École Polytechnique Fédérale de Lausanne
CIVIL-477 Transportation Network Modeling and Analysis
Master of Civil Engineering, Spring 2024-2025

Impact of a light rail network with park and ride facilities on the Sioux Falls road network.

Julien Ars

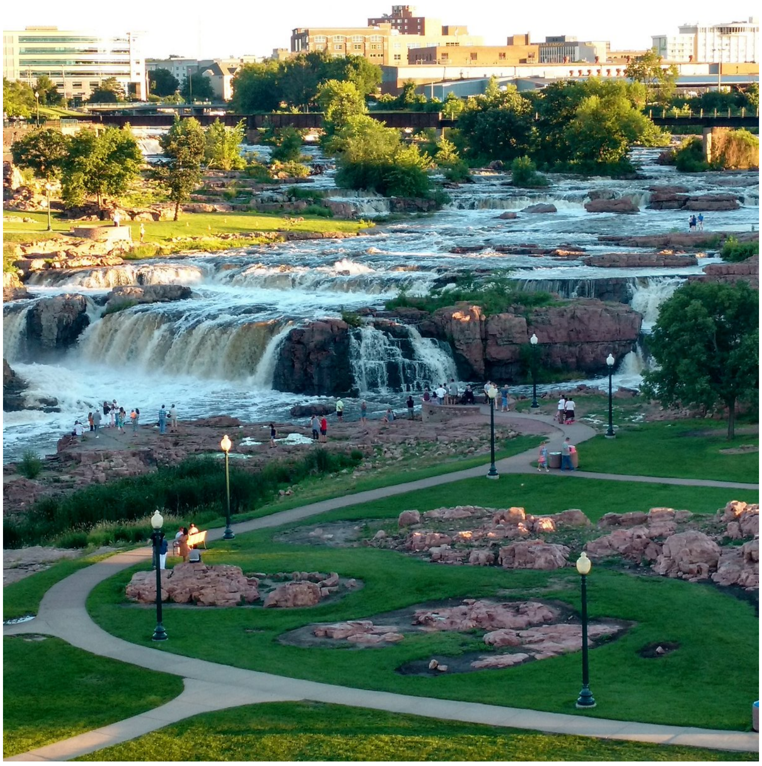


Figure 1: Falls park, in Sioux Falls (South Dakota, US)

Contents

1 Introduction

A major trend in urban planning is the development of light rail transit networks to improve mobility and reduce road congestion. However, in cities where urban growth has historically been car-oriented, low residential and activity densities often make it challenging to achieve high transit ridership. To address this, park-and-ride (P&R) facilities are commonly implemented near transit stations, enabling travelers to access the transit network by car for part of their journey.

Sioux Falls, South Dakota, is a rapidly growing city whose population has increased from 125,000 at the start of the century to over 200,000 today, spread across 210 km^2[1]. For comparison, Geneva, Switzerland, has a similar population but a much denser public transport system, including multiple light rail and suburban train lines, and a dense bus network, despite covering only 16 km^2[2]. In contrast, Sioux Falls' public transportation consists of just 9 bus lines operating 6 days a week, supplemented by on-demand services[3]. The city's road network is also notable as the basis for a widely used benchmark in traffic engineering, due to its manageable size and typical grid structure.

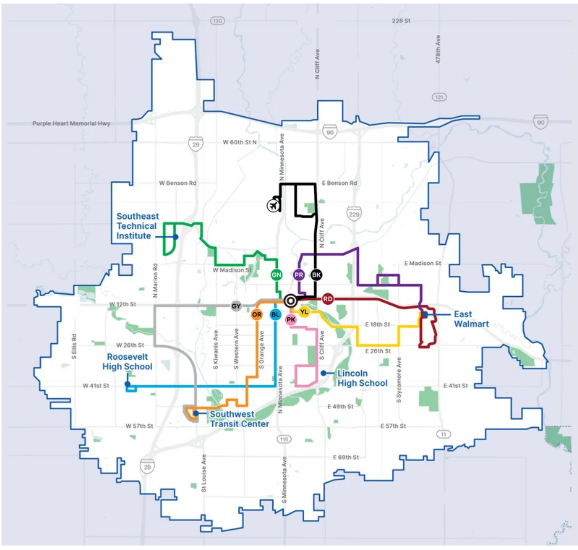


Figure 2: Sioux Falls' current bus network.

This study explores a hypothetical scenario in which Sioux Falls introduces a light rail network to enhance public transportation. Specifically, we analyze the potential reduction in road traffic resulting from converting parts of the existing bus network to light rail and from adding park-and-ride facilities at stations. We model traffic assignment at *User Equilibrium* (UE) on the benchmark network, first simulating the new light rail lines as additional links available only to users whose origin and destination are both on the line. We then relax this constraint to allow access if either the origin or destination is on the line, representing the effect of P&R facilities.

