

TRC-30 Presentation

Joint Modelling and Robustness Analysis of Multimodal Transportation and Electricity Networks

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ENTPE



PRESENTATION OVERVIEW

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METHODOLOGY

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CASE STUDY :
LYON, FRANCE

04

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05

CONCLUSION

01

INTRODUCTION

BACKGROUND

Topical issues



First CO2 emitting sectors in energy combustion worldwide in 2022* :

1. Electricity production 42%
2. Transportation 22%

Massive electrification of vehicles

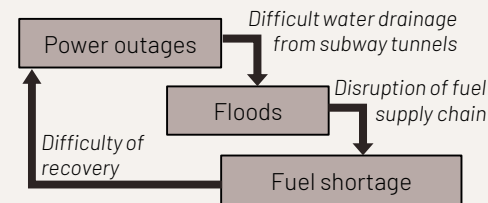


European Union Agreement (2022):
Cessation of new internal combustion engine vehicles sales by 2035

Interdependent transport and electricity networks



- ❖ Complex interdependencies :
Example of Hurricane Sandy (2012)

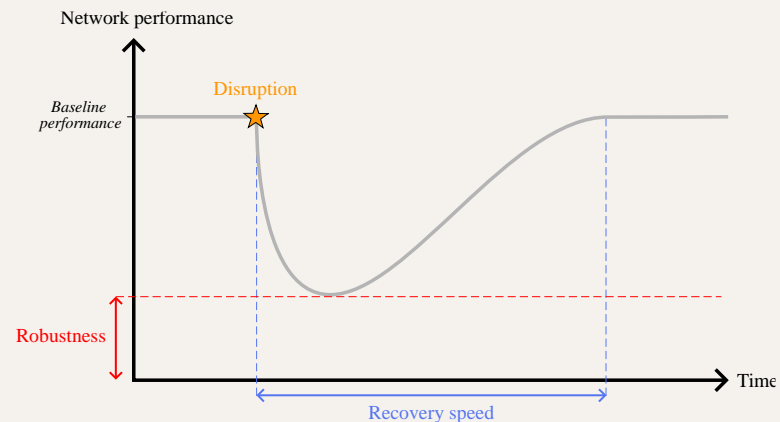


- ❖ Joint networks modelling and resilience analysis needed

* From statistics published by the French Ministry of Ecological Transition

KEY NOTIONS

- ❖ **Resilience:** network ability to adapt to and recover from disruptive events.
- ❖ **Robustness:** network capacity to remain functional during disturbances.



Schematic definition of network resilience

This talk focuses on **topological robustness in public transport networks subject to electrical disruptions.**

STATE OF THE ART



Research gaps on transportation robustness studies

- ❖ Interdependences with the power grid overlooked [1]
- ❖ Traditional topological metrics [2]
- ❖ Single transportation mode models [3]

[1] Oded Cats. (2016) The robustness value of public transport development plans. Journal of Transport Geography.

[2] Kpotissan Adjetej-Bahun et al. (2016) Railway transportation system's resilience: Integration of operating conditions into topological indicators. NOMS 2016 IEEE/IFIP

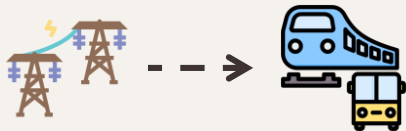
[3] Chao Fang et al. (2020) Vulnerability analysis of critical infrastructure under disruptions: An application to China Railway High-speed. Journal of Risk and Reliability.

RESEARCH CONTRIBUTIONS



Work implications

- ❖ Robustness analysis of **multimodal** public transportation networks under **power outage scenarios**
- ❖ **Demand-weighted** topological metrics



02

METHODOLOGY

NETWORK MODEL

GRAPH CREATION

❖ **Pedestrian graph :**

$$G_W(V_W, E_W)$$

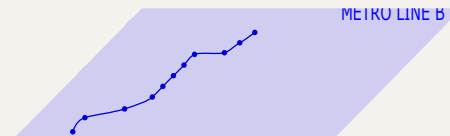
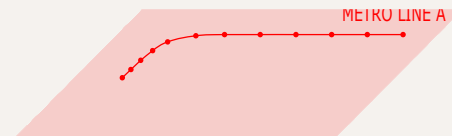
Open Street Map (OSM) data



