani y Banihashemi (2002) – Red de la formulación



Modelos de la literatura: Etapa 3

Haghani y Banihashemi (2002) - Parámetros

Parámetro	Definición
e_{di}	costo del viaje entre el depósito d y el punto de inicio del viaje i.
c_{ijd}	costo del viaje i más el tiempo entre el inicio del viaje j y el tiempo de fin del viaje i (si viajar al depósito d no es factible en el tiempo entre 2 viajes); Min. de lo anterior y el costo total de viaje i más el costo de viajar desde el viaje i al *depot* d y desde el *depot* d al viaje j (si viajar al *depot* d es factible en el tiempo entre 2 viajes).
f_{id}	costo de viajar desde el punto de fin del viaje i al *depot* d más el tiempo del viaje i.

Se considera 4 tipos de costos unitarios asociados a los cuatro períodos de operación para vehículos y personal: operar para viajes programados, operar en viajes *deadhead*, esperar en la calle (*layover*) y estacionado en terminal

Modelos de la literatura: Etapa 3

Haghani y Banihashemi (2002) - Formulación

$$\text{mín} \sum_{di} a_{di} A_{di} + \sum_{di} e_{id} E_{id} + \sum_{ijd} c_{ijd} X_{ijd} + \sum_{di} b_{id} B_{id} + \sum_{di} f_{id} F_{id}, \tag{2.34}$$

s.a.

$$\sum_{i} A_{di} \leq r_d \quad \forall d, \tag{2.35}$$

$$A_{di} + E_{di} + \sum_{j} X_{jid} - w_{id} = 0 \quad \forall i, d, \tag{2.36}$$

$$\sum_{i} E_{di} - \sum_{i} F_{id} = 0 \quad \forall i, d, \tag{2.37}$$

$$B_{id} + F_{id} + \sum_{j} X_{ijd} - w_{id} = 0 \quad \forall d, \tag{2.38}$$

$$\sum_{i} B_{id} \leq r_d \quad \forall d, \tag{2.39}$$

$$\sum_{d} w_{id} = 1 \quad \forall i, \tag{2.40}$$

$$A_{di}, X_{ijd}, B_{id}, E_{di} \text{ y } F_{id} \in Z_0^+ \tag{2.41}$$

Timetabling and vehicle scheduling

- Cortés, C.E., Miranda, J., Muñoz D., Rey P.A. An Integer Programming Approach for Integrated Public Transport Timetabling and Vehicle Scheduling, submitted to **Transportation Science**.
- Cortés C.E., Rey P.A., Gil C., Gschwender A., Núñez C. Mixed integer programming model for synchronizing night urban bus services in Santiago, to be submitted to an special issue of CLAIO in **Annals of Operations Research**.

DTP
Directorio de Transporte Público
Metropolitano

STP Santiago S.A.

Transantiago

Unidad		Empresa Operadora	Recorridos			
Unidad N°1		Recorridos Alsacia También opera los recorridos 408 - 410	100			
Unidad N°2		Recorridos Su Bus	200	G		
Unidad N°3		Recorridos Buses Vule	300	E	H	I
Unidad N°4		Recorridos Express No opera los recorridos 408 - 410	400	D		
Unidad N°5		Recorridos Buses Metropolitana	500	J		
Unidad N°6		Recorridos Red Bus Urbano		B	C	
Unidad N°7		Recorridos STP Santiago		F		

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Research contributions

- We formulate an integer programming model (based on a time-space network structure) to solve the timetabling and vehicle scheduling stages of STP subject to operational conditions (frequency and capacity ranges offered).
- We add into the model, apart from the operational conditions, the option of operating in deadheading some segments to adequately reposition of buses.
- The approach was solved for real instances, and the final solutions were implemented by the company, obtaining outstanding results in terms of regularity.
- We provide tools and insights for a successful implementation of the plan in the field.

Timetabling and vehicle scheduling stages

- Objectives
  - Creation of trips
    - Starting and ending times of a trip.
    - Bus type for performing the trip.
    - Specific route to perform the trip.
  - Vehicle scheduling
    - Which bus is assigned to a determined trip.
    - What is the bus doing after finishing the trip.

Proposed integer programming model

1) **Integrated timetabling-vehicle scheduling**
    - Program inspired by the time-space network proposed for solving the MDVSP by Forbes et al. (1994), and then extended by Haghani and Banishemi (2002) including waiting periods between trips.
    - Nodes correspond to physical locations replicated in time.
    - Activities (travel and waiting periods) are represented by arcs.

2) **Variable velocity over time through the operational day**

3) **Model satisfies operational constraints: thresholds of frequency and offered capacity.**

4) **Demand requirements: implicit in the operational constraints.**

Operational constraints

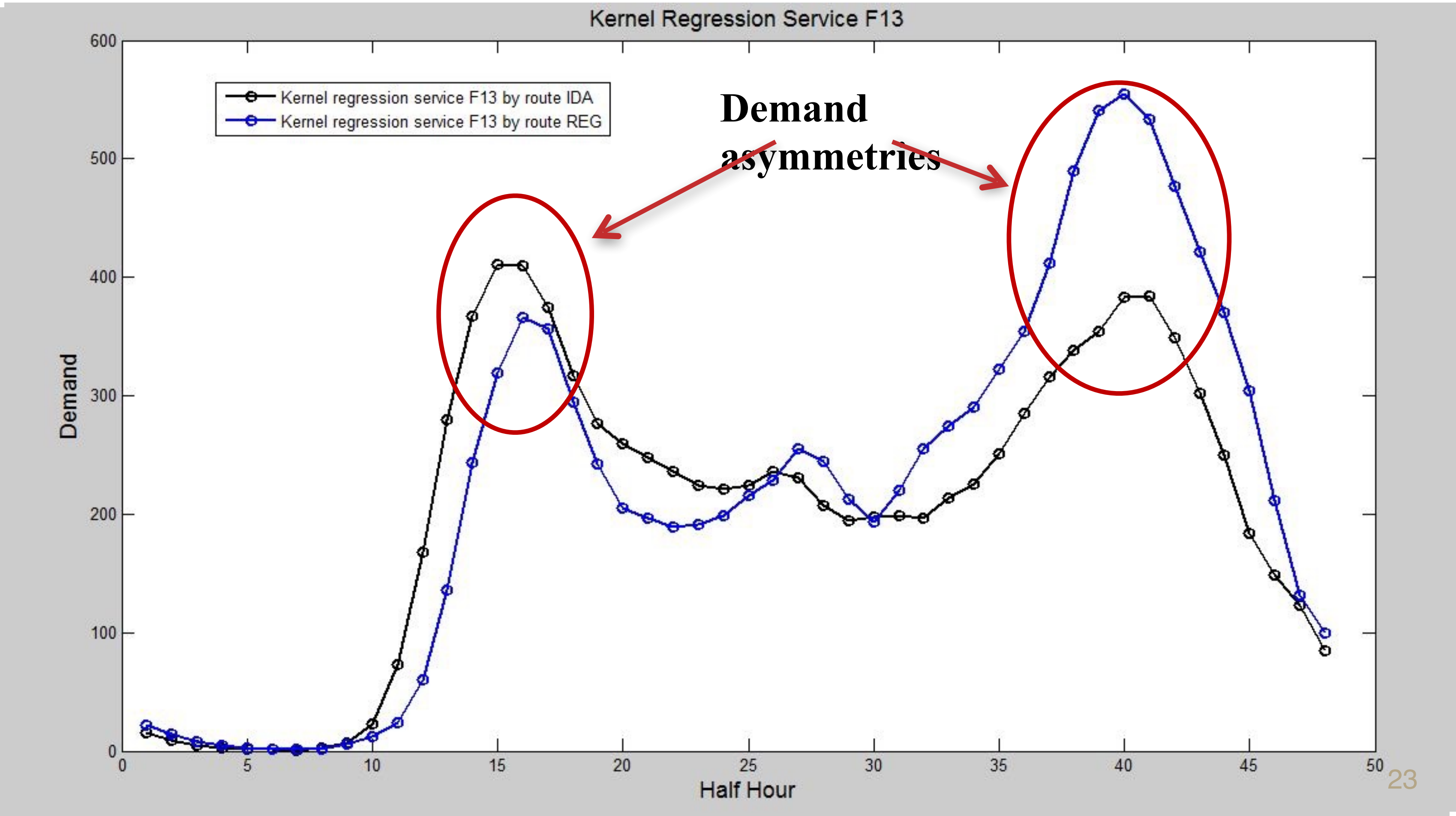
- Transantiago define thresholds in frequency and capacity by hour that have to be satisfied.
- Ranges change in different periods over the operational day for each service.
- Transantiago (**CMB**) monitor the effective fulfillment of the committed trips (with a discount of up to 5% of company income).
  - ✓ **Frequency and regularity indicators.**

- In the model, we used thresholds of headways instead of frequencies: relevant impact in regularity.
- As operational speed is also variable over time, this is a time-dependent assignment optimization problem: time-expanded network.

Modeling issues

- Regarding demand of STP, it can be observed important imbalances in both peaks (morning and afternoon): deadhead routes

<u>Demand in pax per half hour:</u>



Mathematical formulation

Definition of sets:

D : depots.

S : services.

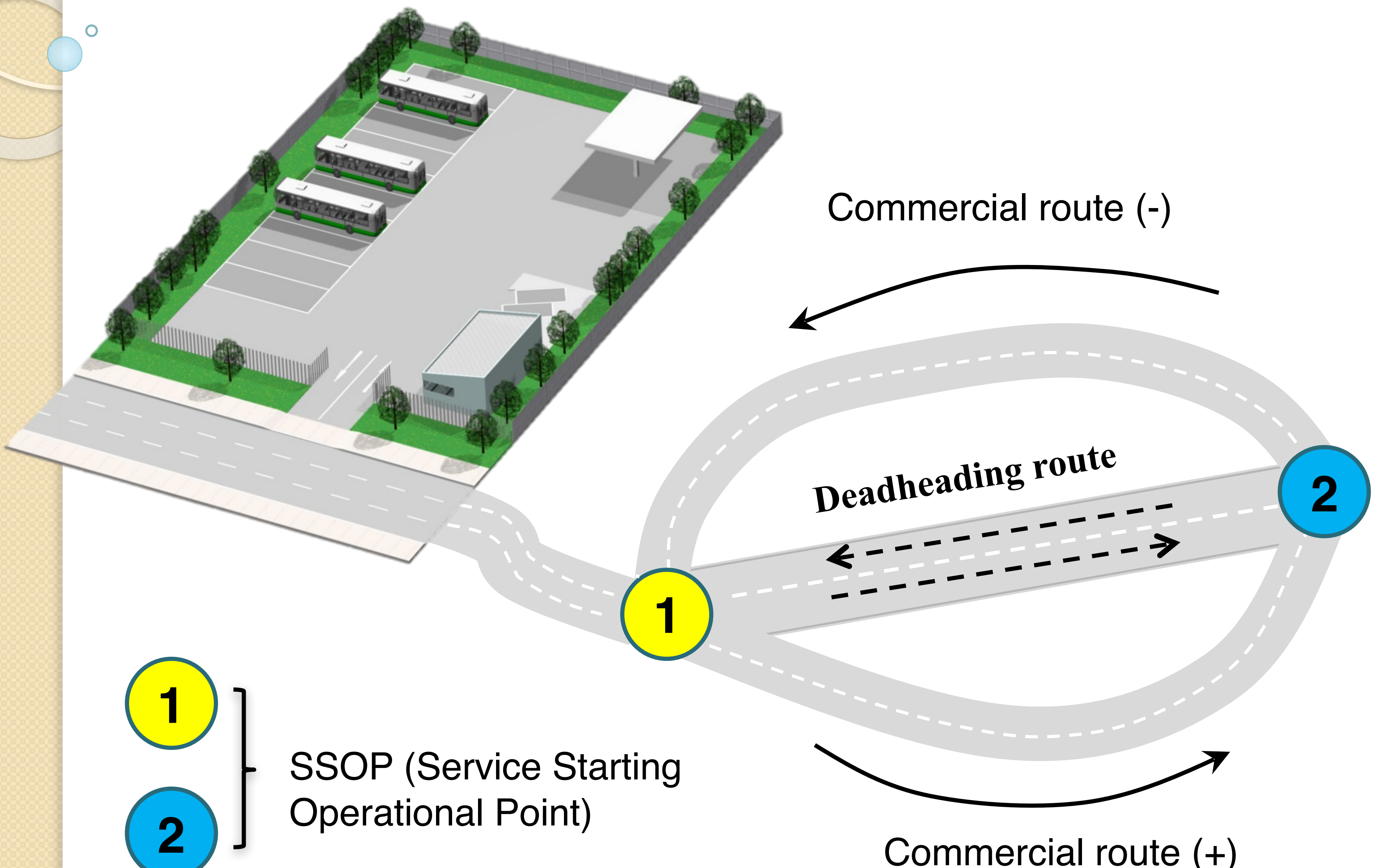
R : routes.

B : buses.

T : time.

I : periods.

What is a service?



Mathematical formulation

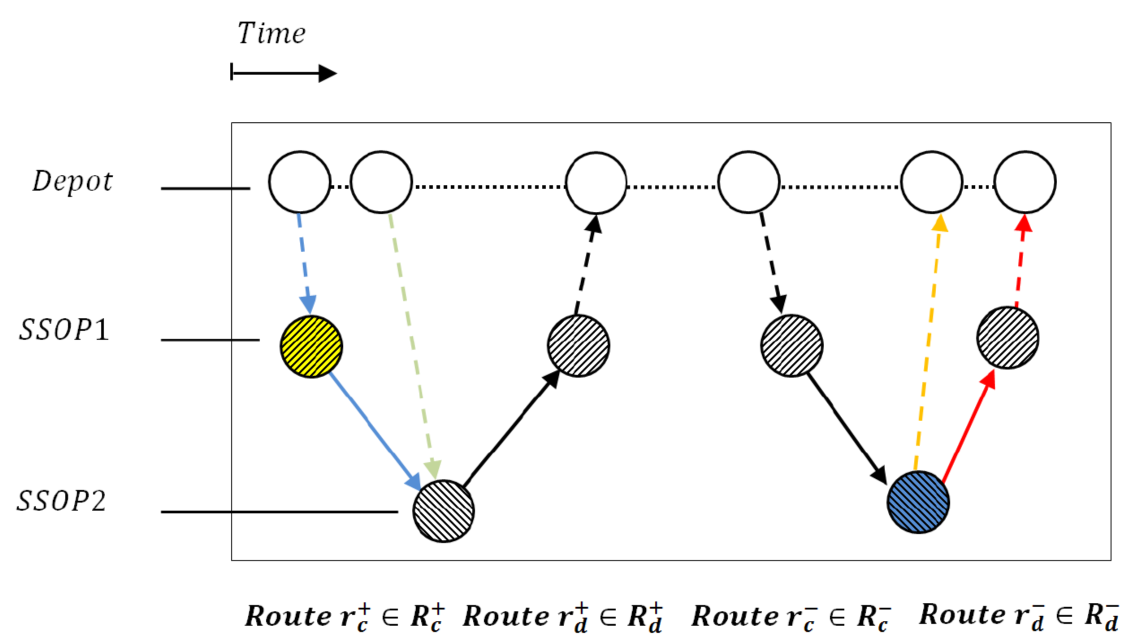
Definition of sets

We differentiate commercial routes from deadheading routes as follows:

1. R_c^+: commercial route $Depot - SSOP1 - SSOP2$.
2. R_c^-: commercial route $SSOP2 - SSOP1 - Depot$.
3. R_d^+: deadheading route $Depot - SSOP2$.
4. R_d^-: deadheading route $SSOP2 - Depot$.