Future research could extend this analysis by considering parking and ticket costs, the inconvenience and time associated with transfers, and waiting times as additional generalized costs. Other possible extensions include limiting P&R facilities to selected stations, imposing parking capacity constraints, refining cost calculations (e.g., including fuel costs), and conducting sensitivity analyses on these parameters.

[1] https://en.wikipedia.org/wiki/Sioux_Falls,_South_Dakota
[2] https://fr.wikipedia.org/wiki/Gen%C3%A8ve
[3] https://siouxareametro.info/bus

2 Methodology

2.1 Problem Statement

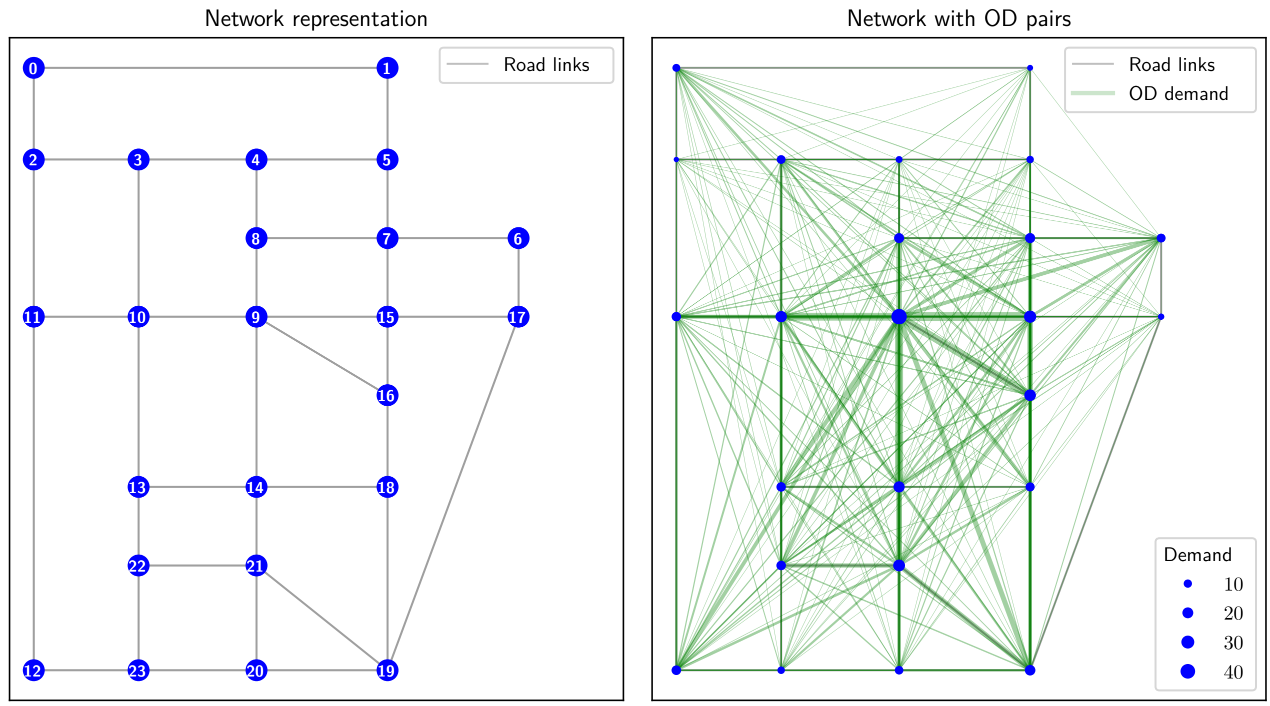
To evaluate the impact of introducing a light rail network and park-and-ride (P&R) facilities, we analyze road link usage under three scenarios:

1. **Base** No light rail is present; all trips are made by road.

2. **Light Rail** The light rail can only be used if both the origin and destination are served by the network, with no transfers between modes allowed.

3. **P&R** The light rail can be used if either the origin or the destination is served by the network, representing the effect of park-and-ride facilities at stations.

We use the simplified Sioux Falls network as a case study. This network is widely used as a benchmark in traffic engineering due to its manageable size and typical grid structure, which allows for efficient computation and clear interpretation of results. Figure 3 shows the road network and the origin-destination (OD) demand used in our analysis. The demand data is taken from the course assignment; while the exact units are not specified, we assume the values represent thousands of users.