❖ **Public transport line graphs :**

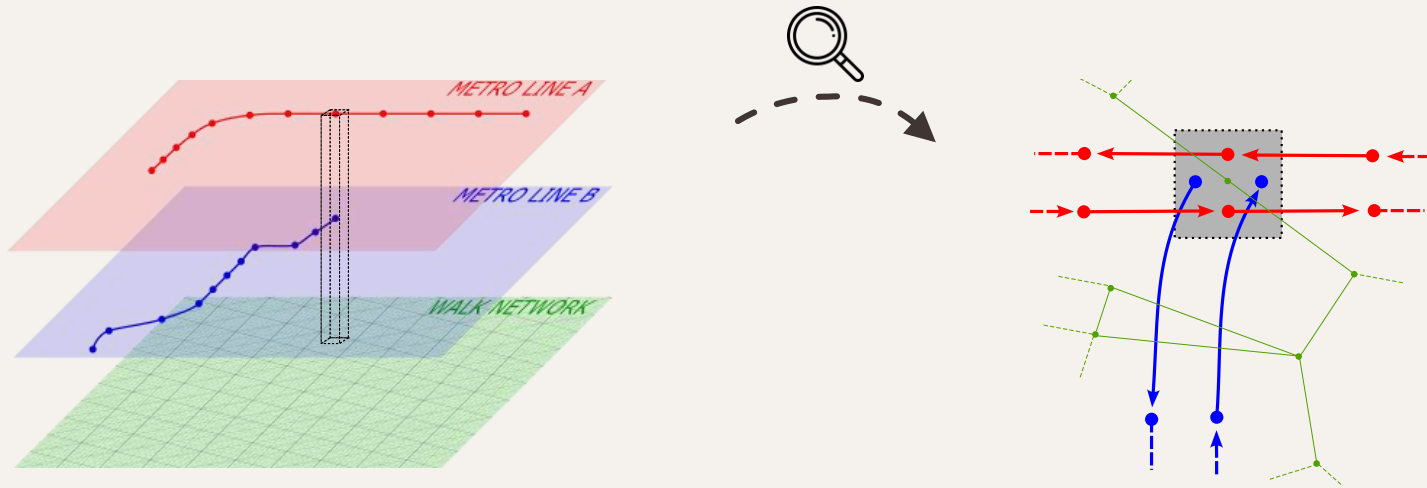
$$G_L(V_L, E_L), L \in PT$$

General Transit Feed Specification (GTFS) data



NETWORK MODEL

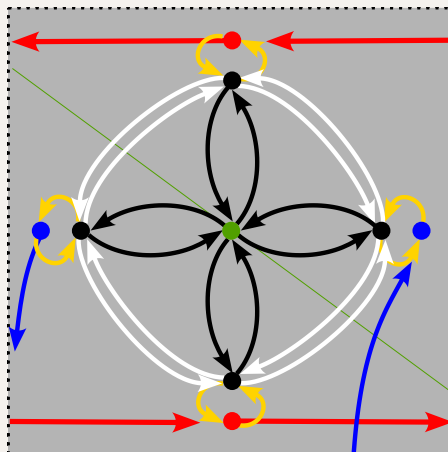
CONNECT LAYERS



NETWORK MODEL

CONNECT LAYERS

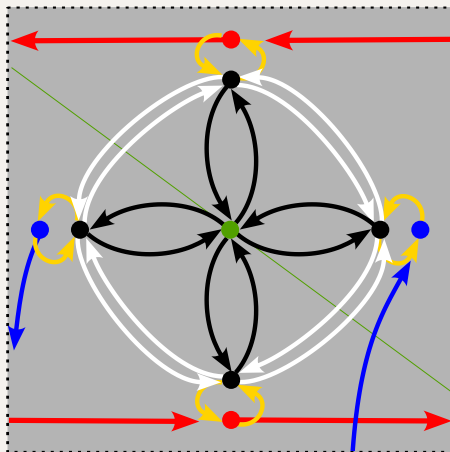
- Walk nodes V_W
- Walk edges E_W
- Public transport nodes V_{PT}
- Public transport edges V_{PT}



- **Intermediate nodes V_{II}**
Duplicates of transit nodes
- **Intermediate edges E_{II}**
Connect each $v_I \in V_I$ to the nearest $v_{II} \in V_{II}$
- **Access edges E_A**
Board or alight vehicle
- **Transfer edges E_t**
Connections between nearby stations