$$R^+ = R_c^+ \cup R_d^+$$

$$R^- = R_c^- \cup R_d^-$$



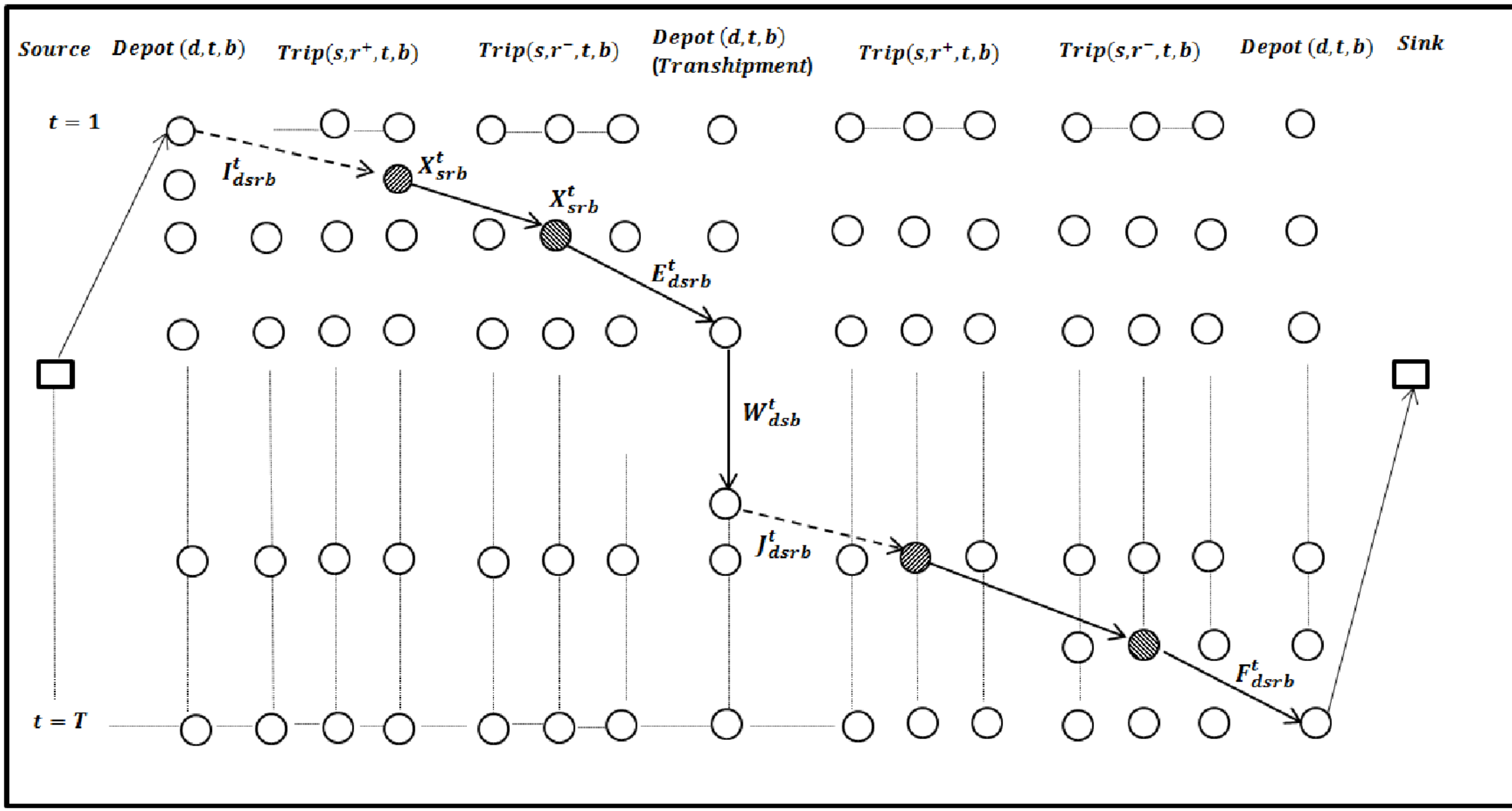
Mathematical formulation

Decision variables

Variable	Type	Definition
I^t_{dsrb}	Binary	Equals 1 if bus b departs from depot d at period t to perform its first trip of the day that corresponds to a service s by route r; equals 0 otherwise.
J^t_{dsrb}	Binary	Equals 1 if bus b departs from depot d at period t to perform one trip (which is not the first one) that corresponds to a service s by route r; equals 0 otherwise.
F^t_{dsrb}	Binary	Equals 1 if bus b proceeds to depot d after finishing its last trip of service s by route r that started at period t; equals 0 otherwise.
E^t_{dsrb}	Binary	Equals 1 if bus b proceeds to terminal d after finishing one trip of service s by route r that started at period t (which is not its last trip of the day); equals 0 otherwise.
X^t_{srb}	Binary	Equals 1 if bus b starts a trip of service s by route r at instant t; equals 0 otherwise.
W^t_{dsb}	Binary	Equals 1 if bus b assigned to service s is waiting at terminal d from instant t to $t+1$.

Mathematical formulation

Time-expanded network



Mathematical formulation

Model parameters

Parameter	Definition
λ_{sr}	Total length of a service s for the route r (in km).
δ_{dsr}	Distance between a depot d and the starting point of the route r of service s (in km).
τ_{srt}	Travel time of service s by route r if it starts at period t (in time steps).
θ_{dsrt}	Travel time from depot d to the starting point of the route r of service s if departing at period t.
φ_b	Fixed cost for using bus b (in \$).
γ_b	Variable cost for operating bus b (in \$/km).
$\underline{q}_{isr}$	Lower bound for the total capacity provided by service s by route r per hour during demand interval i.
$\overline{q}_{isr}$	Upper bound for the total capacity provided by service s by route r per hour during demand interval i.
$\underline{h}_{srt}$	Minimum headway associated with service s by route r between successive trips, with the first one starting at period t (in time steps).
$\overline{h}_{srt}$	Maximum headway associated with service s by route r between successive trips, with the first one starting at period t (in time steps).
p_b	Passenger capacity of bus b (in number of passengers).
$t_1(s,r,t,d)$	Time in which a bus should start a trip in service s and route $r \in R_c^-$ to finish at period t in depot d .
$t_2(s,r,t,d)$	Time in which a bus should depart from depot d to start a trip in service s and route $r \in R_c^+$ at period t.
$t_3(s,r,t)$	Time in which a bus should start a trip in service s and route $r \in R_c^+$ to finish in *Cabezal* 2 at period t.

Mixed integer model

Constraints associated with time-expanded network

(1) Conservation of number of buses at depot

$$\sum_{t\in T}\sum_{r\in R_c^+} I^t_{dsrb} - \sum_{t\in T}\sum_{r\in R_c^-} F^t_{dsrb} = 0, \quad \forall\, d\in D, s\in S, b\in B,$$

(2) Conservation of flow of buses at nodes

$$\sum_{r\in R_c^-} E^{t_1(s,r,t)}_{dsrb} + W^{t-1}_{dsb} = \sum_{r\in R_c^+} J^t_{dsrb} + W^t_{dsb}, \quad \forall\, d\in D, s\in S, b\in B, t\in T, t>1,$$

where $t_1(s,r,t)$ is defined by $t = t_1(s,r,t) + \tau_{srt_1(s,r,t)} + \theta_{dsrt_1(s,r,t)}$,

(3) No buses waiting at the beginning and end of the operation

$$W^0_{dsb} = W^T_{dsb} = 0, \quad \forall\, d\in D, s\in S, b\in B$$

Mixed integer model

Constra ... ork

(1) Conse

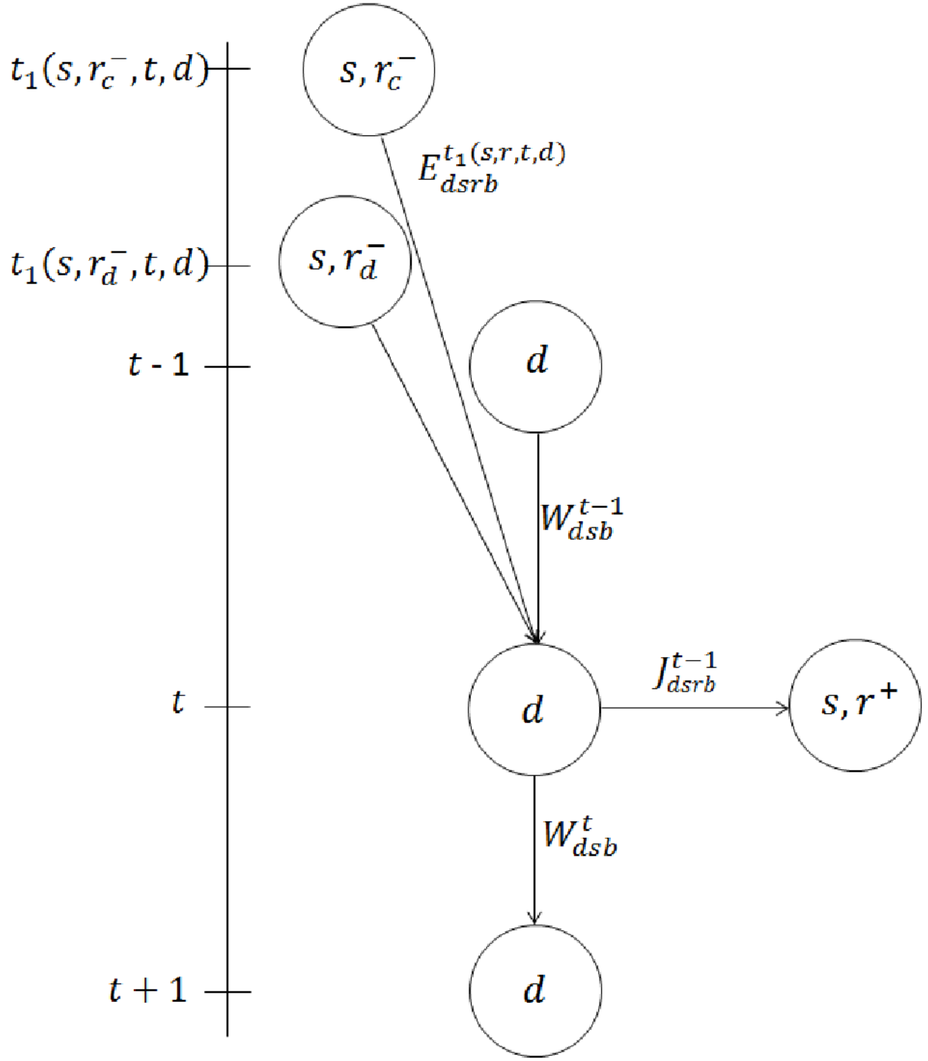
$\in B,$

(2) Conse

$B, t \in T, t > 1,$

where $t_1($

(3) No bus



Mixed Integer Model

Constraints on assignment bus-trip

(4) Each trip that is initiated must be performed by one single bus

$$\sum_{d \in D} I_{dsrb}^{t_2(s,r,t)} + \sum_{d \in D} J_{dsrb}^{t_2(s,r,t)} = X_{srb}^{t}, \quad \forall\ s \in S, r \in R_c^+, t \in T, b \in B,$$

where $t_2(s,r,t)$ is defined by $t = t_2(s,r,t) + \theta_{dsrt_2(s,r,t)}$,

(5) Relation of decision variable X at SSOP2

$$X_{sr_1b}^{t_3(s,r_1,t)} = \sum_{r_2 \in R_c^-} X_{sr_2b}^{t}, \quad \forall\ s \in S, b \in B, t \in T,\ r_1 \in R^+,$$

Mixed Integer Model

Constraints on assignment bus-trip

(6) A bus can reach SSOP2 through deadheading route directly

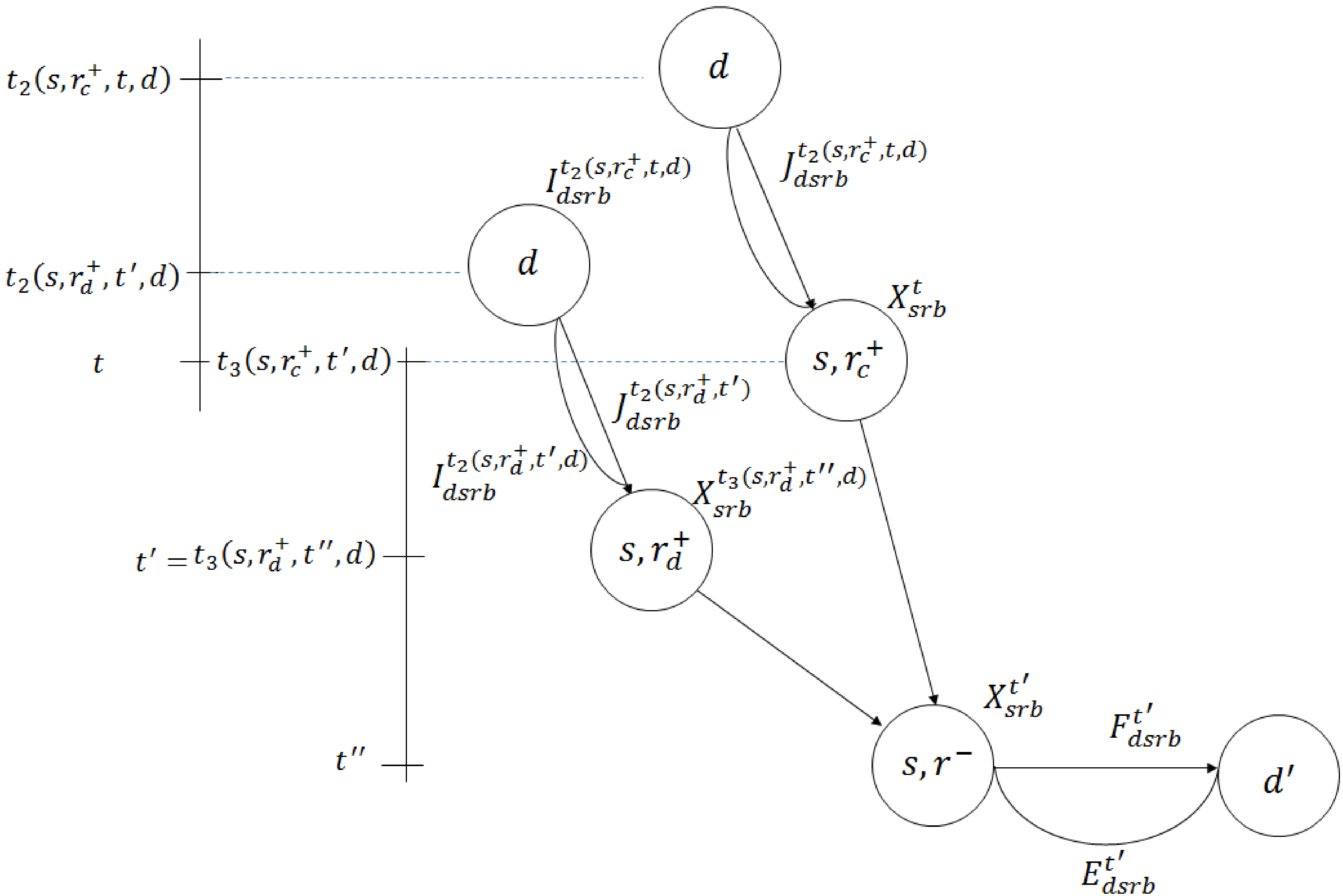
$$X_{sr_3b}^{t_3(s,r_3,t)} = X_{sr_4b}^{t}, \quad \forall\ s \in S, b \in B, t \in T,\ r_3 \in R_d^+,\ r_4 \in R_c^-$$

where $t_3(s,r,t)$ in equations (6) and (7) is defined by $t = t_3(s,r,t) + \tau_{srt_3(s,r,t)}$,

(7) Each initiated trip must return to the depot

$$\sum_{d \in D} F_{dsrb}^{t} + \sum_{d \in D} E_{dsrb}^{t} = X_{srb}^{t}, \quad \forall\ s \in S, r \in R_c^-, t \in T, b \in B,$$

Mixed Integer Model



Mixed Integer Model

Operational Constraints

(8) Available buses at each depot

$$\sum_{(s,r,t)\in SR_c^+ T} I_{dsrb}^t \leq 1, \quad \forall\, d \in D, b \in B,$$

(9) Capacity constraints per hour during period i

$$\underline{q}_{isr} \leq \sum_{b\in B} \left(\sum_{t\in h} p_b \cdot X_{srb}^t \right) \leq \overline{q}_{isr}, \quad \forall\, i \in I, s \in S\, r \in R_c,\ h \in H(i),$$

Mixed Integer Model

Operational constraints

(10) Headway between trips

$$\sum_{b\in B}\left(\sum_{t'=t}^{t+\overline{h}_{srt}-1} X_{srb}^{t'}\right) \geq 1,\ \forall\ s\in S, r\in R_c, t\in T, t<|T|-\overline{h}_{srt}$$

$$\sum_{b\in B}\left(\sum_{t'=t}^{t+\underline{h}_{srt}-1} X_{srb}^{t'}\right) \leq 1,\ \forall\ s\in S, r\in R_c, t\in T, t<|T|-\underline{h}_{srt}$$

(11) External constraint of bus b per service s and route r at period t

$$X_{srb}^{t} = 0,\quad \forall\ (s,r,b,t)\in\Omega,$$

Nature of variables

$$I_{dsrb}^{t}, F_{dsrb}^{t}, J_{dsrb}^{t}, E_{dsrb}^{t}, X_{srb}^{t}, W_{dsrb}^{t} \in \{0,1\}.$$

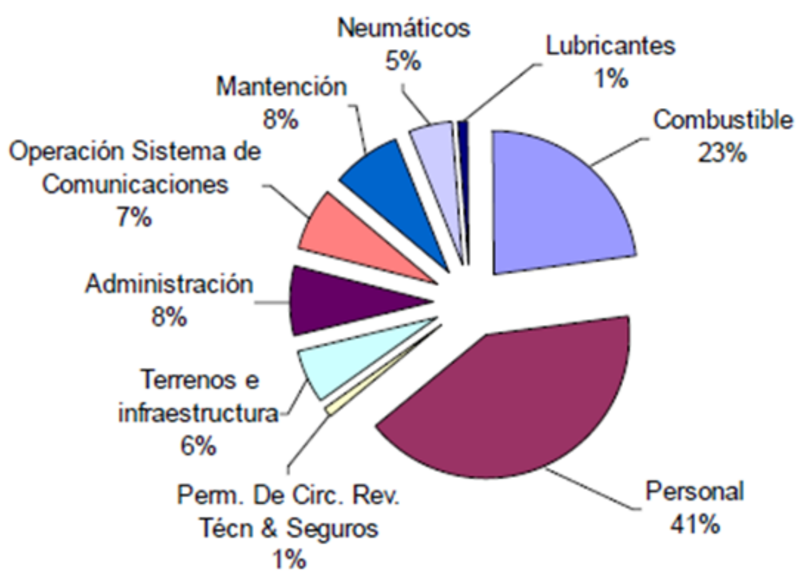
Mixed Integer Model

Objective function: minimization of operational costs

Fixed cost *Variable cost*

$$\min \sum_{d\in D}\sum_{s\in S}\sum_{r\in R}\sum_{b\in B}\sum_{t\in T}[\varphi_b \cdot I^t_{dsrb} + \gamma_b \cdot (\lambda_{sr} + \delta_{dsr}) \cdot (I^t_{dsrb} + J^t_{dsrb} + F^t_{dsrb} + E^t_{dsrb})]$$

Operational costs of a public transport firm



Formulation drawbacks

- ➢ Considering an instance of 150 buses and 9 services we obtain:

- Number of variables around 17 millions
- Number of constraints around 9 millions

- ➢ Inherent symmetry due to similarity of buses of the same type

Exact method becomes very restrictive as the problem cannot be solved to optimality in case of real instances

Mathematical formulation

Redefinition of Sets:

D : depots.