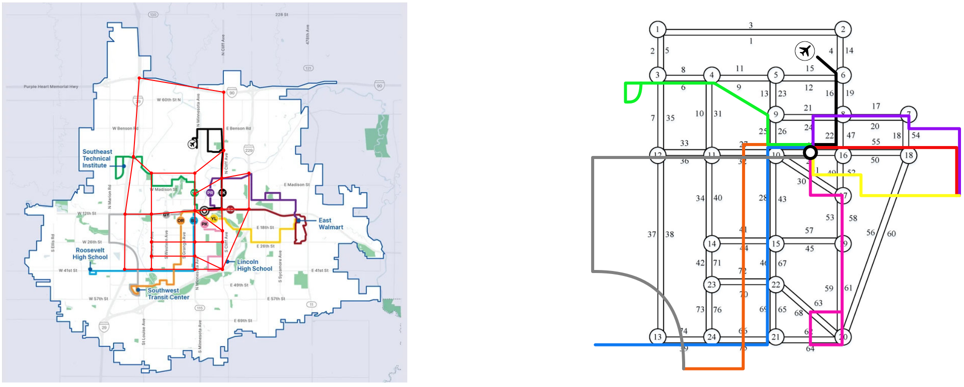
(a) Sioux Falls road network (simplified)

(b) OD pairs considered

Figure 3: Case study road network and demand

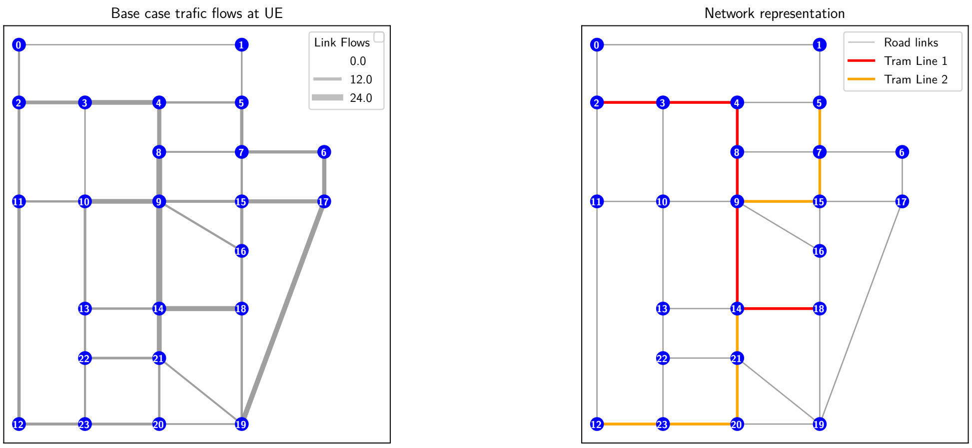
2.2 Defining the Light Rail Lines

To define the light rail lines, we mapped the current Sioux Falls bus lines onto the simplified road network (see Figure 4). We then compared this network with the most heavily used links at user equilibrium in the base scenario to generate two candidate light rail lines (see Figure 5).



(a) Road network on bus map   (b) Bus lines on road network

Figure 4: Mapping between the bus lines and the simplified road network



(a) Link usage at user equilibrium (base scenario)   (b) Light rail network defined

Figure 5: Defining a light rail network

Travel times for the light rail were estimated based on node-to-node distances measured on Google Maps. A speed of 25 miles per hour was used, reflecting average light rail speeds in the US[4]. Individual link travel times are provided in Appendix A.

2.3 Assumptions

The following simplifying assumptions are made:

- Each traveler can only use one P&R facility (i.e., they have one car, which cannot be taken on public transport).
- The costs of using the light rail for part of the trip (waiting time, parking, walking, parking fee, etc.) are considered offset by the comfort and fuel savings, so only travel time is considered.
- The light rail is completely independent of road traffic and has constant travel time.
- The light rail has no capacity constraint.

[4] https://en.wikipedia.org/wiki/Light_rail#Speed_and_stop_frequency

2.4 Modeling Traffic

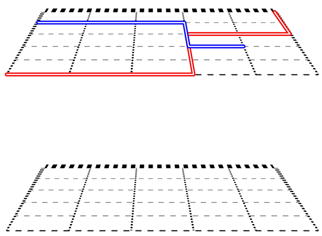
Road traffic is modeled using a Frank-Wolfe optimization algorithm with the Bureau of Public Roads (BPR) formula for travel time:

$$t(x) = t_0 \times \left[1 + \alpha \times \left(\frac{x}{\text{capacity}} \right)^{\beta} \right] \tag{1}$$

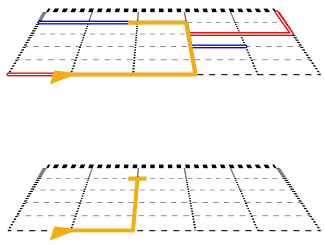
where $\alpha = 0.15$, $\beta = 4$, and t_0 and capacity are link-specific.