NETWORK MODEL

EDGE WEIGHTS



- **Walk edges**
Walking durations
- **Public transport edges**
Mode-based travel times
- **Intermediate edges**
Walking durations
- **Transfer edges**
Connection times between nearby stations
- **Access edges**
Exit : 0
Entry : Average waiting time based on line frequency

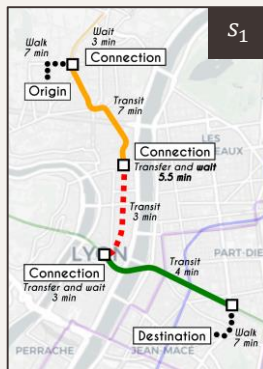
G_{ref} : final model assuming normal operating conditions

POWER GRID DISRUPTIONS

s_0 : "Normal operation"

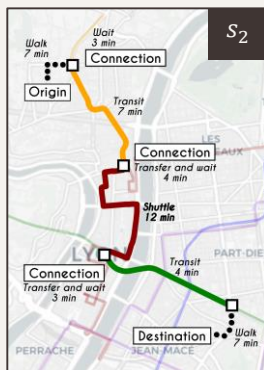


s_1 : "Partial operation"
Line frequency reduction



Description of line functional states

s_2 : "Anticipated disrupted operation"
Line replacement by shuttle service
Google Maps Directions API



s_3 : "Unforeseen disrupted operation"
Line disconnection



POWER GRID DISRUPTIONS



Network state Λ : set of disrupted lines $L^* \in PT$ in states s_1 , s_2 or s_3

For each $L^* \in G_{ref}$:

Increase mode-based travel times of $e_{L^*} \in E_{L^*}$
or waiting times of $e_A \in V_I \times V_{L^*}$

G_Λ : resulting graph

ROBUSTNESS EVALUATION

TOPOLOGICAL METRICS



Average Travel Time (ATT)

Average duration of shortest paths between all transit node pairs in the graph

$$ATT(G_\Lambda) = \frac{1}{|V_{PT}|(|V_{PT}| - 1)} \sum_{v_o \in V_{PT}} \sum_{v_d \in V_{PT} \setminus v_o} SPL(v_o, v_d)$$

Shortest Path Length from origin station v_o to destination station v_d



Node Betweenness Centrality (NBC)

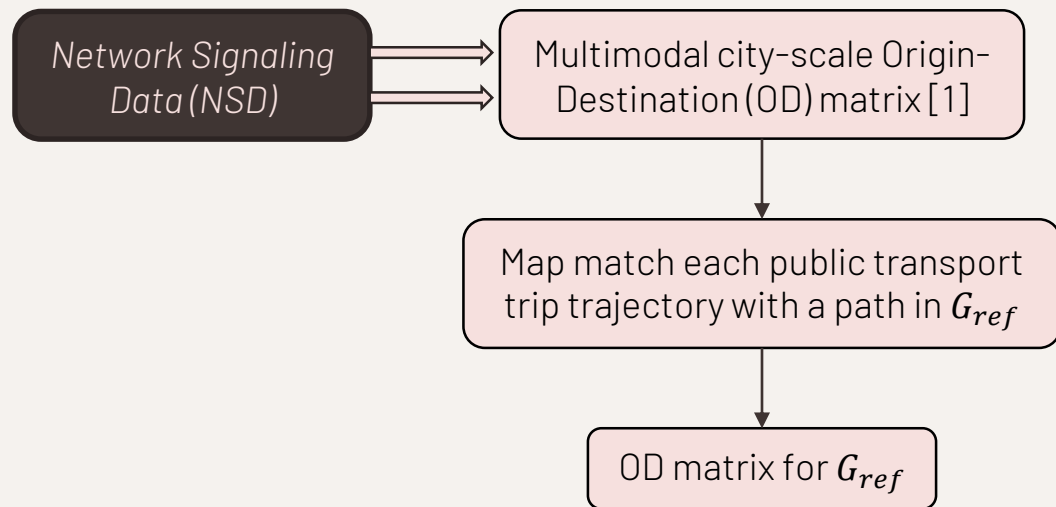
Total frequency with which a transit node is crossed by all shortest paths between any two transit nodes

$$NBC(v_{PT}) = \sum_{v_o \in V_{PT}} \sum_{v_d \in V_{PT} \setminus v_o} \frac{\sigma_{v_o, v_d}(v_{PT})}{\sigma_{v_o, v_d}}$$