S : services.

R : routes.

V : type of buses.

T : time.

I : periods.

Mathematical formulation

Redefinition of Decision Variables of the model:

Variable	Type	Definition
I_{dsrv}^{t}	Binary	Equals 1 if a bus of type v departs from terminal d at period t to perform its first trip of the day that corresponds to a service s by route r; equals 0 otherwise.
J_{dsrv}^{t}	Binary	Equals 1 if a bus of type v departs from terminal d at period t to perform one trip (which is not the first one) that corresponds to a service s by route r; equals 0 otherwise.
F_{dsrv}^{t}	Binary	Equals 1 if a bus of type v proceeds to terminal d after finishing its last trip of service s by route r that started at period t; equals 0 otherwise.
E_{dsrv}^{t}	Binary	Equals 1 if bus of type v proceeds to terminal d after finishing one trip of service s by route r that started at period t (which is not its last trip of the day); equals 0 otherwise.
X_{srv}^{t}	Binary	Equals 1 if a bus of type v starts a trip of service s by route r at instant t; equals 0 otherwise.
W_{dsv}^{t}	Integer	Number of buses of type v that are waiting at terminal d from instant t to $t+1$

Mixed Integer Model

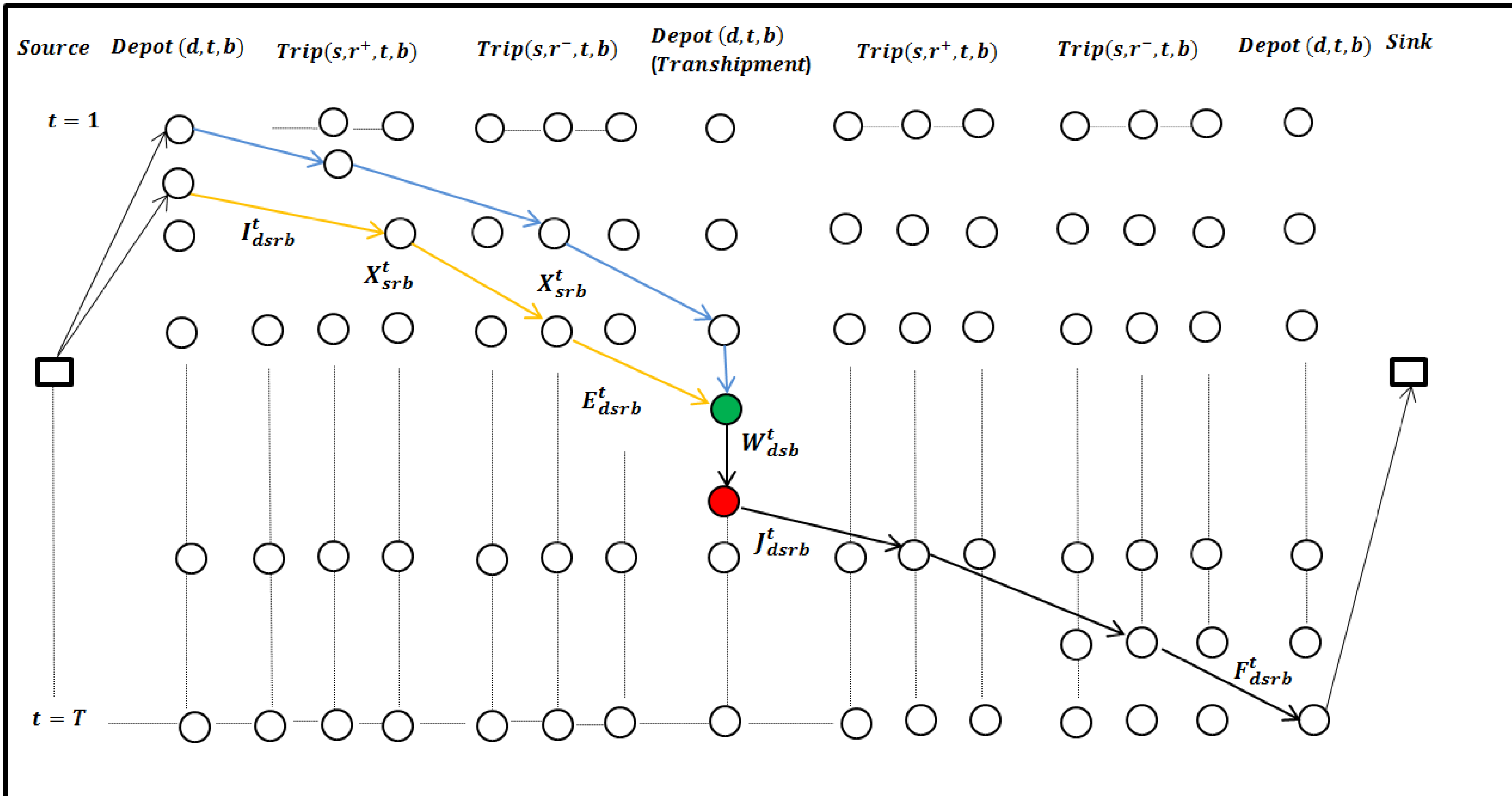
Operational constraints

(9) Available number of buses of each type at each depot

$$\sum_{s,r} I^{t}_{dsrv} \leq \beta_{dv}$$

Mathematical Formulation

Time-expanded network



Buses assigned to trips

- We cannot obtain a daily schedule for a particular bus of the company's fleet directly from the outputs of the model.
- Single buses are grouped by similarity in terms of both passenger capacity and variable cost per kilometer.
- Outputs: number of buses of each type assigned to each series, together with the trips to be performed by the different types of buses.
- Dispatch methodology: the dispatcher can consider for example a FIFO strategy, assigning the next trips to the buses that have waited longer at the depot after their arrival from the previous trip.

Advantages and drawbacks of modified model

Advantages

➢ For an instance of 150 buses and 9 services we have:

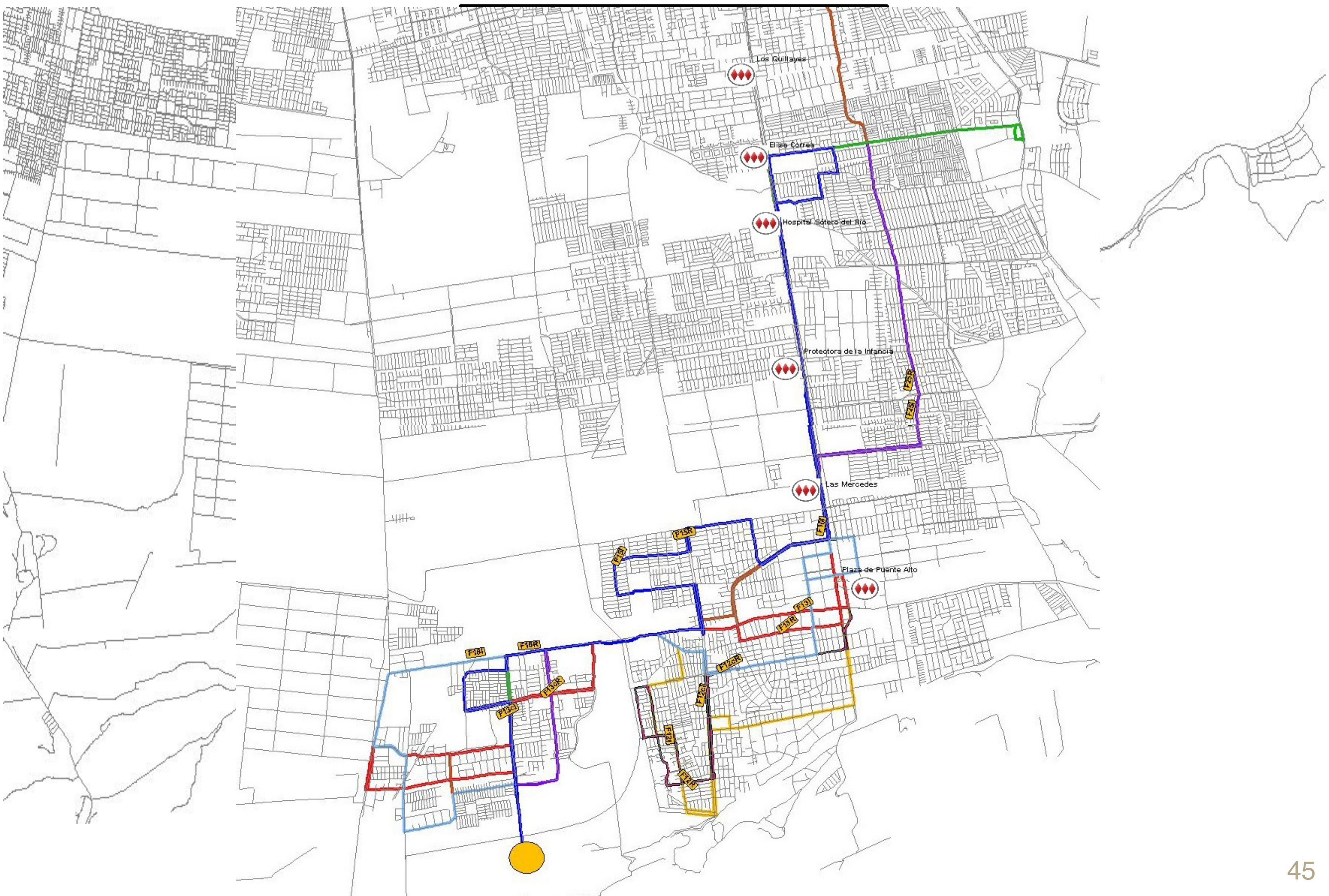
- Number of variables of the order of 240,000.
- Number of constraints of the order of 200,000.

Therefore, the problem is reduced in 98.5% in both the number of variables and constraints.

Disadvantages

➢ It is necessary to perform the assignment of trips to specific buses after running the model.

Real implementation



Features of real instance

- Time discretization in 2 minutes time-steps.
- 9 services, 118 buses, 18 commercial routes and 18 *deadheading* routes.
- 2,076 trips during a lobour day, 282 during morning peak (6:30-8:30) and 407 during afternoon peak (17:30-20:30).

- **Base instance**

1. Travel time through *deadheading* route (DH 30% less):
   30% less than commercial route.
2. *Deadheading* is performed in both directions.

- **We tested three more instances:**

1. No *deadheading routes (SD).*
2. Travel time *deadheading* route 10% less than commercial (DH 10% less).
3. Travel time *deadheading* route 50% less than commercial (DH 50% less).

Sensitivity

- Size of the fleet of buses necessary for the 4 strategies used

Strategy	Without DH	DH-10%	DH-30%	DH-50%
Number of buses	144	142	136	131

Scenario	**No DH**	**DH 10%**	**DH 30%**	**DH 50%**
CPU (sg)	33	630	950	650
gap	0.00%	0.98%	0.35%	1.07%

Table 4 Fleet size for a manual solution and the proposed approach.

Service	S1	S2	S3	S4	S5	S6	S7	S8	S9	**Total**
Manual Solution	21	10	5	27	6	12	14	13	10	**118**
Solution for the proposed approach	24	12	5	29	10	13	16	16	11	**136**
Difference	**+3**	**+2**	**0**	**+2**	**+4**	**+1**	**+2**	**+2**	**+1**	**+18**

Performance indicators

- Frequency (ICF): This indicator calculates the quotient between the number of planned trips in the operation plan and the number of trips observed that performed the services in the real operation

- Regularity (ICR-I): This indicator determines the proportion of periods in which the time between consecutive buses is higher than what was planned in the operation plan.

- Idle capacity (CO): This indicator determines the total number of empty seats for every service (as the difference between total number of seats of bus fleet assigned and the estimated total demand for that service and period).

Results

- Benefits of *Deadheading*.