The travel time on the light rail network is considered constant. Shortest paths are computed using Dijkstra's algorithm, implemented with the Python library `scipy`. The algorithm stops when the gap in total travel times is smaller than 10^{-4}.

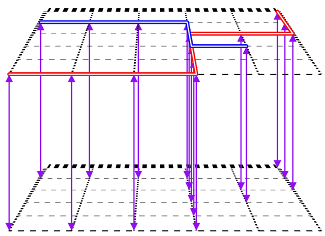
Adding a light rail network is modeled as a two-layer system (Figure 6a), with the light rail as an additional layer on top of the road network. In scenario **2. Light Rail**, the two layers are not connected. For OD pairs eligible to use the light rail, we compute travel times on both layers and assign traffic to the layer with the lowest travel time (Figure 6b).



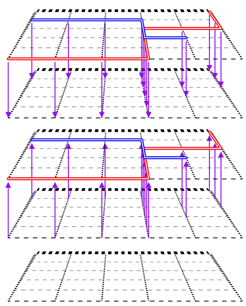
(a) The two layers



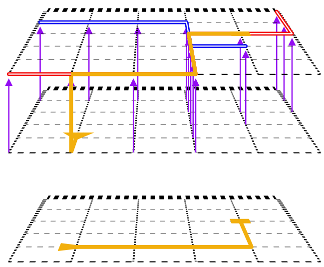
(b) A path on each layer



(c) Adding connections



(d) Three graphs: onboarding, offboarding, and road only



(e) A path on the onboarding and road networks

Figure 6: Two-layer network

In scenario **3. P&R**, we add zero-cost connection links between the two layers at stations (Figure 6c). However, travelers cannot use the tram network in the middle of their trip (see the assumptions). For each all-or-nothing assignment, we consider three graphs (Figure 6d) :

1. **Onboarding graph:** Two layers, with links only from the road layer to the tram layer. For OD pairs where the destination is served by a tram station, we compute the shortest path from the origin node on the road layer to the destination node on the tram layer.

2. **Offboarding graph:** Two layers, with links only from the tram layer to the road layer. For OD pairs where the origin is served by a tram station, we compute the shortest path from the origin node on the tram layer to the destination node on the road layer.

3. **Road graph:** Road network only. We compute the shortest path for all OD pairs.

Depending on the origin-destination pair, we may have computed three different shortest paths. We assign the traffic according to the shortest travel time.

3 Results

This section presents the main results for each scenario, focusing on both graphical and quantitative outcomes. Detailed numerical values are provided in Appendices B and C.

3.1 Base Scenario

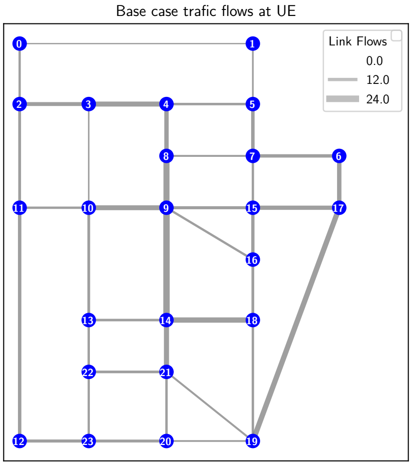
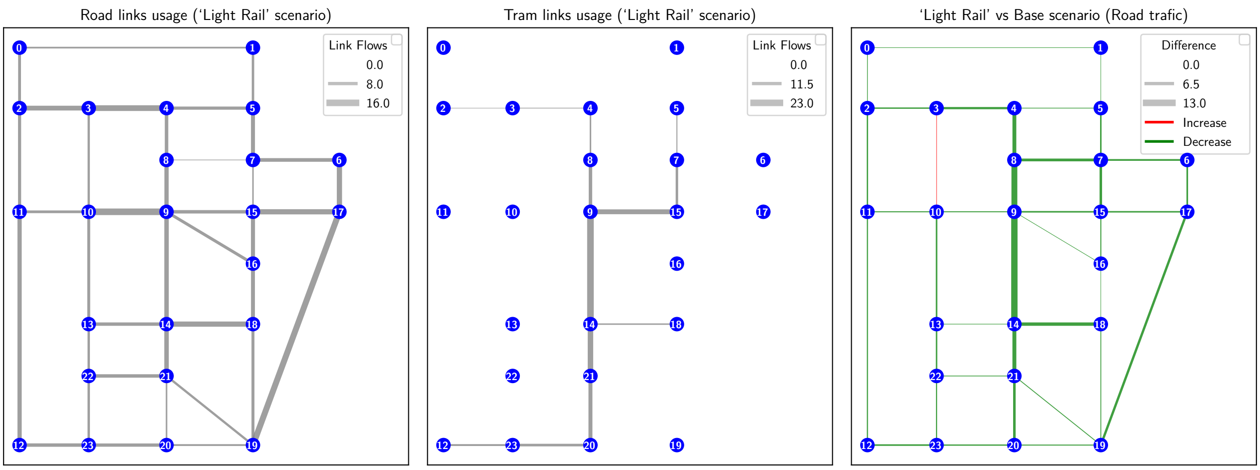