Count of shortest paths from origin station to destination station

Number of these shortest paths that pass through v_{PT}

TRAVEL DEMAND



[1] Loïc Bonnetain et al. (2021) TRANSIT: Fine-grained human mobility trajectory inference at scale with mobile network signaling data. Transportation Research Part C

ROBUSTNESS EVALUATION

DEMAND-WEIGHTED METRICS

- ❖ Average Travel Time:

$$ATT_{OD}(G_\Lambda) = \frac{1}{|V_{PT}|(|V_{PT}| - 1)} \sum_{v_o \in V_{PT}} \sum_{v_d \in V_{PT} \setminus v_o} OD(v_o, v_d) \cdot SPL(v_o, v_d)$$
- ❖ Node Betweenness Centrality:

$$NBC_{OD}(v_{PT}) = \sum_{v_o \in V_{PT}} \sum_{v_d \in V_{PT} \setminus v_o} OD(v_o, v_d) \cdot \frac{\sigma_{v_o, v_d}(v_{PT})}{\sigma_{v_o, v_d}}$$

ROBUSTNESS ANALYSIS

ATT ANALYSIS

Define disruptive scenario $S = \{\Lambda_1 \dots\}$



For each Λ_i , calculate $ATT(G_{\Lambda_i})$ and $ATT_{OD}(G_{\Lambda_i})$



Highlight most vulnerable lines for scenario S

NBC ANALYSIS

For each transit node v_{PT} in G_{ref} ,
calculate $NBC(v_{PT})$ and $NBC_{OD}(v_{PT})$