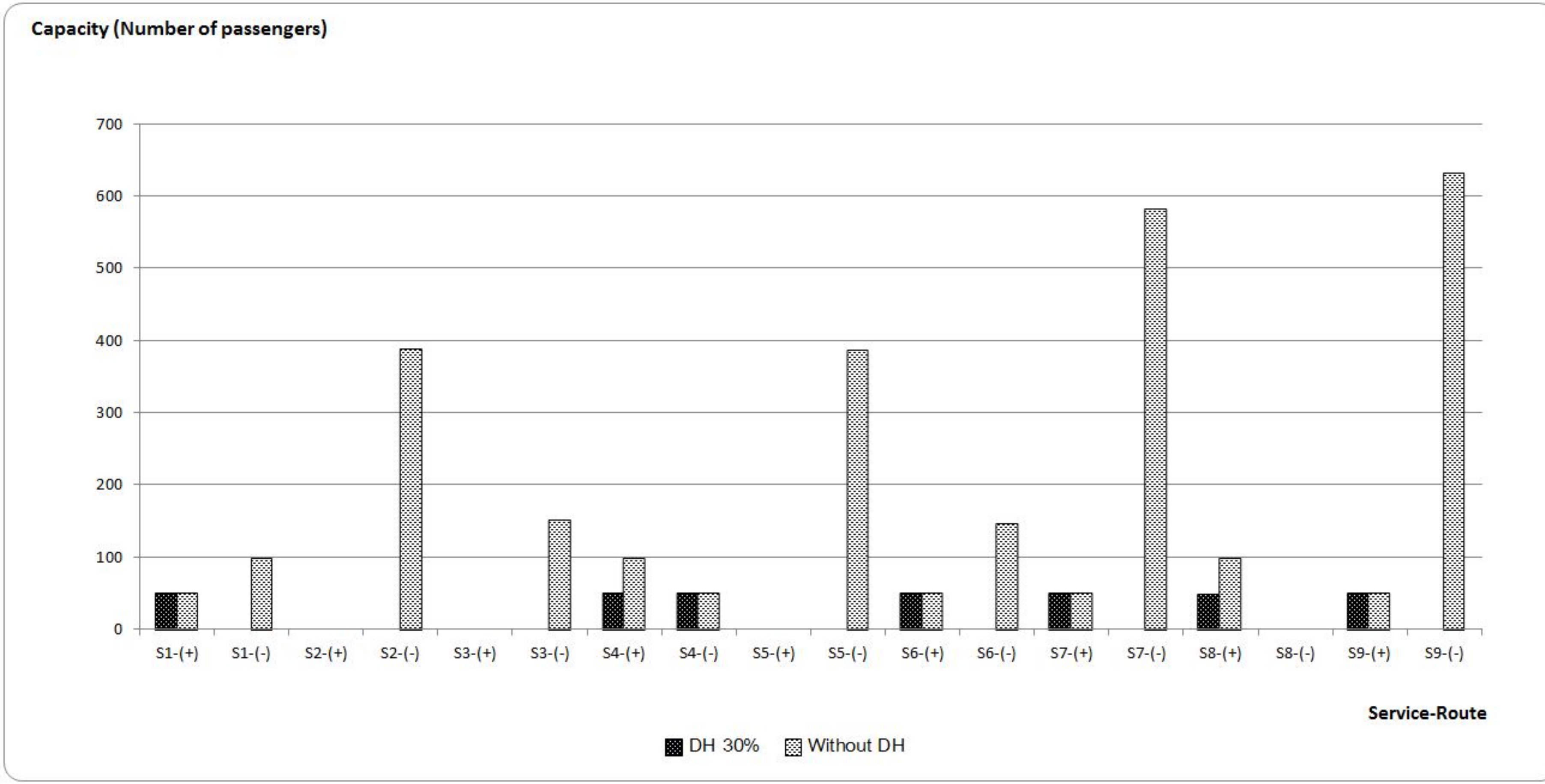
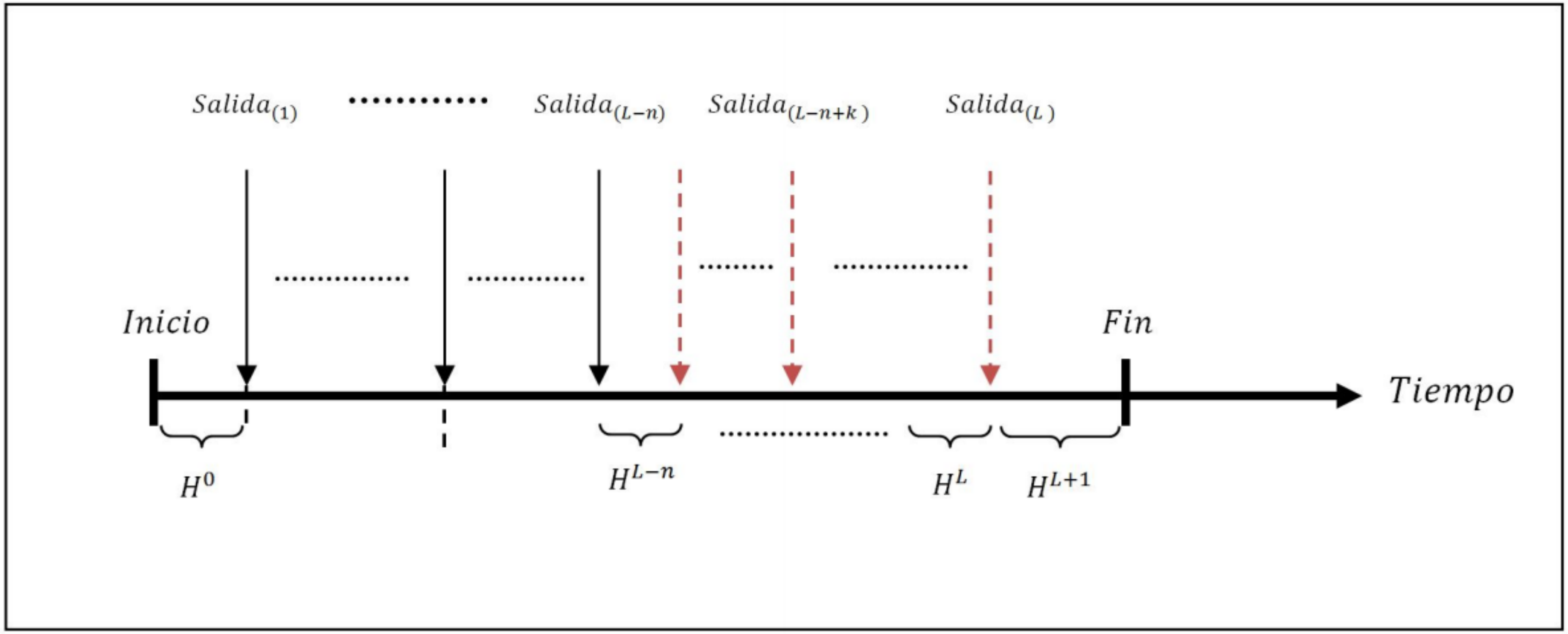


Figure 10 **Comparison of idle capacity in transport (CO) for the different services for** *Juanita Terminal*.

Technological Applications

Optimal regularity for the remaining n dispatches of service j during period p:



Technological Applications

Model to be solved for each service j and period p:

$$\min_{\{H^i_{jp}\}_{i=L-n}^{L+1}} \quad CV_{jp} = \sqrt{\frac{\sum_{l \in L_{jp}} \frac{(H^l_{jp} - \bar{H}_{jp})^2}{(\bar{H}_{jp})^2}}{L_{jp} - 1}} \qquad \forall L_{jp} \geq 1$$

s.t.

$$\sum_{l=0}^{L+1} H^l_{jp} = T_p$$

Solution

$$H^{opt}_{jp} = \frac{T_p - \sum_{l=0}^{L+n-1} H^l_{jp}}{n+1}$$

Technological Applications

Terminal	Pie Andino
Tipo día	Laboral
Hora Reporte	18:50

Ejecutar

09 - Punta Tarde 17:30:00-20:29:59			Salidas Parciales a las:		18:50:59			Ultima PPU Despachada	Hora Ultimo Despacho	Hora próximo despacho :	Óptimo entre despachos
Terminal	Servicio	Sentido	Requeridas	Observadas	Faltantes	ICF	ICR				
Pie Andino	F02	Ida	11	10	-1	91%	96%	ZK-7758	18:46:36	18:52:36	0:06:52
Pie Andino	F02	Regreso	11	8	-3	73%	81%	BBKD-21	18:39:40	18:45:40	0:06:28
Pie Andino	F03	Ida	11	9	-2	82%	70%	CJRC-28	18:49:01	18:56:01	0:07:42
Pie Andino	F03	Regreso	10	7	-3	70%	100%	BWRF-25	18:49:48	18:56:48	0:07:09
Pie Andino	F03c	Ida	5	5	0	100%	96%	WJ-2886	18:45:37	18:59:37	0:14:51
Pie Andino	F03c	Regreso	5	4	-1	80%	100%	WU-5577	18:50:18	19:02:18	0:12:22
Pie Andino	F05	Ida	14	10	-4	71%	95%	CJRD-48	18:50:25	18:54:25	0:04:43
Pie Andino	F05	Regreso	14	14	0	100%	70%	CJRC-78	18:50:26	18:55:26	0:05:49
Pie Andino	F06	Ida	13	10	-3	77%	97%	CJRC-76	18:47:50	18:52:50	0:05:40
Pie Andino	F06	Regreso	14	12	-2	86%	79%	CJRG-31	18:45:18	18:51:18	0:06:07
Pie Andino	F09	Ida	14	16	0	114%	81%	BHRX-56	18:43:41	18:50:41	0:07:04
Pie Andino	F09	Regreso	19	16	-3	84%	90%	BWRF-19	18:50:38	18:53:38	0:03:40
Pie Andino	F11	Ida	9	7	-2	78%	100%	WU-5565	18:40:16	18:49:16	0:09:05
Pie Andino	F11	Regreso	9	8	-1	89%	100%	PW-6150	18:42:05	18:51:05	0:09:44
Pie Andino	F19	Ida	17	14	-3	82%	100%	BBKB-13	18:49:57	18:53:57	0:04:46
Pie Andino	F19	Regreso	15	14	-1	93%	97%	WU-5562	18:38:22	18:43:22	0:05:17
Pie Andino	F20	Ida	10	8	-2	80%	87%	CJRC-77	18:39:50	18:47:50	0:08:28
Pie Andino	F20	Regreso	10	7	-3	70%	100%	CJRD-39	18:40:28	18:47:28	0:07:47
Pie Andino	F21	Ida	15	11	-4	73%	97%	BBKB-14	18:46:26	18:50:26	0:04:41
Pie Andino	F21	Regreso	15	10	-5	67%	95%	ZA-9339	18:49:01	18:53:01	0:04:21
Pie Andino	F22	Ida	11	8	-3	73%	100%	WU-5573	18:42:48	18:48:48	0:06:18
Pie Andino	F22	Regreso	11	10	-1	91%	83%	WJ-2895	18:48:46	18:54:46	0:06:44

Salidas Totales Punta Tarde 17:30:00-20:29:59				
S -S	Requeridas PO	Observadas	Faltantes	ICF
F02 I	24	10	-14	42%
F02 R	24	8	-16	33%
F03 I	21	9	-12	43%
F03 R	20	7	-13	35%
F03c I	11	5	-6	45%
F03c R	11	4	-7	36%
F05 I	30	10	-20	33%
F05 R	30	14	-16	47%
F06 I	27	10	-17	37%
F06 R	28	12	-16	43%
F09 I	30	16	-14	53%
F09 R	42	16	-26	38%
F11 I	18	7	-11	39%
F11 R	18	8	-10	44%
F19 I	34	14	-20	41%
F19 R	34	14	-20	41%
F20 I	20	8	-12	40%
F20 R	20	7	-13	35%
F21 I	32	11	-21	34%
F21 R	32	10	-22	31%
F22 I	24	8	-16	33%
F22 R	24	10	-14	42%

Indicators July-September 2012

Indicador Regularidad en el Trimestre Julio-Agosto-Septiembre

	Indicador Regularidad PUNTA MAÑANA		Indicador Regularidad PUNTA TARDE		Indicador Regularidad DÍA COMPLETO	
Lugar	Empresas	Resultado	Empresas	Resultado	Empresas	Resultado
1º	METROPOLITANA	85,8%	METROPOLITANA	85,3%	METROPOLITANA	87,4%
2º	VULE	81,8%	VULE	81,0%	VULE	86,4%
3º	STP	80,9%	REDBUS	80,5%	REDBUS	84,6%
4º	REDBUS	80,8%	SUBUS	79,7%	SUBUS	82,1%
5º	SUBUS	80,8%	EXPRESS	76,4%	STP	81,1%
6º	EXPRESS	79,6%	STP	75,4%	EXPRESS	79,1%
7º	ALSACIA	75,0%	ALSACIA	73,2%	ALSACIA	76,9%
7º	EXPRESS	90,8%	EXPRESS	85,5%	EXPRESS	90,3%

Source: First ranking of service quality July-September 2012, elaborated by (DTPM).
http://www.dtpm.cl/archivos/Ranking%20de%20Calidad%20de%20Servicio%20Jul-Sep-2012.pdf

Indicators July-September 2012

Indicador Frecuencia en el Trimestre Julio-Agosto-Septiembre

	Indicador Frecuencia PUNTA MAÑANA		Indicador Frecuencia PUNTA TARDE		Indicador Frecuencia DÍA COMPLETO	
Lugar	Empresas	Resultado	Empresas	Resultado	Empresas	Resultado
1º	METROPOLITANA	97,4%	METROPOLITANA	96,1%	METROPOLITANA	97,9%
2º	STP	96,0%	VULE	92,6%	VULE	95,3%
3º	VULE	94,1%	STP	91,0%	REDBUS	95,0%
4º	REDBUS	94,0%	SUBUS	90,7%	STP	94,8%
5º	SUBUS	92,9%	REDBUS	90,5%	SUBUS	93,0%
6º	ALSACIA	90,8%	ALSACIA	87,7%	ALSACIA	92,8%
7º	EXPRESS	90,8%	EXPRESS	85,5%	EXPRESS	90,3%

Source: First ranking of service quality July-September 2012, elaborated by (DTPM).
http://www.dtpm.cl/archivos/Ranking%20de%20Calidad%20de%20Servicio%20Jul-Sep-2012.pdf

Indicators July-September 2013

RANKING DE EMPRESAS REGULARIDAD

	Indicador Regularidad PUNTA MAÑANA		Indicador Regularidad PUNTA TARDE		Indicador Regularidad DÍA COMPLETO	
Lugar	Empresas	Resultado	Empresas	Resultado	Empresas	Resultado
1º	STP	92,6%	STP	91,7%	STP	92,1%
2º	METBUS	88,7%	METBUS	87,6%	METBUS	88,8%
3º	EXPRESS	84,1%	EXPRESS	82,2%	VULE	85,7%
4º	REDBUS	83,9%	SUBUS	80,7%	REDBUS	84,9%
5º	VULE	83,2%	VULE	80,5%	SUBUS	83,4%
6º	SUBUS	82,5%	REDBUS	80,0%	EXPRESS	82,7%
7º	ALSACIA	79,4%	ALSACIA	77,5%	ALSACIA	77,8%

Source: Fifth ranking of serie quality July-September 2013, elaborated by DTPM.
http://www.dtpm.cl/images/Raking%20Empresas%20DTPM%20Julio-Sep-2013.pdf

Indicators July-September 2013

RANKING DE EMPRESAS FRECUENCIA

	Indicador Frecuencia PUNTA MAÑANA		Indicador Frecuencia PUNTA TARDE		Indicador Frecuencia DÍA COMPLETO	
Lugar	Empresas	Resultado	Empresas	Resultado	Empresas	Resultado
1º	METBUS	99,2%	METBUS	98,8%	METBUS	99,3%
2º	REDBUS	98,2%	STP	95,9%	VULE	98,0%
3º	STP	98,1%	VULE	95,9%	REDBUS	97,5%
4º	SUBUS	97,7%	EXPRESS	94,6%	STP	97,4%
5º	VULE	97,5%	REDBUS	93,6%	SUBUS	97,0%
6º	EXPRESS	97,5%	SUBUS	93,3%	EXPRESS	96,7%
7º	ALSACIA	94,5%	ALSACIA	89,1%	ALSACIA	93,2%

Source: Fifth ranking of serie quality July-September 2013, elaborated by DTPM.
http://www.dtpm.cl/images/Raking%20Empresas%20DTPM%20Julio-Sep-2013.pdf

Indicators January-March 2014

RANKING DE EMPRESAS REGULARIDAD
Trimestre Enero - Marzo 2014

DÍA COMPLETO

Lugar	Empresas	Resultado
1º	STP	89,0%
2º	METBUS	87,3%
3º	VULE	84,8%
4º	SUBUS	81,8%
5º	REDBUS	81,5%
6º	EXPRESS	80,4%
7º	ALSACIA	77,6%

En el caso de Regularidad para el Día Completo, 6 concesionarias superan el 80%, nivel mínimo deseado, liderados por **STP Santiago** con un 89,0%. Por su parte, **Inversiones Alsacia** se encuentra por debajo del objetivo con un 77,6% de cumplimiento.

PUNTA MAÑANA

Lugar	Empresas	Resultado
1º	STP	91,8%
2º	METBUS	86,7%
3º	VULE	83,3%
4º	SUBUS	81,3%
5º	REDBUS	80,7%
6º	EXPRESS	79,5%
7º	ALSACIA	77,3%

Con respecto a la Regularidad en Punta Mañana, 5 empresas concesionarias cumplen el estándar mínimo del 80%. En el primer lugar se ubica **STP Santiago** con un 91,8%. Por otro lado, **Inversiones Alsacia** (77,3%) y **Express Santiago Uno** (79,5%) no cumplen con el objetivo deseado.

PUNTA TARDE

Lugar	Empresas	Resultado
1º	STP	90,1%
2º	METBUS	87,5%
3º	VULE	80,8%
4º	SUBUS	80,3%
5º	EXPRESS	79,5%
6º	REDBUS	76,4%
7º	ALSACIA	75,9%

En el caso de regularidad en Punta Tarde, sólo 4 concesionarias sobrepasan el 80%. **STP Santiago**, logra el primer lugar con un 90,1%. Por su parte, **Inversiones Alsacia** (75,9%), **Redbus Urbano** (76,4%) y **Express Santiago Uno** (79,5%), no alcanzan el objetivo mínimo exigido.

Source: Seventh ranking of service quality January-March 2014, elaborated by DTPM.
http://www.dtpm.gob.cl/archivos/Ranking%20Enero-Marzo_2014.pdf

Indicators January-March 2014

RANKING DE EMPRESAS FRECUENCIA

Trimestre Enero - Marzo 2014

DÍA COMPLETO

Lugar	Empresas	Resultado
1º	METBUS	99,1%
2º	VULE	97,6%
3º	STP	97,4%
4º	SUBUS	97,1%
5º	EXPRESS	96,1%
6º	REDBUS	94,6%
7º	ALSACIA	94,4%

En el Indicador de Frecuencia para el Día Completo, se observa que todas las concesionarias cumplen con un desempeño mayor al 90%. El Ranking lo lidera **METBUS** con un 99,1%.

