Tactical Design of Electric Bus Network Using Optimization Tools

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TOSA TROLLEYBUS OPTIMISATION SYSTEME ALIMENTATION 2013

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TRANSP-OR

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Motivation

Figure : BNP Paribas Building in Geneva[1]

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[1] – *source: ingustravel.com*

Agenda

Overview

▸ video link

No Good Deed Goes Unpunished

Diesel Bus

- *Direct CO2 Emissions*
- *Initial Cost - 5.5 MUSD*
- *Annual Cost - 8.8 MUSD*
- *Noise Pollution*

Trolley Bus

- No Direct CO2 Emissions
- Initial Cost - 25 MUSD
- Annual Cost - 9.8 MUSD
- Overhead Wires

Tosa Bus

- No Direct CO2 Emissions
- Initial Cost - 25 MUSD
- Annual Cost - 9.6 MUSD

Tram

- No Direct CO2 Emissions
- Initial Cost - ? MUSD
- Annual Cost - ? MUSD
- Overhead Wires + Rail

Mode Overview of Operating Line 5 in Geneva

Parties Involved

LES PARTENAIRES

tpg

opi
industries
technologies

SIG

ABB

CE PROJET EST POSSIBLE GRACE AU SOUTIEN DE

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Energie BFE
Office fédéral de l'énergie OFEN

REPUBLIQUE
ET CANTON
DE GENEVE

POST TENEBRAS LUX

AVEC LA COLLABORATION DE

EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

haute école
neuchâtel berne jura
arc

— HEAD
HAUTE ÉCOLE D'ART ET
DE DESIGN GENÈVE
GENEVA UNIVERSITY
OF ART AND DESIGN

HESS

hepia
Haute école du paysage, d'ingénierie
et d'architecture de Genève

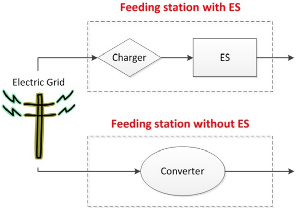
palexpo

Assumptions/Hard Constraints

- all buses fully charged overnight at depot(s)
- after visiting a terminal, bus will be fully recharged (cycles are identical)
- the energy storage has to be able to recharge between 2 consecutive buses
- every bus has to have enough energy to go back to depot at any point of its route
- the battery is never replenished (can't go below certain threshold, e.g. 60%)
- the power of on-board-charger is superior to the power of any other elements

Primary Decisions I

- $x_i \begin{cases} 1 & \text{if station } i \text{ has FFS,} \\ 0 & \text{otherwise.} \end{cases}$
- $z_i \begin{cases} 1 & \text{if station } i \text{ has ES,} \\ 0 & \text{otherwise.} \end{cases}$

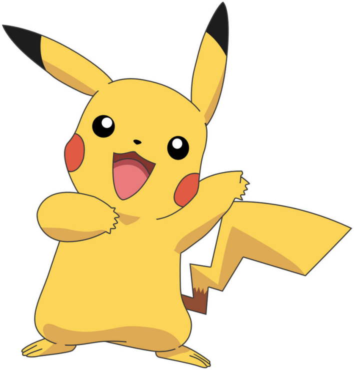


- $p_i^{Converter}$ – the converter power (kW)
- p_i^{ES} – the ES charger power (kW)
- r_i – the ES capacity (kWh)

Primary Decisions II

- buses are homogenous (for easier maintenance)
- $r^{Battery}$ – the battery size on the bus (kWh)
- p^{OBC} – the power of on-board-charger (kW)

Secondary Decisions



- y_i – the amount of energy of a bus, when it leaves station i (kWh)
- q_i – the amount of energy, that is drawn by a bus at station i (kWh)
- w – the total amount of energy, that is drawn from the grid (kWh)
- u – the amount of energy, that is drawn from the grid and exceeds the peak threshold (kWh)

Objective

$$
\begin{aligned}
\text{min}: \quad & N \cdot (A^{OBC} + V) \sum_{i=0}^{\lfloor P/Q_v \rfloor} (1+R)^{-iQ_v} + \\
& N \cdot A^{Battery} r^{Battery} \sum_{i=0}^{\lfloor P/Q_b \rfloor} (1+R)^{-iQ_b} + \\
& \overline{N}(A^{Converter} p_0^{Converter} + F_0) + \\
& \sum_{i \in \mathcal{I}} [(A^{ESC} + C_i) p_i^{ESC} + (A^{Converter} + C_i) p_i^{Converter} + \\
& A^{ES} r_i \sum_{i=0}^{\lfloor P/Q_b \rfloor} (1+R)^{-iQ_b} + F_i x_i] + \\
& N \cdot O \sum_{i=0}^{12P} (1 + R/12)^{-i} + \\
& (A^{Electricity} w + A^{Tax} u) \sum_{i=0}^{365P} (1 + R/365)^{-i}
\end{aligned}
$$

With great power
comes huge
electricity bill.