Figure 7: Base scenario traffic

Figure 7 shows the computed traffic flows in the base scenario. Line 1 (nodes 2-3-4-8-9-14-18) follows a path where roads are well used, while line 2 (nodes 12-23-20-21-14-9-15-7-5) mainly serves streets with low to moderate traffic, except for its shared segment with line 1. However, line 2 could also help absorb traffic from adjacent roads.

The **total travel time** in this scenario is **74.8 [1000 user · h]**.

3.2 Light Rail Scenario



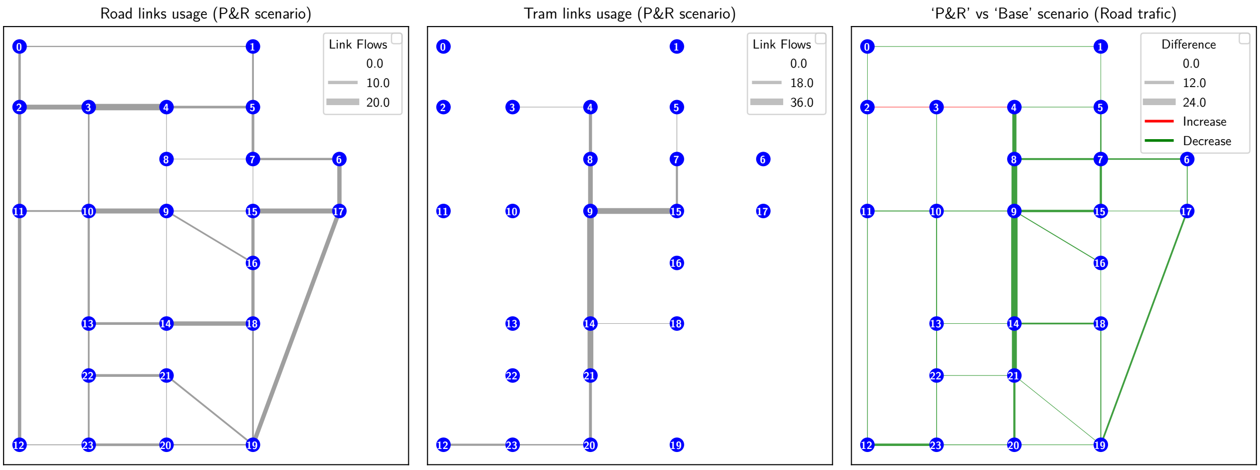
(a) Road traffic (b) Tram usage (c) Road traffic difference

Figure 8: 'Light rail' scenario results

Figure 8 illustrates the effect of adding two tram lines, without park-and-ride facilities. The **total travel time** drops to **43.5 [1000 user · h]**, representing a 40% improvement over the base scenario. The most heavily used tram links are between nodes 9 and 14 (served by both lines), 21 and 14 (line 2), and 9 and 15 (line 2). Notably, line 2, although not aligned with the highest road traffic, carries the most crowded tram segments. The overlap of both lines on the busiest link is a positive feature for network design.

As shown in Figure 8c, the tram network reduces road usage on nearly all links, with the greatest improvements in the central district (nodes 8-9-14-18). Only the link between nodes 3 and 10 sees a slight increase in traffic (less than 1%). Improvements are also observed on links not directly served by the tram, such as 7-8 and 17-19. This shows that the development of public transport can have a positive impact on congestion throughout the road network, not just in the surroundings of the new public transport.