PUNTA MAÑANA

Lugar	Empresas	Resultado
1º	METBUS	98,8%
2º	STP	97,9%
3º	VULE	97,8%
4º	SUBUS	97,3%
5º	EXPRESS	96,2%
6º	REDBUS	95,2%
7º	ALSACIA	95,0%

Al igual que en el Ranking de Día Completo, para el período Punta Mañana, se aprecia que todas las empresas concesionarias cumplen el objetivo de frecuencia. **METBUS** nuevamente encabeza el grupo con un 98,8%.

PUNTA TARDE

Lugar	Empresas	Resultado
1º	METBUS	99,0%
2º	STP	97,0%
3º	VULE	96,4%
4º	SUBUS	95,2%
5º	EXPRESS	95,1%
6º	ALSACIA	92,1%
7º	REDBUS	88,9%

Finalmente, en el indicador de Frecuencia para Punta Tarde, sigue destacándose **METBUS**, por su capacidad de gestión en la operación. En contraposición **Redbus Urbano** con un 88,9% no cumple el objetivo, obteniendo el último lugar

Source: Seventh ranking of service quality January-March 2014, elaborated by DTPM.
http://www.dtpm.gob.cl/archivos/Ranking%20Enero-Marzo_2014.pdf

STP in the news

Inicio » País » Transportes

20/08/2013 | ENVIAR | IMPRIMIR

TRANSANTIAGO: METBUS Y STP LIDERAN RANKING DE FRECUENCIA Y REGULARIDAD

El ministerio de Transportes, al entregar el cuarto ranking tras la vigencia de los nuevos contratos, destacó la mejora histórica en el cumplimiento de la frecuencia del sistema.

Martes 20 de agosto de 2013 | por Nación.cl - Foto: Archivo de Nación.cl + Sigue a **Nación.cl** en Facebook y Twitter

Los operadores **Metbus** y **STP lideran** el **cuarto ranking de frecuencia y regularidad del Transantiago, según informó este martes el ministerio de Transportes y Telecomunicaciones.**

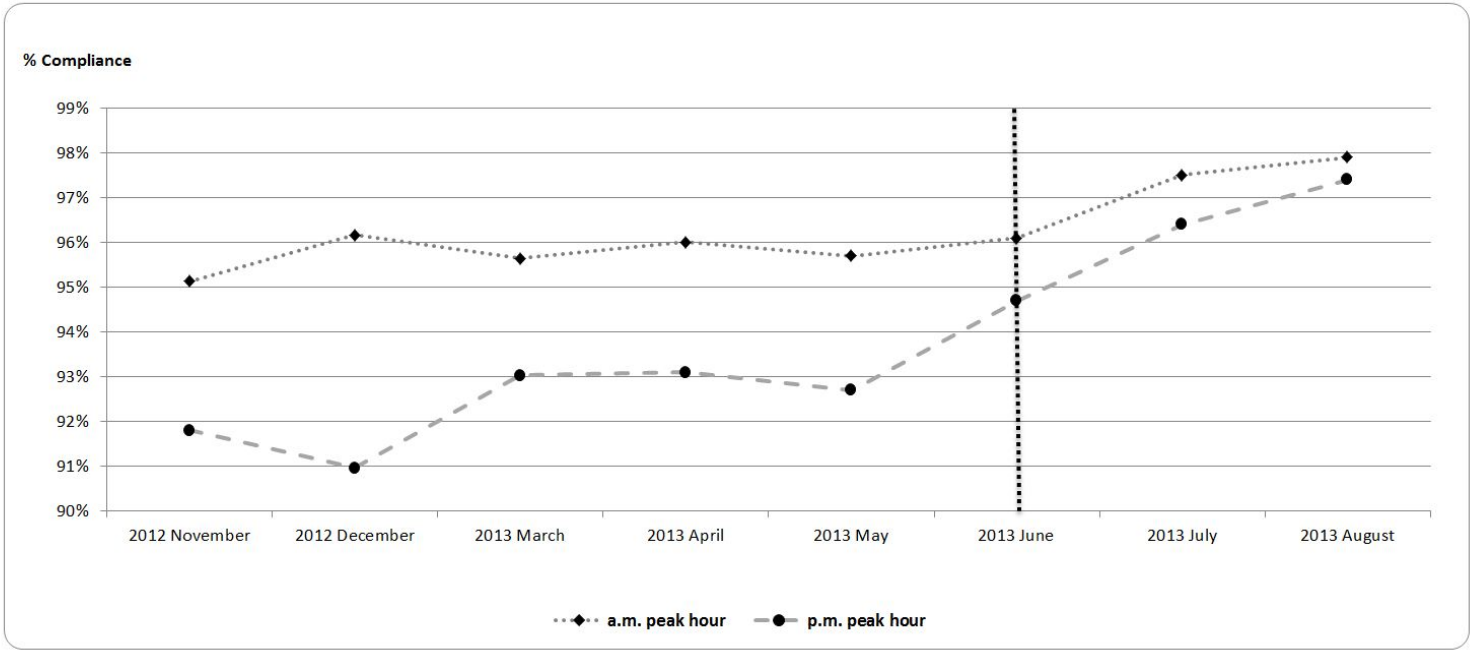


Figure 8 **Evolution of performance, frequency indicator (ICF) for** $Juanita\ Terminal$.

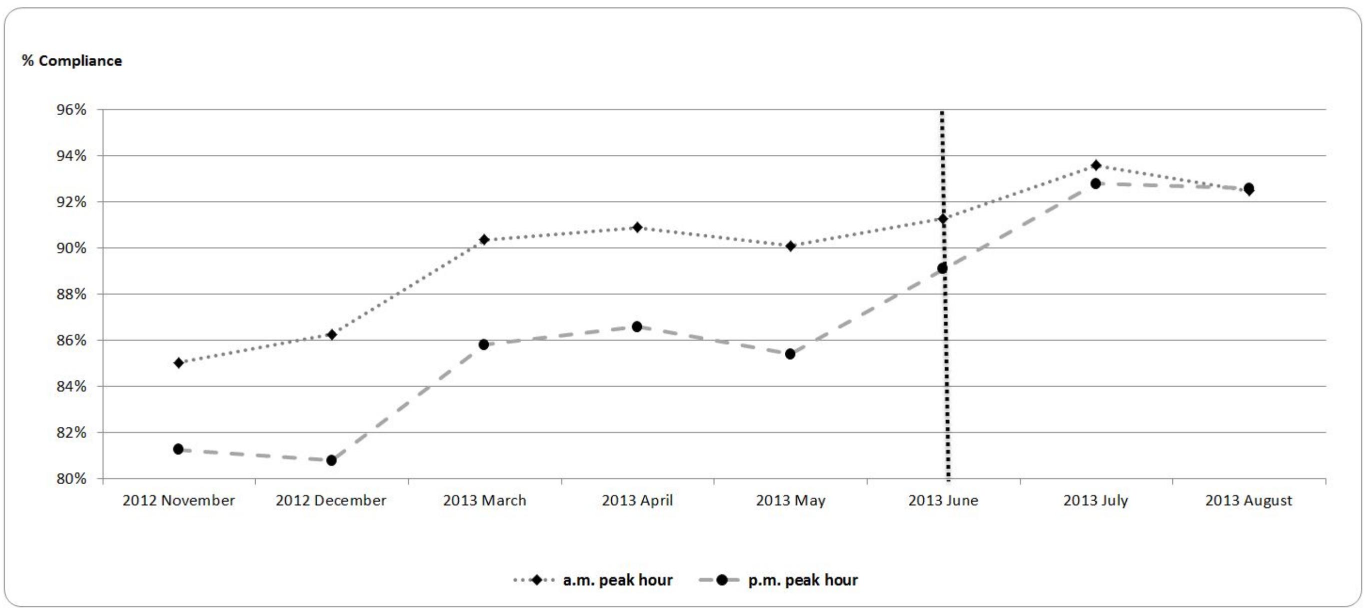


Figure 9 **Evolution of performance, regularity indicator (ICR-I) for** $Juanita\ Terminal$.

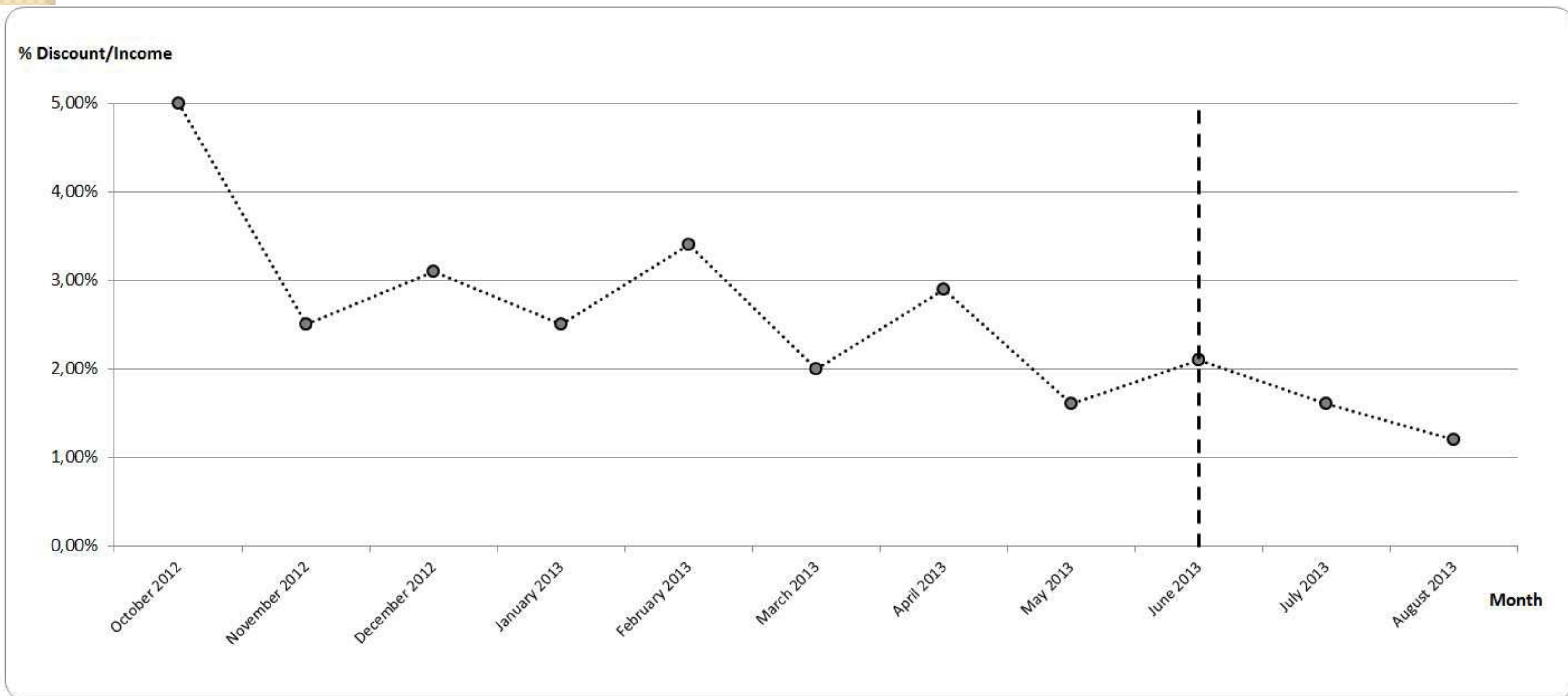


Figure 11 **Evolution of contractual discounts of frequency and regularity.**

Comparison of performance indicators of STP with respect to the industry

Table 6 ICF and ICR-I indicators of performance for full day.

Period	Jul-Sept 2012	Oct-Dec 2012	Jan-Mar 2013	Apr-Jun 2013	Jul-Sept 2013
ICF STP	94.80%	96.70%	96.80%	96.80%	97.40%
ICF Industry	94.16%	94.54%	96.26%	96.21%	97.01%
ICR-I STP	81.10%	84.30%	89.70%	89.60%	92.10%
ICR-I Industry	82.51%	82.57%	84.51%	84.23%	85.06%

Table 7 Indicators of performance ICF and ICR-I for a.m. peak hours.

Period	Jul-Sept 2012	Oct-Dec 2012	Jan-Mar 2013	Apr-Jun 2013	Jul-Sept 2013
ICF STP	96.00%	96.40%	96.60%	96.70%	98.10%
ICF Industry	93.71%	94.90%	96.54%	96.19%	97.53%
ICR-I STP	80.90%	84.40%	91.20%	91.00%	92.60%
ICR-I Industry	80.67%	81.64%	84.51%	83.26%	84.91%

Table 8 Indicators of performance ICF and ICR-I for p.m. peak hours.

Period	Jul-Sept 2012	Oct-Dec 2012	Jan-Mar 2013	Apr-Jun 2013	Jul-Sept 2013
ICF STP	91.00%	93.70%	94.10%	94.10%	95.90%
ICF Industry	90.59%	91.63%	95.03%	93.39%	94.46%
ICR-I STP	75.40%	79.70%	86.90%	87.40%	91.70%
ICR-I Industry	78.79%	79.54%	82.66%	81.87%	82.89%

Services with least observed waiting time excess.

Tabla 18: Ranking de los 10 servicios con menor exceso de tiempo de espera observado en período Punta Tarde durante el año 2013

RANKING	SERVICIO	EMPRESA	PROMEDIO ANUAL DE TIEMPO ESPERA PROGRAMADO [MINUTOS]	PROMEDIO ANUAL DE TIEMPO ESPERA REAL [MINUTOS]	PROMEDIO ANUAL DE TIEMPO EN EXCESO [MINUTOS]	PROMEDIO ANUAL DE TIEMPO EN EXCESO [%]
1	F03c	STP	11,96	8,86	-3,10	-25,9%
2	B63	REDBUS	12,98	10,09	-2,89	-22,2%
3	B69	REDBUS	12,92	10,27	-2,65	-20,5%
4	F12c	STP	7,66	6,31	-1,34	-17,6%
5	F01	STP	7,71	6,82	-0,88	-11,5%
6	F21	STP	5,09	4,33	-0,76	-15,0%
7	F22	STP	6,33	5,61	-0,72	-11,3%
8	F09	STP	4,36	3,74	-0,61	-14,1%
9	531	METBUS	9,58	9,10	-0,48	-5,1%
10	B73	REDBUS	16,21	15,88	-0,33	-2,0%

Source: First report analysis waiting time 2013, Observatorio Transantiago (Sept. 2014). Available in:
http://www.uandes.cl/noticias/observatorio-transantiago-revela-desempeno-real-del-sistema-de-buses-de-santiago.html

Some insightful remarks

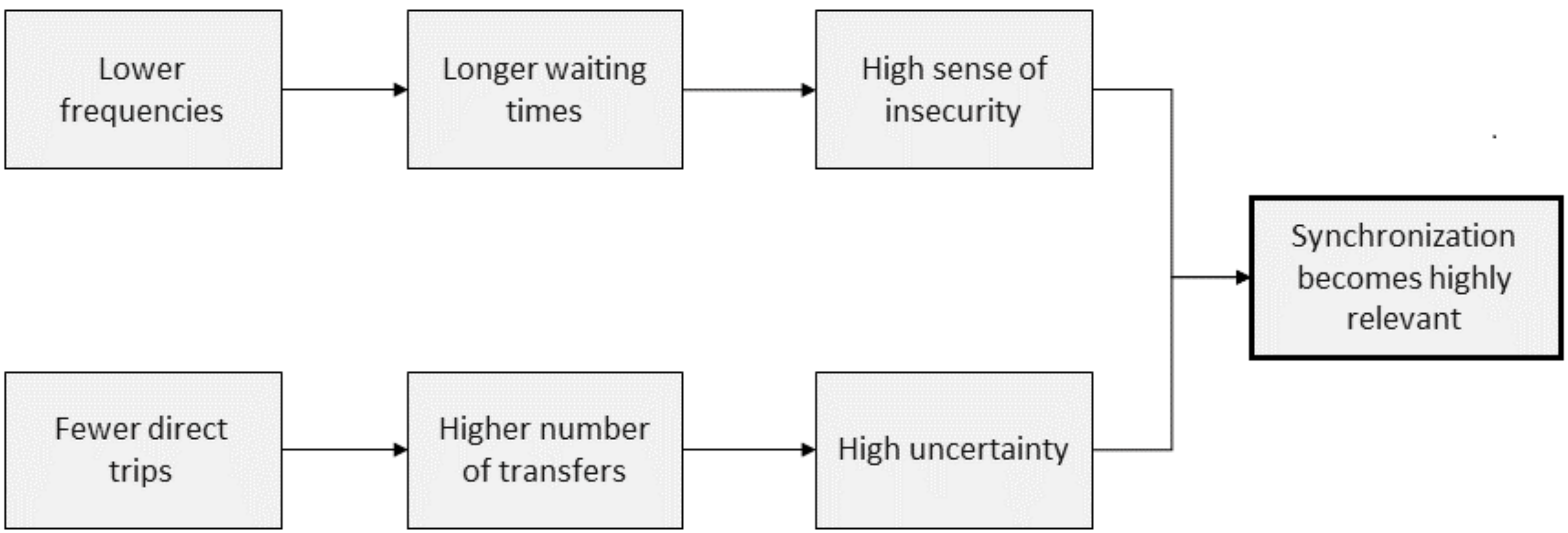
- Mixed integer programming model to determine optimal timetabling and vehicle scheduling in an integrated way based on a time-expanded network
  - The bus scheduling are paths on that network.
  - Programmed trips are visited nodes along those paths

- Model is sufficiently flexible to adapt capacity, frequency and travel times for several time periods, for both commercial and deadhead routes.
- The d*eadheading* strategy shows a considerable benefit in fleet reduction when a demand asymmetry is detected.
- STP has consistently improved the performance indicators associated with frequency and regularity.
- Technological developments for operational control were a key issue for the success of this implementation on the field.