POSITIWITTY.COM

Constraints I

$$\begin{aligned}
s.t. \quad & x_0 = 1, x_1 = 1, x_{k*} = 1, x_{K+1} = 1 && (1)\\
& z_0 = 0, z_1 = 0, z_{k*} = 0, z_{K+1} = 0 && (2)\\
& x_i \geq z_i, \forall i \in \mathcal{I}^{\Omega} && (3)\\
& p^{OBC} \geq p_i^{Converter}, \forall i \in \mathcal{I}^{\Omega} && (4)\\
& Mx_i \geq q_i, \forall i \in \mathcal{I}^{\Omega} && (5)\\
& q_0 \leq r^{Battery} && (6)\\
& q_i \leq r^{Battery} - [y_{i-1} - E \cdot D_{i-1,i}, \forall i \in \mathcal{I}^{\Omega} - \{0\} && (7)\\
& q_i \leq p^{OBC} T_i, \forall i \in \mathcal{I}^{\Omega} && (8)\\
& q_i \leq r_i + M(2 - x_i - z_i), \forall i \in \mathcal{I}^{\Omega} && (9)\\
& q_i \leq p_i^{Converter} T_i + Mz_i, \forall i \in \mathcal{I}^{\Omega} && (10)\\
& q_0 = y_0 && (11)\\
& y_i \leq r^{Battery}, \forall i \in \mathcal{I}^{\Omega} && (12)
\end{aligned}$$

Constraints II

$$y_i = y_{i-1} + q_i - E \cdot D_{i-1,i}, \forall i \in \mathcal{I}^{\Omega} - \{0\} \tag{13}$$

$$y_i \geq E \cdot D_{i,i+1}, \forall i \in \mathcal{I}^{\Omega} - \{K+1\} \tag{14}$$

$$y_i \geq E^{d} \cdot D_{i,0}, i \in \mathcal{I}^{\Omega} - \{0\} \tag{15}$$

$$y_1 = r^{Battery}, y_{k*} = r^{Battery}, y_{K+1} = r^{Battery} \tag{16}$$

$$r^{Battery} - E \cdot D_{0,1} \geq S_t \cdot r^{Battery} \tag{17}$$

$$y_{k*-1} - E \cdot D_{k*-1,k*} \geq S_t \cdot r^{Battery} \tag{18}$$

$$y_K - E \cdot D_{K,K+1} \geq S_t \cdot r^{Battery} \tag{19}$$

$$r^{Battery} - E^{d} \cdot D_{1,0} \geq S_d \cdot r^{Battery} \tag{20}$$

$$Hp_i^{ESC} \geq r_i, \forall i \in \mathcal{I}^{\Omega} \tag{21}$$

$$p_1^{Converter} = p_{K+1}^{Converter} \tag{22}$$

$$w = N \cdot q_0 + G \cdot N(\sum_{i=1}^{K+1} q_i) + \sum_{i \in \mathcal{I}} r_i \tag{23}$$

Constraints III

$$u \geq w - B \tag{24}$$

$$L^{ESC} z_i \leq p_i^{ESC} \leq U^{ESC} z_i, \forall i \in \mathcal{I}^{\Omega} \tag{25}$$

$$L_{TF}^{Converter}(x_i - z_i) \leq p_i^{Converter} \leq U_{TF}^{Converter}(x_i - z_i), \forall i \in \mathcal{I}^{\Omega} - \{0\} \tag{26}$$

$$L_D^{Converter} \leq p_0^{Converter} \leq U_D^{Converter} \tag{27}$$

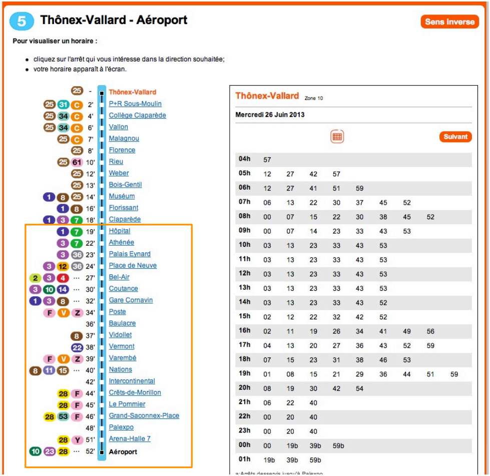
$$L^{ES} z_i \leq r_i \leq U^{ES} z_i, \forall i \in \mathcal{I}^{\Omega} \tag{28}$$

$$L^{Battery} \leq r^{Battery} \leq U^{Battery} \tag{29}$$

$$p^{OBC} \leq U^{OBC} \tag{30}$$

$$x_i, z_i \in \{0, 1\}, q_i, y_i \geq 0, \forall i \in \mathcal{I}^{\Omega}, w, u \geq 0 \tag{31}$$

Bus #5



5 Thônex-Vallard - Aéroport

Pour visualiser un horaire :

- cliquez sur l'arrêt qui vous intéresse dans la direction souhaitée;
- votre horaire apparaît à l'écran.