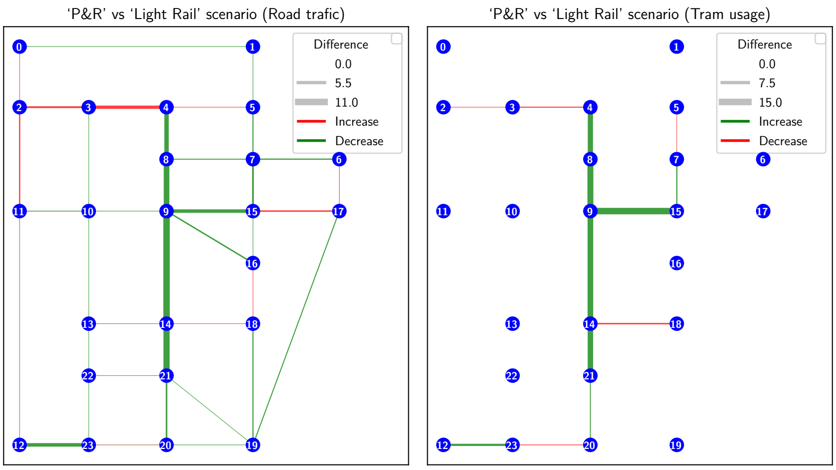
3.3 P&R Scenario



(a) Road traffic (b) Tram usage (c) Road traffic difference

Figure 9: 'Park-and-ride' scenario results

Figure 9 presents the results for the scenario with park-and-ride facilities at every station. The **total travel time** is further reduced to **38.1 [1000 user · h]**, the lowest among all scenarios. The impact is especially strong on central links, with even greater improvements than in the previous scenario. However, some links (e.g., nodes 2-3-4) experience increased traffic despite being served by light rail, due to the light rail not being competitive for those OD pairs—users now drive to node 4 and no longer use the tram for that segment.



(a) Road traffic difference (b) Tram usage difference

Figure 10: Comparison between 'Light Rail' scenario and 'Park-and-ride' scenario

Comparing the addition of a light rail network with or without park-and-ride facilities (Figure 10), we can see an increase in the usage of the tram network in the center of the lines, but a decrease on the peripheral links. With P&R, the light rail network yields better traffic reduction in the center of the city but has less impact for peripheral nodes. Park-and-ride facilities could therefore replace line extensions, increasing the return on investment and allowing for greater impact with less money. Figure 10 is particularly useful for designing effective stations where park-and-ride facilities should be added: we suggest nodes 4, 14, 15, and 21. We also recommend studying a reduced network without tram lines beyond these nodes to reduce overall cost.

4 Conclusion

This study evaluated the impact of introducing a light rail network and park-and-ride (P&R) facilities on the Sioux Falls road network. The results demonstrate that P&R facilities not only improve overall system performance — measured by total travel time — but can also allow a more compact network to achieve similar or even greater efficiency compared to a larger network without P&R. Our findings suggest that strategically placing P&R facilities at selected stations (we propose nodes 4, 14, 15, and 21) and focusing the light rail network on the central core could provide the best balance between cost and effectiveness.

Several limitations of the current analysis should be addressed in future work. The model only considers travel time, neglecting factors such as waiting time, transfer penalties, parking and ticket costs, and capacity constraints. Incorporating these elements - by adding costs to onboarding and offboarding links, modeling transfers between lines, and introducing capacity limits - would yield a more realistic assessment and help determine operational requirements such as headways and rolling stock needs.

Finally, the assumption that users always choose the route with the lowest modeled travel time may oversimplify real-world behavior. Incorporating more advanced mode choice models, such as logit models, could better capture user preferences and variability, and better represent the real impact of adding a public transport infrastructure.

Disclosure

This work was completed independently and reflects my own understanding and effort. To improve clarity and correctness of language, I used large language model (LLM)-based tools for grammar and style suggestions.

All code and results produced for this project are available on GitHub: `https://github.com/merlebleue/CIVIL-477-Transport-Networks---End-project`

Appendices

A Light rail travel times

Start node	End node	Line	Distance [miles]	Time [min]	Time [hours]
2	3	Line 1	1.6	3.84	0.064
3	2	Line 1	1.6	3.84	0.064
3	4	Line 1	1.5	3.60	0.060
4	3	Line 1	1.5	3.60	0.060
4	8	Line 1	0.9	2.16	0.036
8	4	Line 1	0.9	2.16	0.036
8	9	Line 1	0.4	0.96	0.016
9	8	Line 1	0.4	0.96	0.016
9	14	Lines 1+2	1.1	2.64	0.044
14	9	Lines 1+2	1.1	2.64	0.044
14	18	Line 1	1.0	2.40	0.040
18	14	Line 1	1.0	2.40	0.040
12	23	Line 2	1.0	2.40	0.040
23	12	Line 2	1.0	2.40	0.040
23	20	Line 2	1.5	3.60	0.060
20	23	Line 2	1.5	3.60	0.060
20	21	Line 2	0.5	1.20	0.020
21	20	Line 2	0.5	1.20	0.020
21	14	Line 2	0.5	1.20	0.020
14	21	Line 2	0.5	1.20	0.020
9	15	Line 2	1.0	2.40	0.040
15	9	Line 2	1.0	2.40	0.040
15	7	Line 2	1.1	2.64	0.044
7	15	Line 2	1.1	2.64	0.044
7	5	Line 2	1.0	2.40	0.040
5	7	Line 2	1.0	2.40	0.040