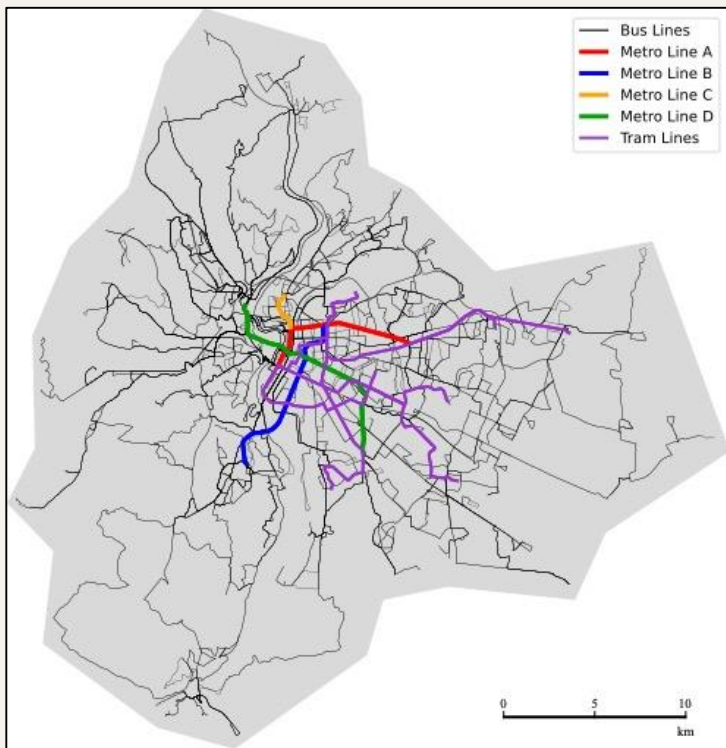


Highlight most central stations

03

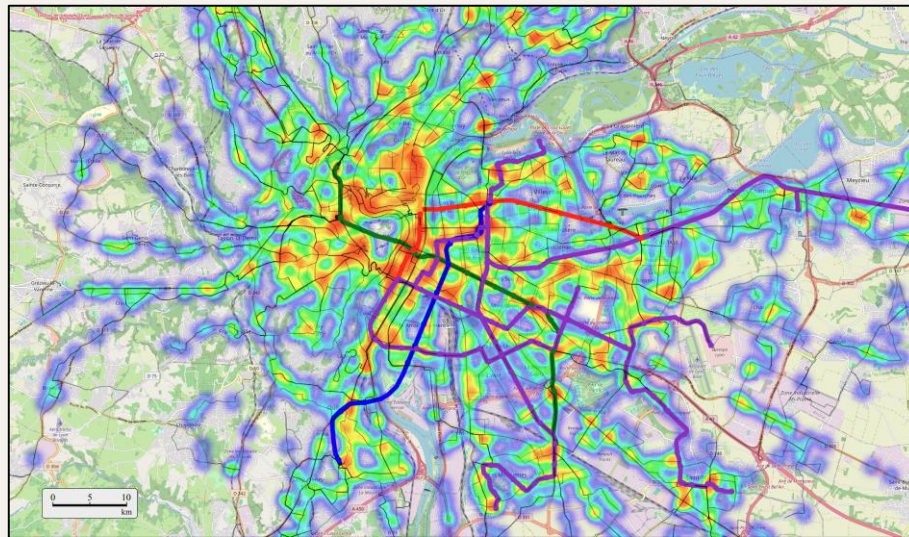
CASE STUDY : LYON, FRANCE

NETWORK DESCRIPTION



- ❖ Networks : metro / tramway / bus / walk
- ❖ Disruptions affecting metro (4) and tramway (11) lines

Network demand heat map



04

RESULTS AND DISCUSSIONS

ATT ANALYSIS

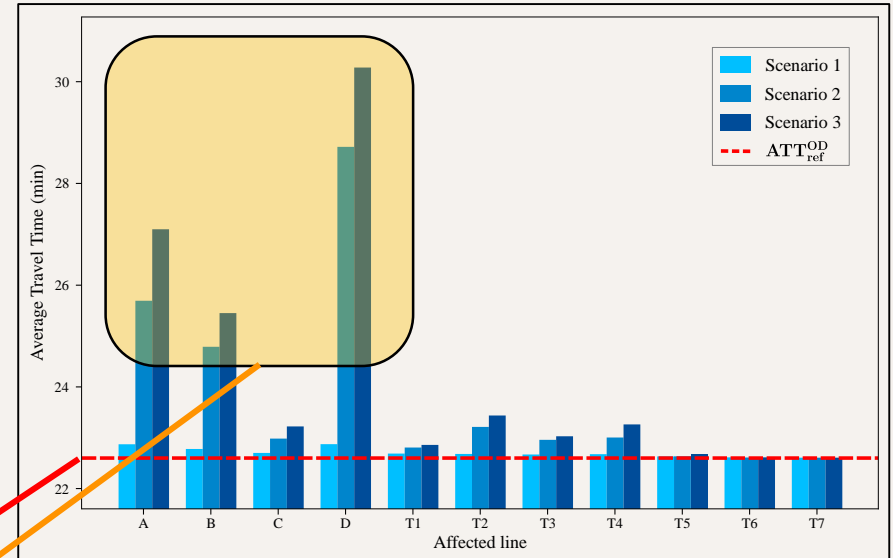
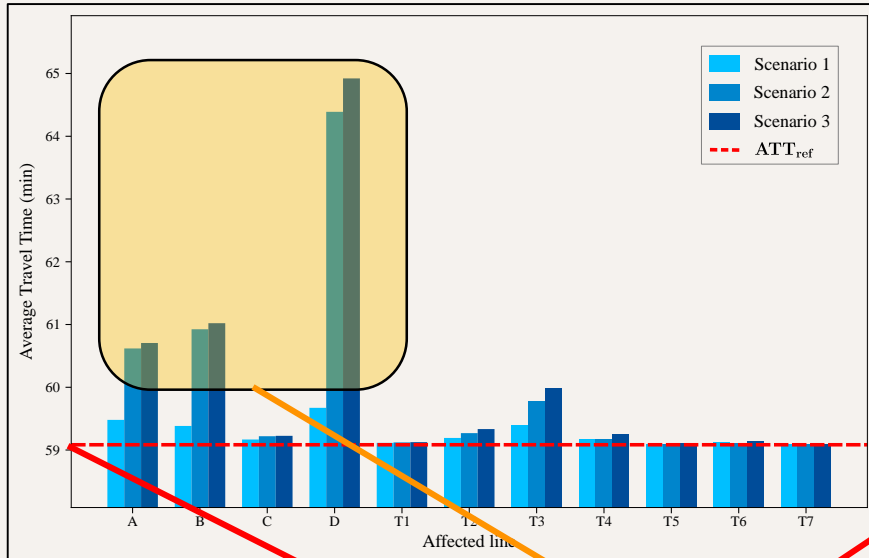
SCENARIOS