25	-	**Thônex-Vallard**
25 31 C	2'	P+R Sous-Moulin
25 34 C	4'	Collège Claparède
25 34 C	6'	Vallon
25 C	7'	Malagnou
25	8'	Florence
25 61	10'	Rieu
25	12'	Weber
25	13'	Bois-Gentil
1 8 25	14'	Muséum
1 8	16'	Florissant
1 3 7	18'	Claparède
1 7	19'	Hôpital
3 7	22'	Athénée
3 36	23'	Palais Eynard
3 12 36	24'	Place de Neuve
2 3 4 ···	27'	Bel-Air
3 10 14 ···	30'	Coutance
1 3 8 ···	32'	Gare Cornavin
F V Z	34'	Poste
	36'	Baulacre
8	37'	Vidollet
22	38'	Vermont
F V Z	39'	Varembé
8 11 15 ···	40'	Nations
	42'	Intercontinental
28 F	44'	Crêts-de-Morillon
28 F	45'	Le Pommier
28 53 F	46'	Grand-Saconnex-Place
	48'	Palexpo
28 Y	51'	Arena-Halle 7
10 23 28 ···	52'	**Aéroport**

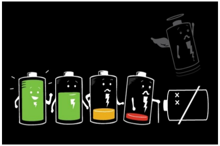
Thônex-Vallard Zone 10

Mercredi 26 Juin 2013

04h	57								
05h	12	27	42	57					
06h	12	27	41	51	59				
07h	06	13	22	30	37	45	52		
08h	00	07	15	22	30	38	45	52	
09h	00	07	14	23	33	43	53		
10h	03	13	23	33	43	53			
11h	03	13	23	33	43	53			
12h	03	13	23	33	43	53			
13h	03	13	23	33	43	53			
14h	03	13	23	33	43	52			
15h	02	12	22	32	42	52			
16h	02	11	19	26	34	41	49	56	
17h	04	13	20	27	36	43	52	59	
18h	07	15	23	31	38	46	53		
19h	01	08	15	21	29	36	44	51	59
20h	08	19	30	42	54				
21h	06	22	40						
22h	00	20	40						
23h	00	20	40						
00h	00	19b	39b	59b					
01h	19b	39b	59b						

Technical Details

Battery Size -- 68.6 kWh

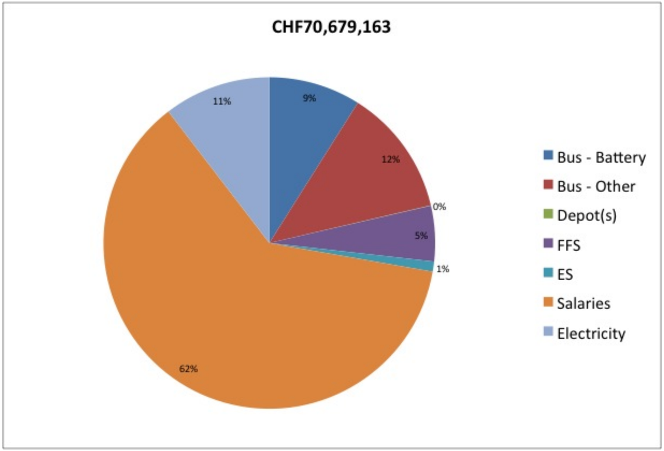


On-board-power -- 200 kW

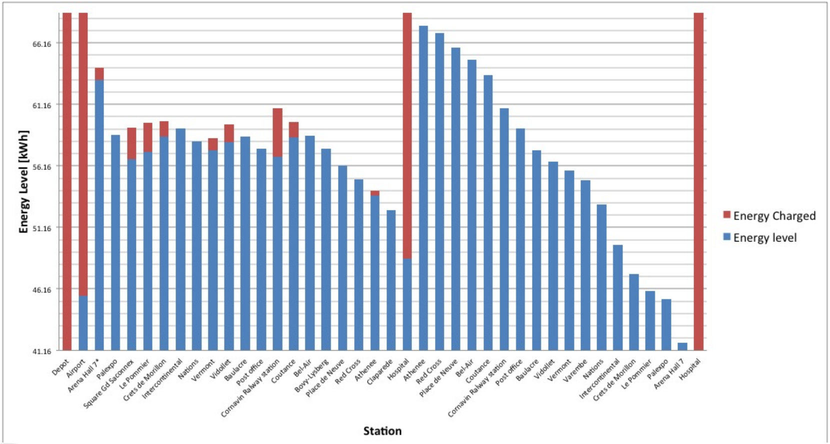
9 x FFS
- *5 with ES*
- *power - 200 or 115 kW*

ES
- *power - 50 kW*
- *capacity - 1 or 1.2 kWh*

Costs (30 Years Lifetime)



Charging Scheme



Conclusions

- Expected cost vs. reality $+2$M CHF ($+$ 20 years)
- Multiple solutions (degrees of freedom for decision makers)
- FFS only in the first part of the route (the energy consumption in the first part is $+14$ kWh, the dwelling time at the hospital terminal is lower than at the airport)

Future Work

- Warnings (some power settings are not possible)
- Network level (preprocessed conflicts)
- Robustness

Thank you for your attention.