Table 1: Travel time of tram links

B Flow on road links

Link ID	Start Node	End Node	Capacity	t_0	Tram Travel Time	Road Travel Time Base	Road Travel Time Light Rail	Road Travel Time P&R	Flow Base	Flow Light Rail	Flow P&R
0	0	1	25.9	0.06	-	0.06	0.06	0.06	4.5	4.0	3.5
1	0	2	23.4	0.04	-	0.04	0.04	0.04	8.1	6.8	7.3
2	1	0	25.9	0.06	-	0.06	0.06	0.06	4.5	4.0	3.5
3	1	5	5.0	0.05	-	0.07	0.06	0.06	6.0	5.8	5.3
4	2	0	23.4	0.04	-	0.04	0.04	0.04	8.1	6.8	7.3
5	2	3	17.1	0.04	0.06	0.04	0.04	0.04	14.0	11.5	14.4
6	2	11	23.4	0.04	-	0.04	0.04	0.04	10.0	7.4	9.5
7	3	2	17.1	0.04	0.06	0.04	0.04	0.04	14.0	11.4	14.5
8	3	4	17.8	0.02	0.06	0.02	0.02	0.02	18.0	13.8	19.1
9	3	10	4.9	0.06	-	0.07	0.07	0.07	5.2	5.3	4.9
10	4	3	17.8	0.02	0.06	0.02	0.02	0.02	18.0	13.8	19.3
11	4	5	4.9	0.04	-	0.10	0.07	0.07	8.8	7.5	7.5
12	4	8	10.0	0.05	0.04	0.10	0.05	0.05	15.8	8.3	1.0
13	5	1	5.0	0.05	-	0.07	0.06	0.06	6.0	5.8	5.3
14	5	4	4.9	0.04	-	0.10	0.07	0.07	8.8	7.5	7.5
15	5	7	4.9	0.02	0.04	0.15	0.06	0.04	12.5	9.6	7.9
16	6	7	7.8	0.03	-	0.06	0.04	0.03	12.1	8.8	6.8
17	6	17	23.4	0.02	-	0.02	0.02	0.02	15.8	12.6	12.9
18	7	5	4.9	0.02	0.04	0.15	0.06	0.04	12.5	9.6	7.9
19	7	6	7.8	0.03	-	0.06	0.04	0.03	12.0	8.7	6.8
20	7	8	5.1	0.10	-	0.15	0.10	0.10	6.9	1.5	0.0
21	7	15	5.0	0.05	0.04	0.11	0.05	0.05	8.4	3.4	0.6
22	8	4	10.0	0.05	0.04	0.10	0.05	0.05	15.8	8.3	1.0
23	8	7	5.1	0.10	-	0.15	0.10	0.10	6.8	1.5	0.0
24	8	9	13.9	0.03	0.02	0.06	0.03	0.03	21.7	10.3	1.0
25	9	8	13.9	0.03	0.02	0.06	0.03	0.03	21.8	10.3	1.0
26	9	10	10.0	0.05	-	0.12	0.10	0.09	17.7	15.8	15.0
27	9	14	13.5	0.06	0.04	0.14	0.06	0.06	23.1	10.7	0.0
28	9	15	4.9	0.04	0.04	0.20	0.09	0.04	11.0	8.2	2.5
29	9	16	5.0	0.08	-	0.16	0.13	0.09	8.1	7.2	4.9
30	10	3	4.9	0.06	-	0.07	0.07	0.07	5.3	5.3	4.9
31	10	9	10.0	0.05	-	0.12	0.10	0.09	17.6	15.8	15.0
32	10	11	4.9	0.06	-	0.14	0.09	0.07	8.4	6.4	5.2
33	10	13	4.9	0.04	-	0.14	0.06	0.06	9.8	6.9	6.2
34	11	2	23.4	0.04	-	0.04	0.04	0.04	10.0	7.5	9.5
35	11	10	4.9	0.06	-	0.14	0.09	0.07	8.4	6.4	5.2
36	11	12	25.9	0.03	-	0.03	0.03	0.03	12.3	10.1	9.9
37	12	11	25.9	0.03	-	0.03	0.03	0.03	12.4	10.3	10.0
38	12	23	5.1	0.04	0.04	0.18	0.08	0.04	11.1	8.1	2.4
39	13	10	4.9	0.04	-	0.14	0.06	0.06	9.8	6.9	6.2
40	13	14	5.1	0.05	-	0.12	0.10	0.09	9.0	8.1	8.0
41	13	22	4.9	0.04	-	0.09	0.05	0.05	8.4	5.6	5.1
42	14	9	13.5	0.06	0.04	0.14	0.06	0.06	23.2	10.7	0.0
43	14	13	5.1	0.05	-	0.12	0.10	0.09	9.1	8.1	8.0
44	14	18	14.6	0.03	0.04	0.04	0.03	0.03	19.1	12.6	13.1
45	14	21	9.6	0.03	0.02	0.09	0.04	0.03	18.4	10.8	0.6
46	15	7	5.0	0.05	0.04	0.11	0.05	0.05	8.4	3.4	0.6
47	15	9	4.9	0.04	0.04	0.20	0.09	0.04	11.1	8.2	2.5
48	15	16	5.2	0.02	-	0.09	0.06	0.05	11.7	9.8	9.4
49	15	17	19.7	0.03	-	0.03	0.03	0.03	15.3	12.5	14.8
50	16	9	5.0	0.08	-	0.16	0.13	0.09	8.1	7.2	4.9