- ❖ **Scenario S_1** : A single line L^* operates at state s_1 , while the others function properly s_0
 $S_1 = \{\Lambda_1, \dots, \Lambda_{11}\}_1$ where $\Lambda_i = \{L_i^* \mid L_i^* \in PT^*, s = s_1\}$
- ❖ **Scenario S_2** : A single line L^* operates at state s_2 , while the others function properly s_0
 $S_2 = \{\Lambda_1, \dots, \Lambda_{11}\}_2$ where $\Lambda_i = \{L_i^* \mid L_i^* \in PT^*, s = s_2\}$
- ❖ **Scenario S_3** : A single line L^* operates at state s_3 , while the others function properly s_0
 $S_3 = \{\Lambda_1, \dots, \Lambda_{11}\}_3$ where $\Lambda_i = \{L_i^* \mid L_i^* \in PT^*, s = s_3\}$

ATT ANALYSIS

TRADITIONAL METRIC

DEMAND-WEIGHTED METRIC



High Difference between ATT^D and ATT^E for vulnerable Metro lines A, B and D show greater vulnerability

NBC ANALYSIS

Rank	<i>NBC</i>	Station	Line	<i>NBC_{OD}</i>	Station	Line
1	18764	Manufacture Montluc	T4	158705	Saxe - Gambetta	D
2	17062	Lycée Colbert	T4	146363	Bellecour	D
3	16300	Saxe - Gambetta	D	134977	Garibaldi	D
4	16191	Archives Depart.	T4	127684	Guillotière Gabriel Péri	D
5	15707	Jet d'Eau - M. France	T4	124059	Sans Souci	D
6	15644	Gare Part-Dieu Villette	T4	103673	Monplaisir Lumière	D
7	15320	Guillotière Gabriel Péri	D	100737	Saxe Gambetta	B
8	15204	Bellecour	D	97698	Vieux Lyon	D
9	14144	Lycée Lumière	T4	96890	Bellecour	A
10	13711	Vieux Lyon	D	94450	Hôtel de Ville L. Pradel	A

NBC and *NBC_{OD}* values are not directly comparable. High difference in stations ranking between traditional *NBC* and demand-weighted *NBC_{OD}*

DISCUSSIONS

- ❖ Complementarity : *ATT* and *NBC* capture different characteristics of the network
- ❖ Convergence in identifying the most vulnerable and central lines : A, B and D
- ❖ Valuable information for emergency preparedness

05

CONCLUSION

CONCLUSION

Novel topological approach to evaluate the performance of multimodal public transportation networks under power outage scenarios :

- ❖ Introduction of line functional states
- ❖ Integration of travel demand into traditional topological metrics
- ❖ Different metrics for a detailed robustness analysis

Future work :

- ❖ Electricity layer modelling
- ❖ Dynamic aspects to cover network recoverability

THANK YOU

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APPENDICES

DESCRIPTION OF G_{ref}

	type	number	proportion
NODES	walk	131390	90%
	transit	7016	5%
	intermediary	7016	5%
EDGES	walk	354934	85%
	transit	6756	2%
	intermediary	14032	3%
	access	14032	3%
	transfer	27378	7%

TRAVEL DEMAND

Rank	Trips count	Origin station	Origin line	Destination station	Destination line
1	4462	Grange Blanche	D	Bellecour	D
2	3980	Bellecour	D	Grange Blanche	D
3	2697	Laennec	D	Bellecour	D
4	2592	Bellecour	D	Laennec	D
5	2543	Grange Blanche	D	Vieux Lyon	D
6	2364	Monplaisir Lumière	D	Vieux Lyon	D
7	2320	Sans Souci	D	Gorge de Loup	D
8	1978	Vieux Lyon	D	Grange Blanche	D
9	1974	Gorge de Loup	D	Sans Souci	D
10	1895	Debourg	B	Gare Part-Dieu V.Merle	B
11	1862	Sans Souci	D	Gare de Vaise	D
12	1660	Charpennes	A	Perrache	A
13	1647	Vieux Lyon	D	Monplaisir Lumière	D
14	1634	Gare de Vaise	D	Sans Souci	D
15	1626	Perrache	A	Charpennes	A
16	1561	Flachet	A	Hôtel de Ville L. Pradel	A
17	1540	Charpennes	B	Place Jean Jaurès	B
18	1490	Cordeliers	A	Gratte Ciel	A
19	1452	Gratte Ciel	A	Bellecour	A
20	1451	Brotteaux	B	Debourg	B