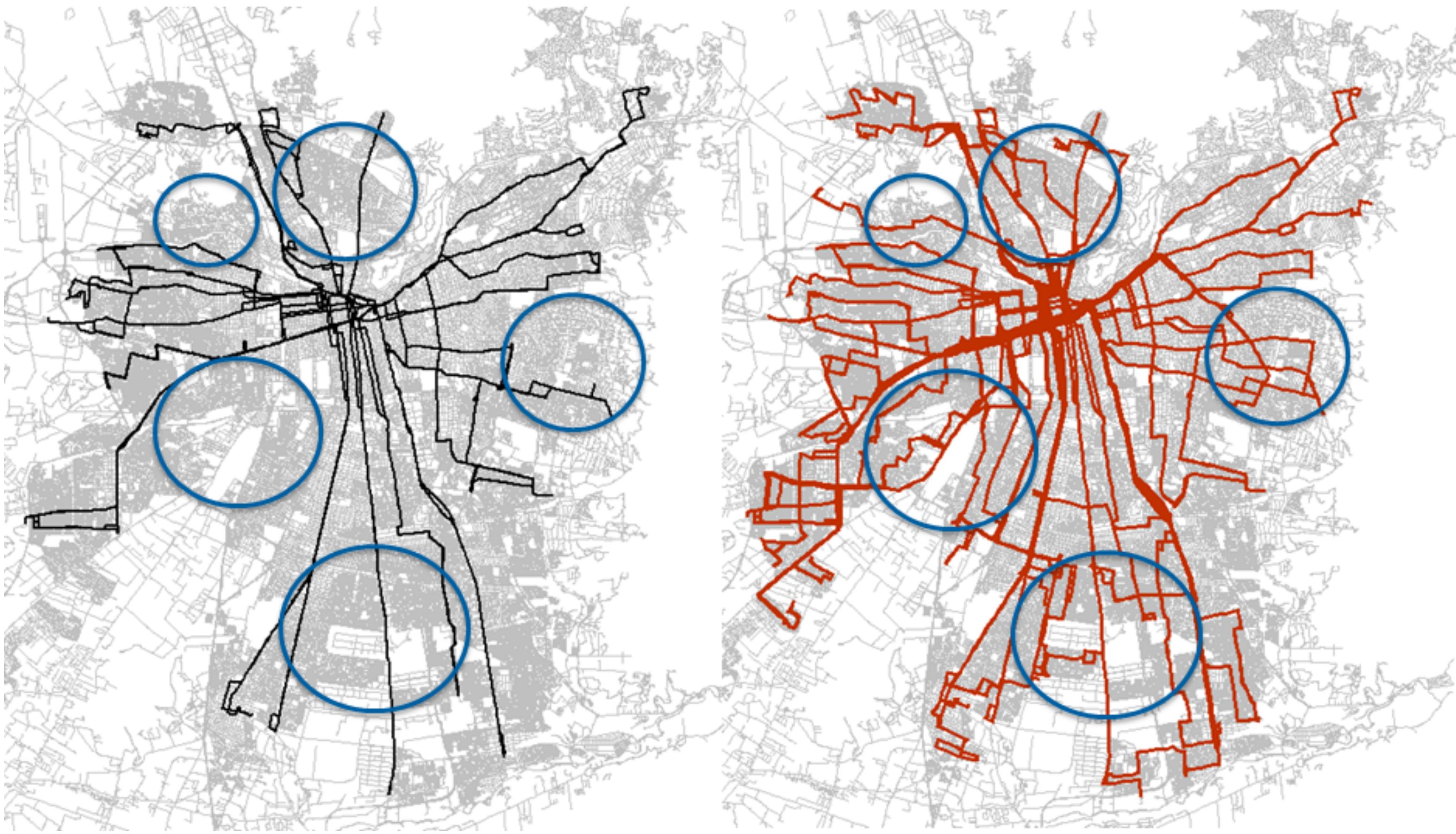
Timetabling and Synchronization problems for night services

- Research motivated by a real problem: design of Transantiago night services
- This requires to perform all planning stages in the context of a proper transit system operating during the night.
- In terms of design, coverage is relevant.
- In terms of timetabling, synchronization is the key issue
- In this work, we propose a MIP model to perform proper timetabling of Transantiago night services, considering fixed headways, potential dwelling times and synchronization of services

Relevance of Synchronization for night urban services.



Santiago night services with fixed schedule: expected coverage in year 2017.



Timetabling and Synchronization problems for night services

- Given a network of night urban services, the goal is to maximize the number of encounters of buses belonging to different lines that are able to perform a synchronized operation of passengers' transfers at the bus stops, under a fixed schedule, satisfying systems conditions.
- Trips that synchronize arrive within a time window of allowable waiting time.
- Trips may hold at certain bus stops where such an operation is allowed.
- Maximum dwelling time per trip and bus stop capacity are addressed.
- A boundary constraint is proposed to deal with the transition between day shift and night shift.

Models for stage 2: Timetabling

Ceder et al. (2001).

$$\text{máx} \sum_{k=1}^{M-1} \sum_{q=k+1}^{M} Y_{kq}, \quad (2.1)$$

s.a.

$$X_{1k} \leq Hmax_k \qquad 1 \leq k \leq M, (2.2)$$

$$X_{F_k k} \leq T \qquad 1 \leq k \leq M, (2.3)$$

$$Hmin_k \leq X_{(i+1)k} - X_{ik} \leq Hmax_k \qquad 1 \leq k \leq M, 1 \leq i \leq F_k - 1, (2.4)$$

$$B \cdot D_{nijkq} \geq X_{ik} + T_{kn} - (X_{jq} + T_{qn}), \quad \forall\, k \in M, \forall\, n \in \bar{N}, \forall\, q \in M, i \leq F_k, j \leq F_q, (2.5)$$

$$B \cdot D_{nijkq} \geq X_{jq} + T_{qn} - (X_{ik} + T_{kn}), \quad \forall\, k \in M, \forall\, n \in \bar{N}, \forall\, q \in M, i \leq F_k, j \leq F_q, (2.6)$$

$$Y_{kq} \leq \sum_{n \in A_{kq}} \sum_{i=1}^{F_k} \sum_{j=1}^{F_q} (1 - D_{nijkq}) \qquad 1 \leq k \leq M, 1 \leq q \leq M, q \neq k, (2.7)$$

$$X_{ik} \in [0, T], Y_{kq} \in \mathbb{Z}^+, D_{nijkq} \in \{0, 1\} \qquad (2.8)$$

BTP Model including dwelling and waiting times at transfer stops

Objective function:

Maximize synchronizations between trips of different lines at transfer nodes

Subject to:

(1) Departure time upper bound of first trip of each line
(2) Departure time upper bound of last trip of each line
(3) Lower bound of waiting time if two trips synchronize at node
(4) Upper bound of waiting time if two trips synchronize at node
(5) Cumulative dwelling times of lines at trasfer nodes
(6) Setting one service starting at time zero

Decision variables

Y^{ij}_{pqb} $\begin{cases} \text{1, if the arrivals of trip p of line i and trip q of line j at node b are} \\ \text{separated by a time that is within the required waiting time limit.} \\ \text{0, otherwise.} \end{cases}$

X^i departure time of the first trip of line i, $X^i \in \left[0, h^i\right]$

Z^i_b dwelling time of line i at transfer node b, $Z^i_b \in \left[0, L^i_b\right]$

S^i_b cumulative dwelling times of line i before its arrival at transfer node b

Parameters

T length of planning horizon in minutes

f^i number of trips of line i in the planning horizon, $f^i = \lceil T/h_i \rceil$

h_i headway of line i in the existing timetable, $i \in I$

t^i_b travel time from depot of line i to node b during the planning horizon

$\underline{W}_b$ minimum allowable waiting time between synchronized trip arrivals at node b

$\overline{W}_b$ maximum allowable waiting time between synchronized trip arrivals at node b

O^b_i position of node b in set Ω_i ordered by t^i_b

$$L^i_b = \begin{cases} min(\overline{L}, h_i) & \text{if} \quad b \in E^i \\ 0, \text{ otherwise.} \end{cases}$$

BTP Model including dwelling and waiting times at transfer stops

$$F_{BTP} = max \sum_{i \in I} \sum_{j \in J(i)} \sum_{b \in B_{ij}} \sum_{p=\mathbf{1}}^{f_i} \sum_{q=\mathbf{1}}^{f_j} Y^{ij}_{pqb}$$

$$X^i \leq h^i \quad \forall i \in I \tag{1}$$

$$T - h^i \leq X^i + \left(f^i - 1\right) \cdot h^i \leq T \quad \forall i \in I \tag{2}$$

$$(X^j + t^j_b + (q-1) \cdot h^j + S^j_b + Z^j_b) - (X^i + t^i_b + (p-1) \cdot h^i + S^i_b) \geq \underline{W}_b \cdot Y^{ij}_{pqb} - \underline{M}^{ij}_{pqb} \cdot (1 - Y^{ij}_{pqb})$$

$$\forall i \in I, j \in J(i), p = 1..f^i, q = 1..f^j, b \in B^{ij} \tag{3}$$

$$(X^j + t^j_b + (q-1) \cdot h^j + S^j_b + Z^j_b) - (X^i + t^i_b + (p-1) \cdot h^i + S^i_b) \leq \overline{W}_b \cdot Y^{ij}_{pqb} + \overline{M}^{ij}_{pqb} \cdot (1 - Y^{ij}_{pqb})$$

$$\forall i \in I, j \in J(i), p = 1..f^i, q = 1..f^j, b \in B^{ij} \tag{4}$$

$$S^i_{b'} = \sum_{b \in E^i : t^i_{b'} > t^i_b} Z^i_b \quad \forall i \in I, b' \in \Omega_i \tag{5}$$

$$\exists i \in I, \quad X_i = 0 \tag{6}$$

New valid inequalities

(7) Preprocessing: Unfeasible synchronization due to time windows
(8) Least common multiple rule constraint
(9) Forward synchronization constraint
(10) Strengthening: Synchronization pattern constraints
(11) Maximum dwelling time per trip
(12) Bus stop capacity
(13) Border condition

New valid inequalities

$$
\begin{aligned}
&\textit{if} \quad (0 + t_b^j + (q-1)\cdot h^j + 0) - (h^i + t_b^i + (p-1)\cdot h^i + L_i^b \cdot O_b^i) > 0 \\
&\textit{or} \quad (0 + t_b^i + (p-1)\cdot h^i + 0) - (h^j + t_b^j + (q-1)\cdot h^j + L_j^b \cdot O_b^j) > 0 \\
&\qquad\qquad \textit{then} \quad Y_{pqb}^{ij} = 0
\end{aligned} \tag{7}
$$

$$
\begin{aligned}
&Y_{pqb}^{ij} = Y_{p+k,q+m,b}^{ij} \\
&\textit{Such that } m,k \in \mathbb{N} \textit{ where } m\cdot h^j \ = \ k\cdot h^i \ = LCM(h^i, h^j) \ < \ T
\end{aligned} \tag{8}
$$

$$
\sum_{q=q'}^{q'+\lfloor L_i^b/h^j \rfloor} Y_{pqb}^{ij} \leq 1 + (Z_b^i/h_j) \tag{9}
$$

$$
(1 - Y_{p,q+\mathbf{1},b}^{ij}) \geq (1 - Y_{pqb}^{ij}) \tag{10}
$$

New valid inequalities

$$\sum_{b \in E^i} Z_b^i \leq \left(\frac{1}{10}\right) \cdot \max_{b \in E^i} t_b^i \qquad (11)$$

$$\sum_{j \in J(i): b \in B^{ij}} \sum_{q=1}^{f^j : L_b^j > 0} Y_{pqb}^{ij} \cdot SIZE_j \leq CAP_b - 1 \qquad (12)$$

$$X^i \leq CB_i \qquad (13)$$

4652 synchronizations achieved between trips of lines at transfer nodes where the departure times (in minutes) of their first trips are:

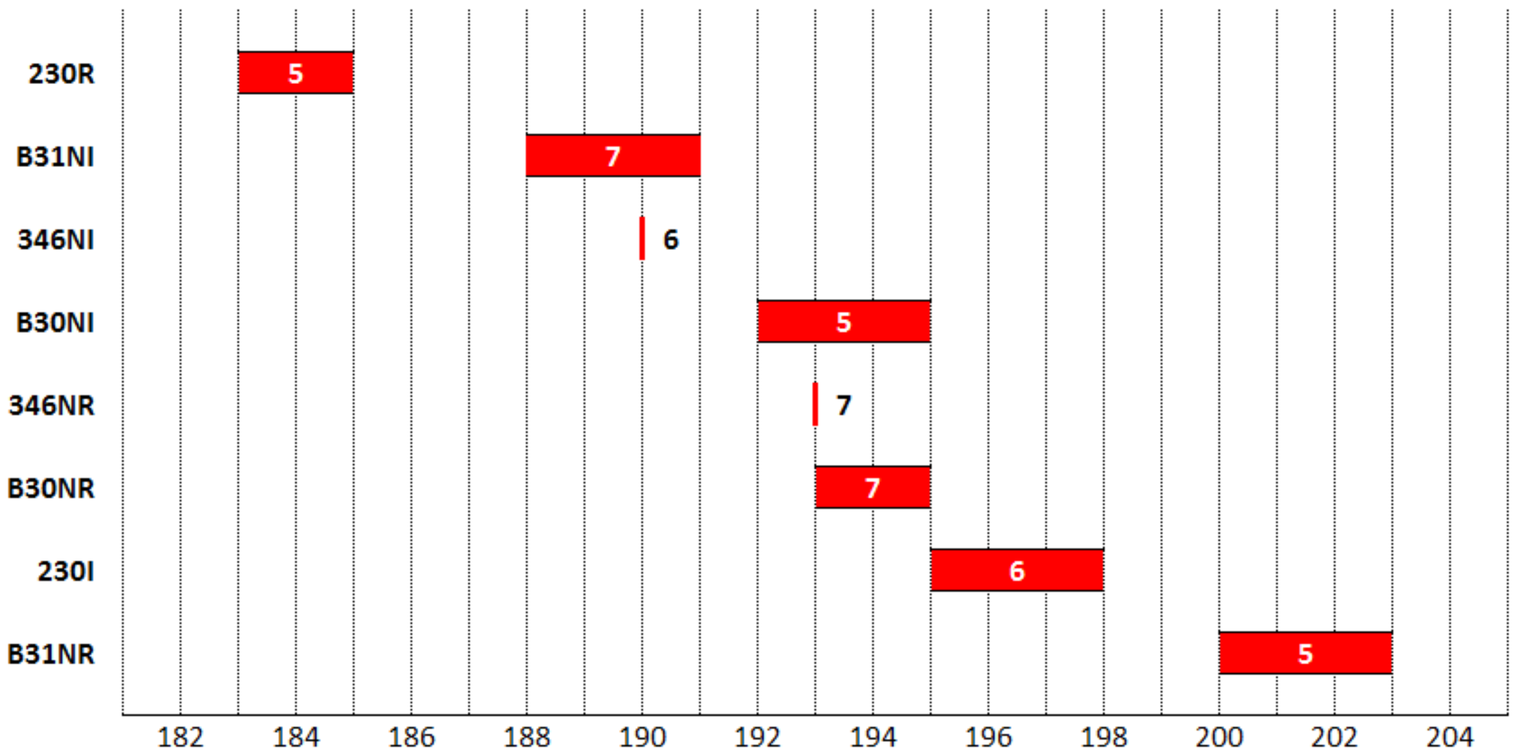
104R	0
104I	10
107I	4
107R	4
112NI	1
112NR	12
201I	15
201R	1
210I	5
210R	3
230I	6
230R	8
301I	3
301R	4
303I	14
303R	14
346NI	2
346NR	12
405I	2
405R	2

426I	14
426R	13
506I	5
506R	6
513I	15
513R	12
516I	1
516R	15
B02NI	15
B02NR	3
B30NI	12
B30NR	12
B31NI	7
B31NR	5
F28NI	9
F28NR	7
F30NR	4
F30NI	0
401NR	1
401NI	0

Holding times of lines at transfer nodes are:

	Rejas	Bellavista	Departamental	Militar	Irarrazabal	Moneda	StaLucia	PlazaItalia
107R	3	0	3	0	0	0	0	0
112NI	0	0	0	2	0	0	0	0
112NR	0	0	0	3	0	0	0	0
201I	0	0	2	0	0	3	0	0
230I	0	0	0	0	0	0	3	0
230R	0	0	0	0	0	0	2	0
303I	0	0	0	0	0	3	0	0
303R	0	0	0	0	0	0	0	3
346NI	0	0	0	0	0	3	0	0
405I	2	0	0	0	0	1	0	0
405R	3	0	0	0	0	0	0	1
426I	0	0	0	2	0	3	0	3
426R	0	0	0	3	0	2	0	1
506I	0	0	0	0	1	0	0	0

The trips arriving between minute 182 and 204 of the planning horizon at bus stop Metro Santa Lucia are:



Remarks

- Cyclic timetabling model
- Transition from day to night and from night to morning.
- Decomposition for timetabling model applied to a much bigger instance increasing considerably the number of lines with fixed schedules at night.
- Network design for night services together with a proper timetabling. Objective function?