Table 2: Flows on road links (1/2)

Link ID	Start Node	End Node	Capacity	t_0	Tram Travel Time	Road Travel Time Base	Road Travel Time Light Rail	Road Travel Time P&R	Flow Base	Flow Light Rail	Flow P&R
51	16	15	5.2	0.02	-	0.09	0.06	0.05	11.7	9.7	9.4
52	16	18	4.8	0.02	-	0.07	0.06	0.07	10.0	9.4	9.5
53	17	6	23.4	0.02	-	0.02	0.02	0.02	15.9	12.7	12.9
54	17	15	19.7	0.03	-	0.03	0.03	0.03	15.3	12.5	14.9
55	17	19	23.4	0.04	-	0.04	0.04	0.04	19.0	14.4	12.8
56	18	14	14.6	0.03	0.04	0.04	0.03	0.03	19.1	12.6	13.1
57	18	16	4.8	0.02	-	0.07	0.06	0.07	9.9	9.4	9.5
58	18	19	5.0	0.04	-	0.09	0.06	0.05	8.7	7.1	5.3
59	19	17	23.4	0.04	-	0.04	0.04	0.04	19.0	14.4	12.8
60	19	18	5.0	0.04	-	0.09	0.06	0.05	8.7	7.1	5.3
61	19	20	5.1	0.06	-	0.08	0.07	0.06	6.3	4.4	4.3
62	19	21	5.1	0.05	-	0.08	0.06	0.06	7.0	5.5	5.3
63	20	19	5.1	0.06	-	0.08	0.06	0.06	6.2	4.3	4.2
64	20	21	5.2	0.02	0.02	0.04	0.02	0.02	8.6	3.6	1.0
65	20	23	4.9	0.03	0.06	0.12	0.06	0.06	10.3	7.9	7.8
66	21	14	9.6	0.03	0.02	0.09	0.04	0.03	18.4	10.8	0.6
67	21	19	5.1	0.05	-	0.08	0.06	0.06	7.0	5.4	5.3
68	21	20	5.2	0.02	0.02	0.04	0.02	0.02	8.6	3.6	1.1
69	21	22	5.0	0.04	-	0.12	0.08	0.08	9.7	8.2	8.1
70	22	13	4.9	0.04	-	0.09	0.05	0.05	8.4	5.6	5.1
71	22	21	5.0	0.04	-	0.12	0.08	0.08	9.6	8.2	8.1
72	22	23	5.1	0.02	-	0.04	0.02	0.02	7.9	5.7	5.3
73	23	12	5.1	0.04	0.04	0.18	0.08	0.04	11.1	8.2	2.3
74	23	20	4.9	0.03	0.06	0.12	0.06	0.06	10.3	7.8	7.9
75	23	22	5.1	0.02	-	0.04	0.02	0.02	7.9	5.7	5.3

Table 2: Flows on road links (2/2)

C Light Rail Usage

				Usage	
Start Node	End Node	Line	Travel Time	Light Rail scenario	P&R scenario
2	3	1	0.064	0.2	0.0
3	2	1	0.064	0.2	0.0
3	4	1	0.060	2.3	0.0
4	3	1	0.060	2.3	0.0
4	8	1	0.036	5.2	16.8
8	4	1	0.036	5.2	17.0
8	9	1	0.016	11.9	25.2
9	8	1	0.016	12.0	25.5
9	14	1+2	0.044	22.9	35.7
14	9	1+2	0.044	22.9	35.8
14	18	1	0.040	4.7	1.5
18	14	1	0.040	4.7	1.5
12	23	2	0.040	6.5	11.3
23	12	2	0.040	6.5	11.4
23	20	2	0.060	8.7	7.2
20	23	2	0.060	8.8	7.3
20	21	2	0.020	13.6	15.6
21	20	2	0.020	13.7	15.6
21	14	2	0.020	19.0	31.4
14	21	2	0.020	19.1	31.4
9	15	2	0.040	16.6	31.3
15	9	2	0.040	16.7	31.3
15	7	2	0.044	8.5	11.0
7	15	2	0.044	8.6	11.1
7	5	2	0.040	3.3	3.1
5	7	2	0.040	3.3	3.1

Table 3: Usage on the tram links