Other topics of interest

- Dynamic routing of inspectors for STP: expanded network approach

- Mesoscopic-microscopic simulation approach for testing the feasibility of operational plans provided by PT companies. Also, for proposing better operational policies (Transantiago)

Simulation for public transport planning

- **Public transport systems** (PTS) are increasingly complex, incorporating various types of services.

- The need to integrate and operate these systems efficiently poses a challenge for planners and operators.

- Simulation models have been established as the main tool for the evaluation of the system at the operational level, providing a dynamic perspective on traffic operations, allowing comparisons of different scenarios and the representation of complex interactions among the main components of the network:

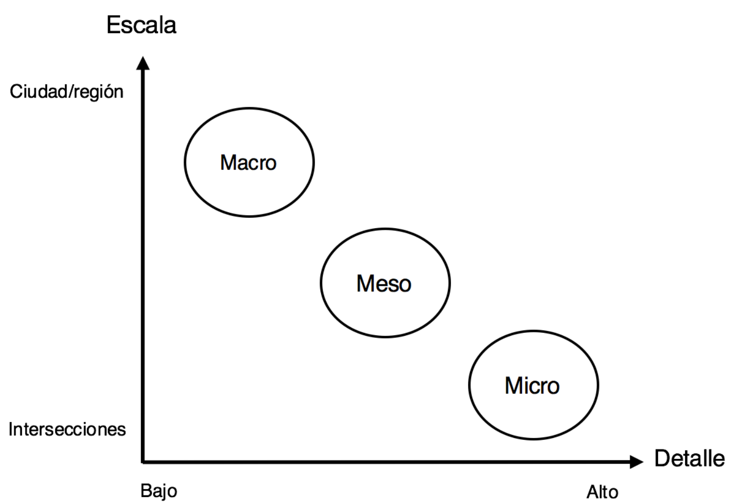
    - Traffic

    - Vehicles of the network

    - Passengers

Simulation for public transport planning

- PTS modelling has focused on **microscopic** simulation. However, these models are inefficient when applied on a large scale because of the level of detail.
- In contrast, **mesoscopic** simulation models avoid detailed modelling from second to second, being unable to analyze the different classes of vehicles.
- **Macroscopic** modelling instead considers flows or streams of vehicles, but is not able to analyze regional dynamics



Trade-off between scale and level of detail

Simulation for public transport planning

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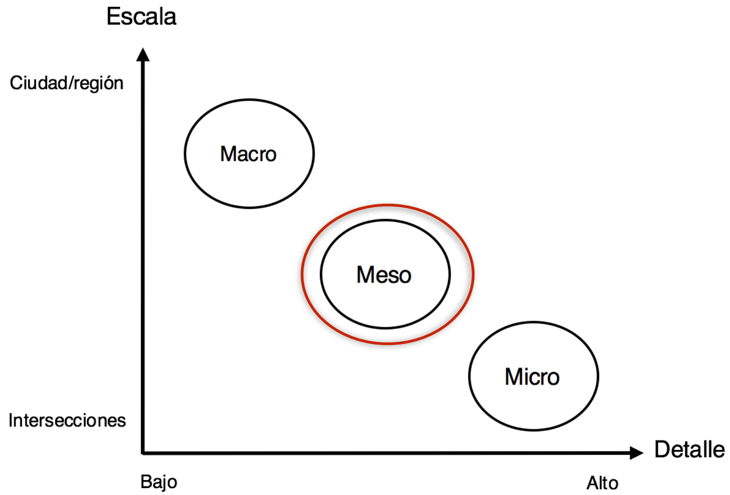

Trade-off between scale and level of detail

<<The challenge will be focused on a mesoscopic environment, to cover a larger region>>

Simulation for public transport planning

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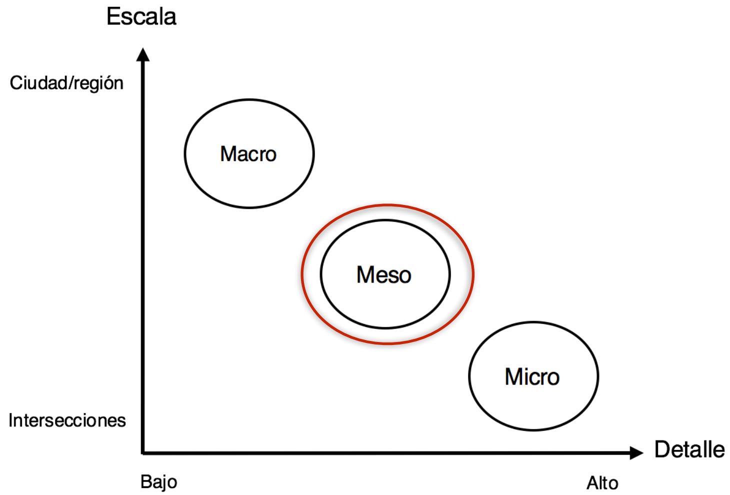


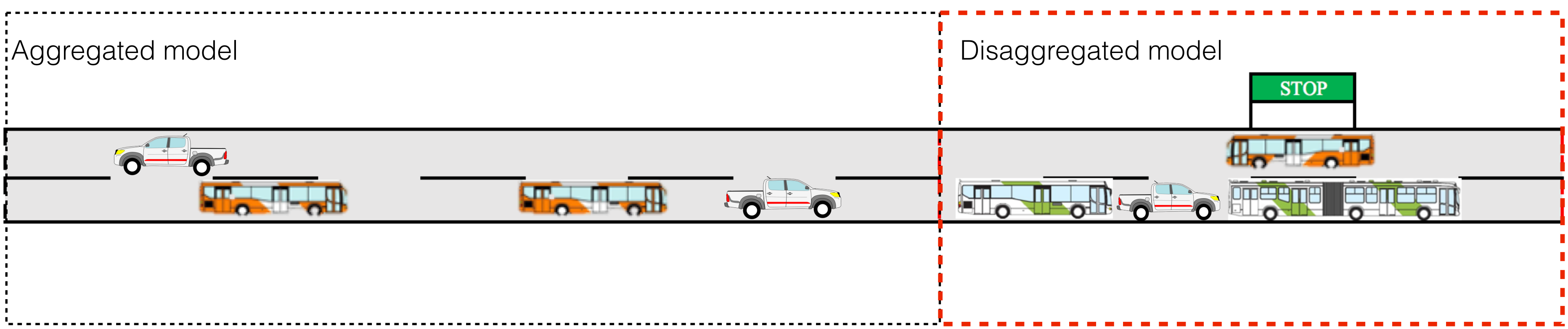
Trade-off between scale and level of detail

<<The challenge will be focused on a mesoscopic environment, to cover a larger region>>

Can public transport buses be simulated in a more macroscopic fashion?

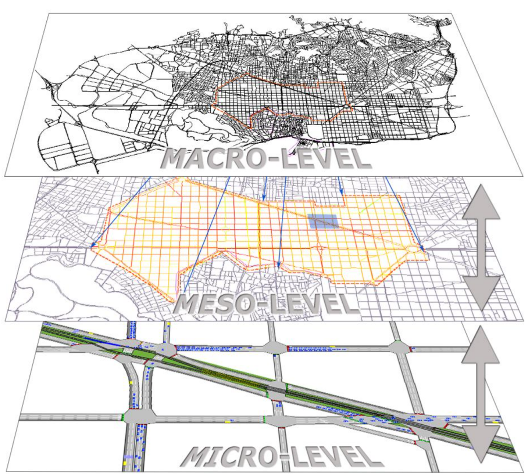
Designing a meso-simulator for supporting public transport planning

- Transport public modeling:
  - Modelling mixed traffic public-private.
  - Microscopic level of disaggregation is required at bus-stops.
  - Consideration of analytical formulas at stops (**Dwelling times and transference**)
  - The movement between stops can be modelled in a more aggregated manner. Private vehicles has to be added in the analysis.



Implementing a meso-simulator for supporting public transport planning

- Simulation coding:
  - Coding the simulator from scratch (Python, Java, C++, etc.)
  - Consider different simulation softwares as a base platform (Simio, TRANSYT, Paramics, AIMSUN, etc.)
  - APIs in PARAMICS or AIMSUN can be used for extending the simulation tool to customized requirements.
  - API in Paramics for public transport microsimulation has been developed by our research group.



Microscopic simulation of traffic

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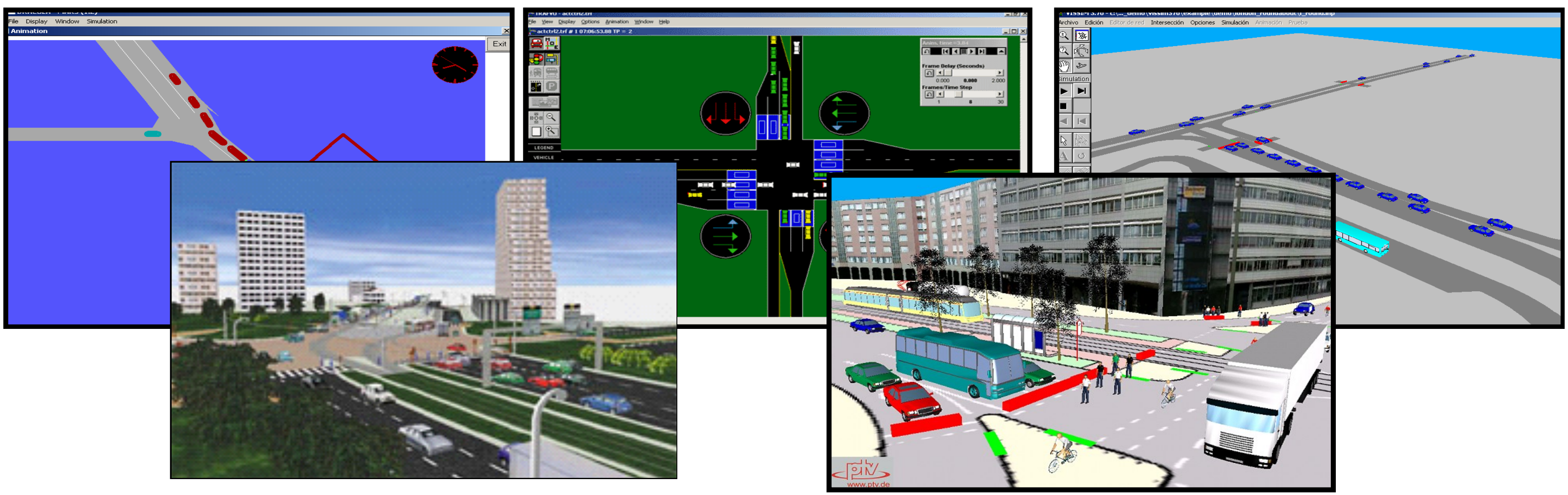
- Traffic microsimulation packages
- Internal models: car following, lane changing
- Used for traffic management, real-time control, DVRP, ITS
- Ejemplos: NETSIM, WATSIM, HUTSIM, DRACULA, CORSIM, AIMSUN NG, PARAMICS, VISSIM.



Microscopic simulation of traffic

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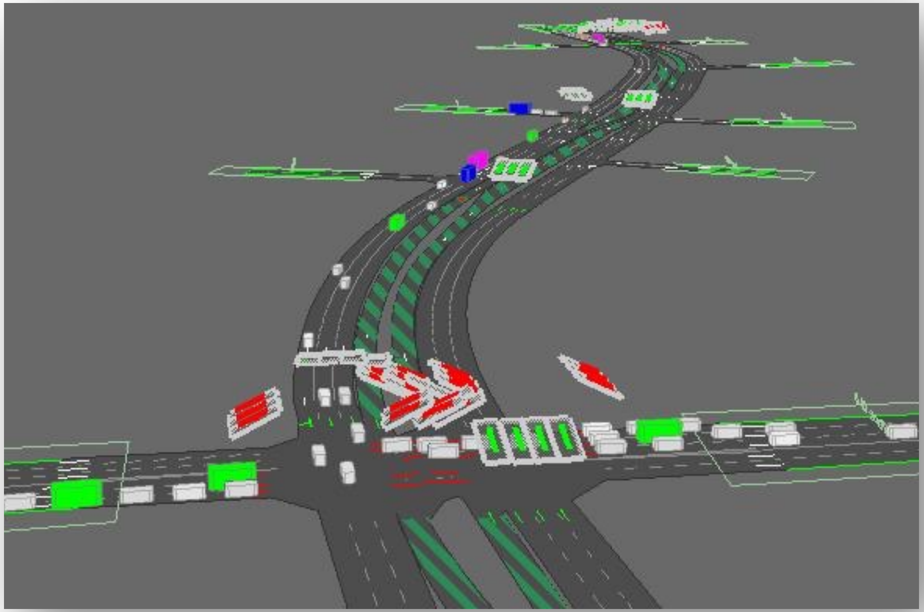
Microsimulator:

PARAMICS Suite v6.7

Modeller, Programmer, Analyzer

(Lenguaje de programación: C, C++)



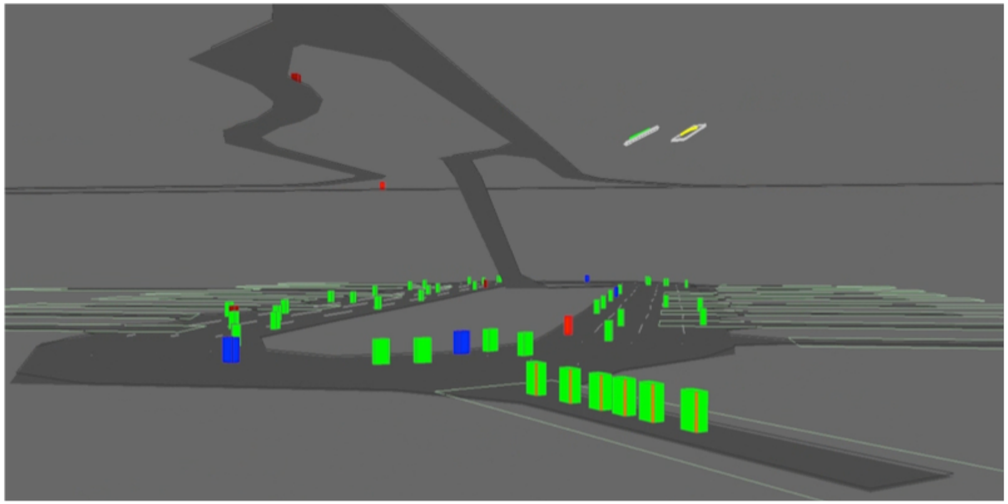
Programmer (Library):

It permits to modify and control different aspects of the simulation for sophisticated implementations: Actuated signals, HOV, evaluation of management projects, VMS strategies for *vehicle guidance*, etc.
4 types of functions (QPO, QPX, QPS, QPG)

Potential applications

- Public transport modelling
- Dispatch fleets for passengers and freight (dynamic problem)
- Emergency vehicles (ongoing)

- Adaptation of the model to other non-conventional applications: Santiago airport BHS.



MTP approach

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- Models developed, calibrated and incorporated in Paramics software via API to replicate the Chilean PT behavior:
- Modeling buses: new features such as number of seats, number of doors, etc.
- Incorporating passengers in microsimulation
  - O/D matrices for passengers
  - Statistics of waiting time, level of service.
- Specific models
  - Service time models at bus-stops
  - Overtaking manœuvres

Santa Rosa corridor

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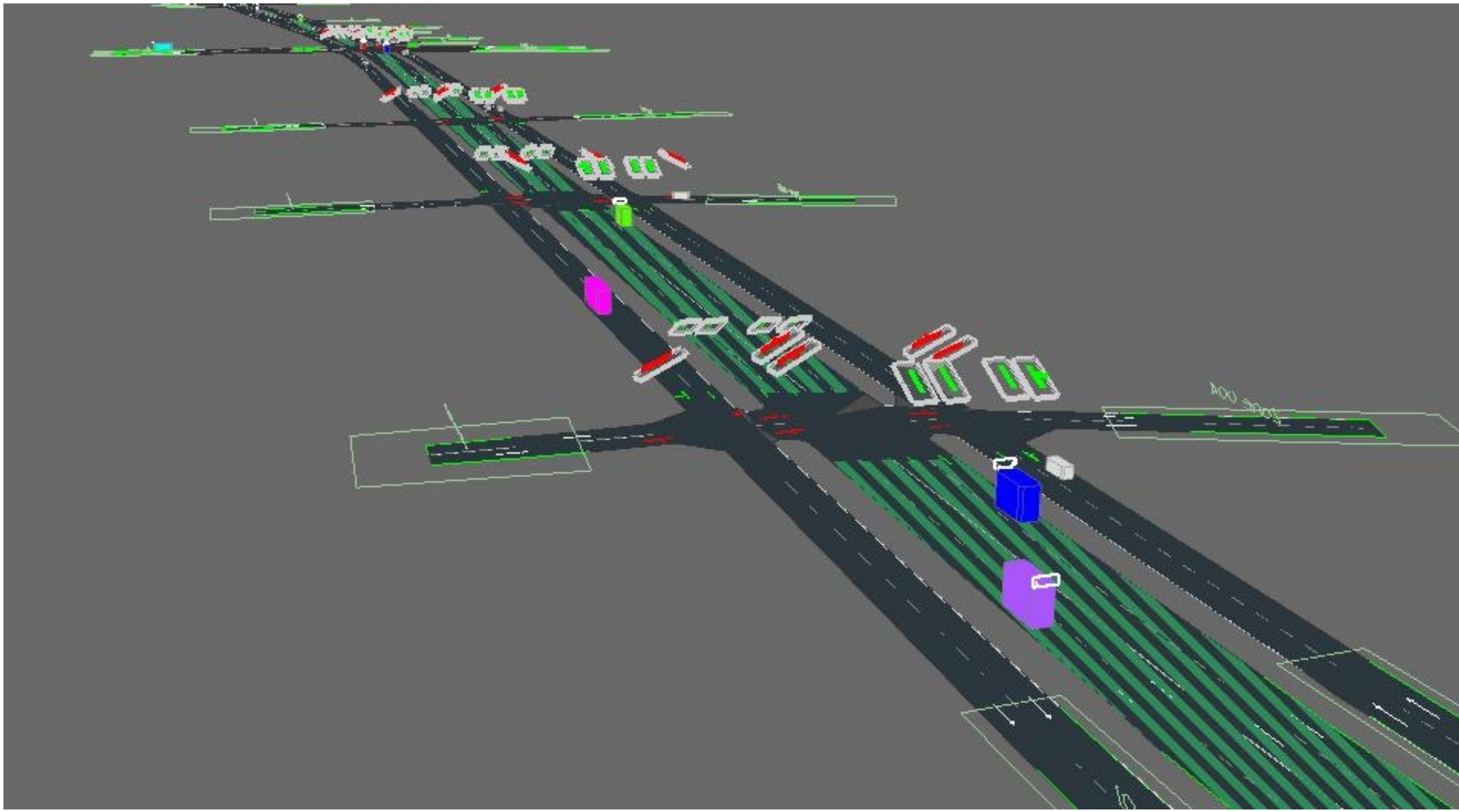

MTP implementation

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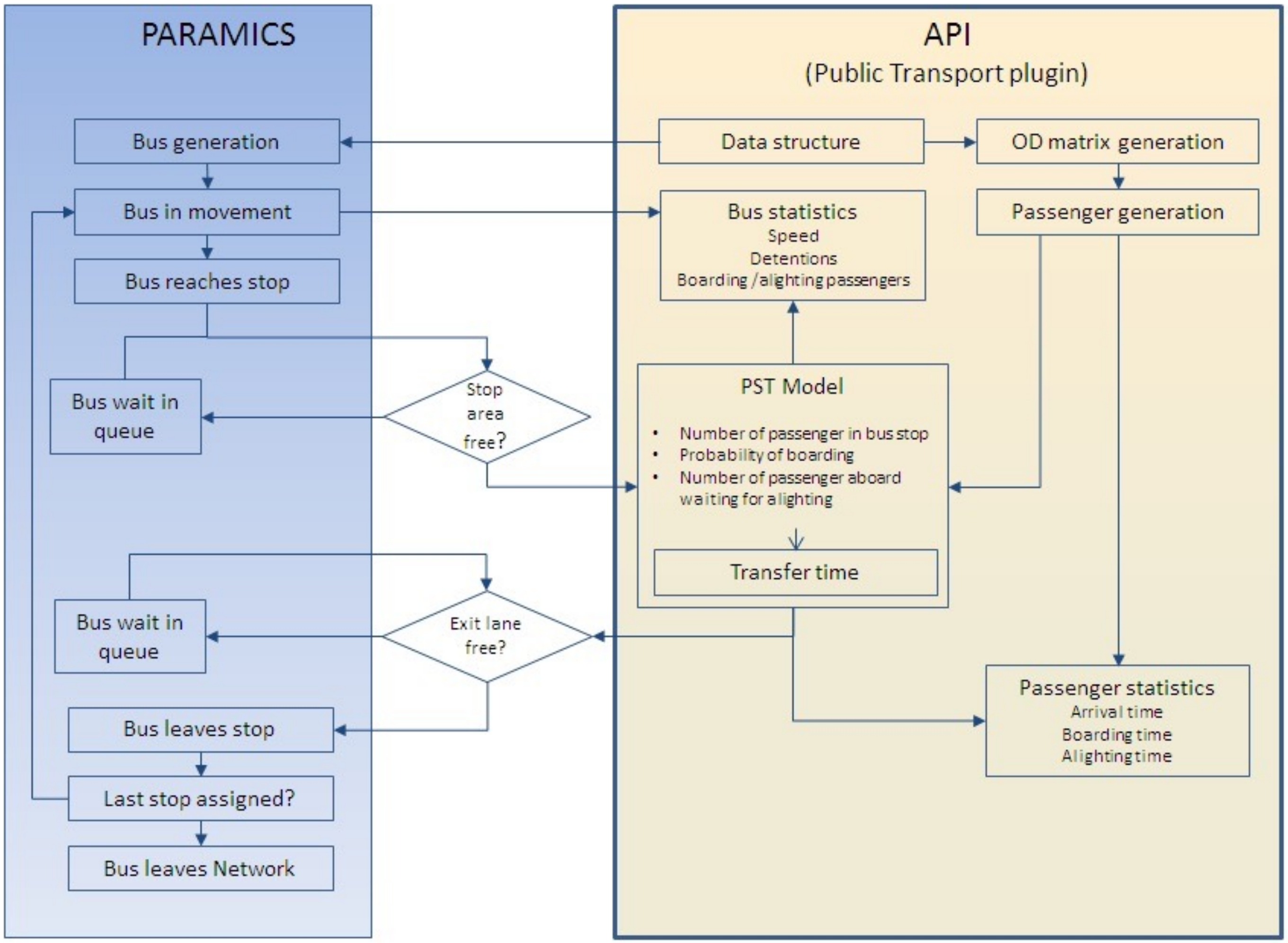
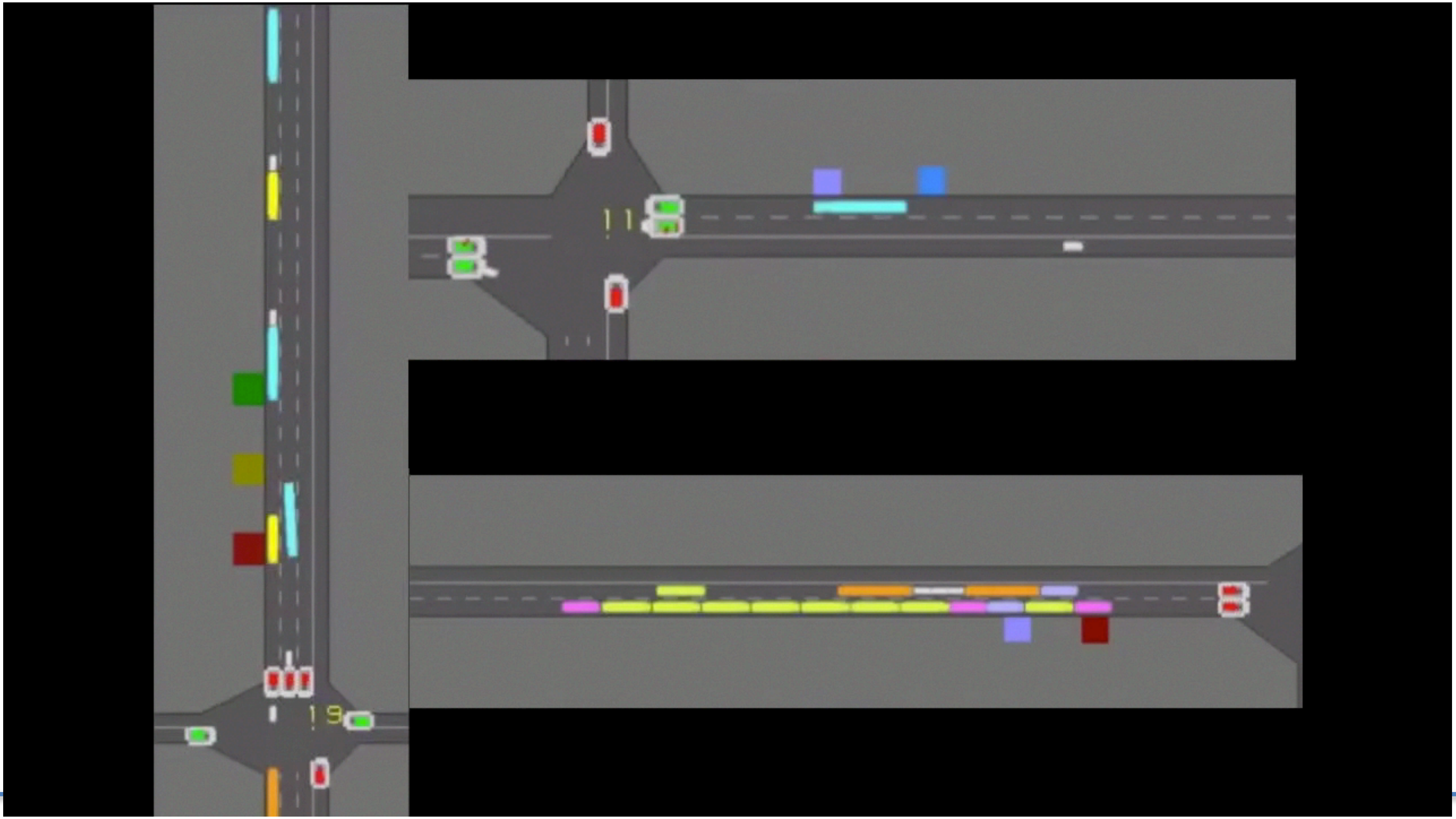
- API in C++ allowing interaction and addition of modules
- Passengers
  - Stochastic arrivals
    - Regular deterministic
    - Uniform
    - Poisson
    - Cowan M3
  - Trip matrices
  - Bus choice
- Buses
  - Car following model close to stops
  - Lane changing models (operation in the stop zone)
  - Stochastic arrivals
- Simulator
  - Stoppage of buses
  - Operation at stops
  - Passenger transference
  - Statistics collection

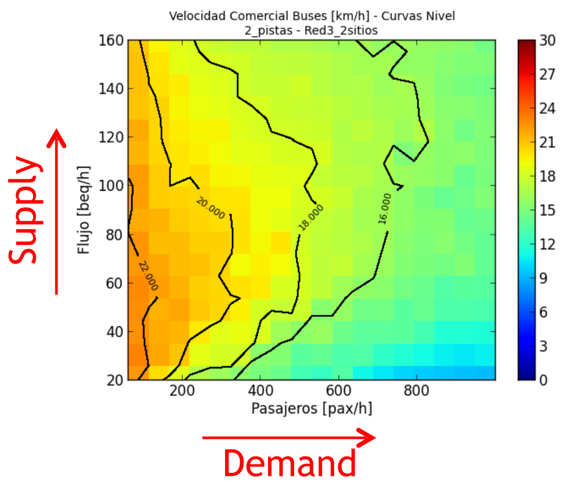
Bus progression in the simulation



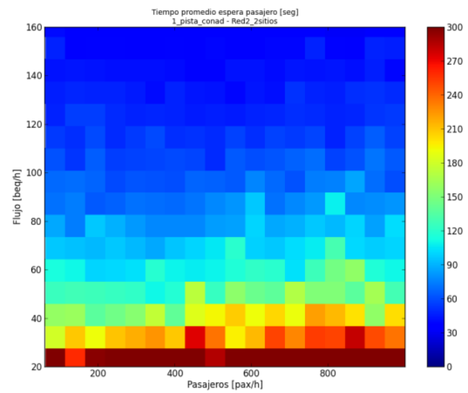
Stop operation



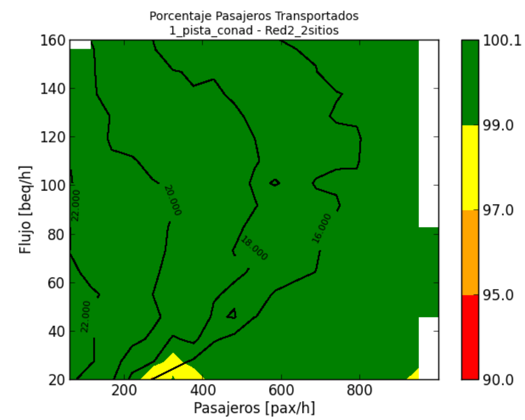
Example of indicators of MTP



Commercial speeds heat maps



Waiting times



Percentage of transported passengers

Indices

ERRORES RELATIVOS				
indicador	promedio	desviacion	minimo	maximo
flujo_buses	149.5	0.87	148.5	150.0
composicion_buses	0.14	45.62	-50.0	51.0

PORCENTAJES				
indicador	promedio	desviacion	minimo	maximo
operacion_segunda_pista	0.0	0.0	0.0	0.0
buses_no_paran	0.0	0.0	0.0	0.0
pasajeros_transportados	68.67	3.51	65.0	72.0

PARADEROS	Paradero #4				Paradero #3			
indicador	promedio	desviacion	minimo	maximo	promedio	desviacion	minimo	maximo
buses_operan	79.0	1.73	77.0	80.0	50.0	0.0	50.0	50.0
tiempo_transferencia	93.41	55.05	5.0	191.0	75.89	54.07	5.0	242.0
demora_aproximacion	141.75	280.04	1.0	1838.5	26.4	45.39	0.0	237.5
pasajeros_bajan	1250.33	162.19	1131.0	1435.0	991.33	12.86	982.0	1006.0
pasajeros_suben	1643.67	328.69	1390.0	2015.0	1034.0	10.82	1022.0	1043.0
tiempo_espera_pasajeros	499.14	619.04	0.01	2975.2	347.24	454.64	0.03	1978.23
distribucion_tiempo_buses_llegada	4.0	72.62	87.77	0.0	1153.5	3.0	92.15	94.52
distribucion_tiempo_pasajeros	4.0	5.23	5.17	0.0	33.95	3.0	-0.0	195.69

CIMS3
Ciudades inteligentes: Modelado y simulación de sociedades sustentable

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