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.

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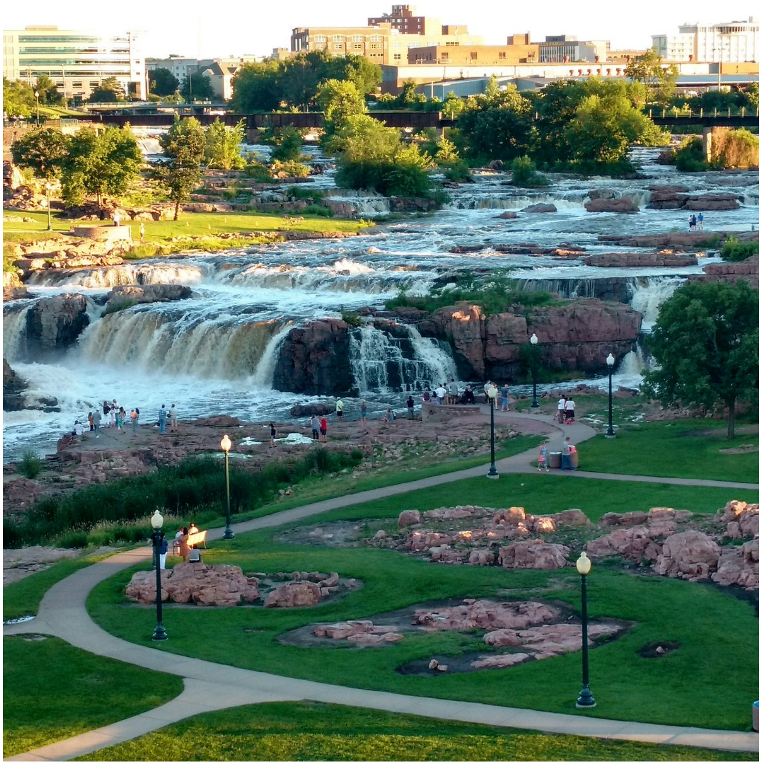


Figure 1: Falls park, in Sioux Falls (South Dakota, US)

Contents

1 Introduction

One of the major trends in city planning is the introduction of light rail transit networks. However, when spatial development has previously been based on the automobile, the often low densities of residences and activities may not provide ideal conditions for a transit line. To facilitate the integration of a new transit line into the existing road network, a common approach is to include park-and-ride facilities around transit stations, allowing car-based access to the transit line.

Sioux Falls, South Dakota, is a city that has experienced rapid growth in recent years. The city, which had a population of 125,000 at the start of the century, now has a population of over 200,000 within an area of 210 km^2[1]. In terms of population, this is comparable to the city of Geneva, which has multiple light rail lines, suburban train lines, and a dense bus network (although Geneva covers only 16 km^2[2]). In comparison, Sioux Falls' public transport relies only on 9 bus lines, which run just 6 days a week, and on-demand transport[3]. Additionally, Sioux Falls' road network inspired the homonymous benchmark network, which is well-known in traffic engineering for its small size and typical grid structure.

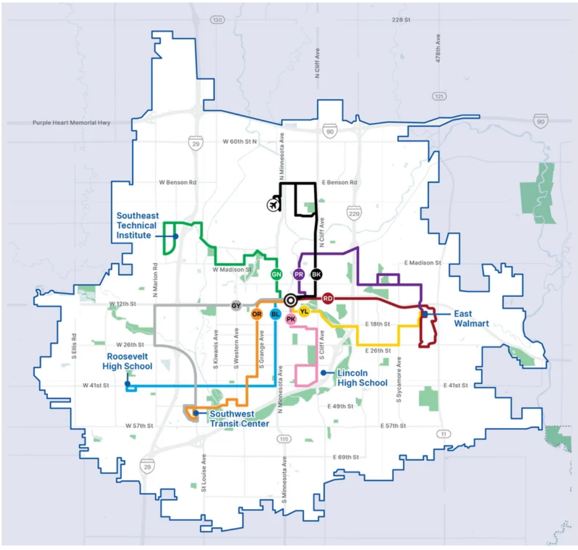


Figure 2: Sioux Falls' current bus network.

In a hypothetical scenario, the city of Sioux Falls is considering the construction of a light rail line to improve public transportation usage. This study will analyze the potential decrease in traffic from converting one existing bus line into a light rail line, as well as the introduction of park-and-ride facilities at the stations. To do this, we will solve for traffic at *User Equilibrium* (UE) in the benchmark network, and then simulate the introduction of the new light rail line as new links between the nodes, with the restriction that a user may use it only if both their origin and destination are along the line. Finally, the introduction of park-and-ride facilities will be simulated by replacing the previous constraint and allowing users to access the light rail line if either their origin or destination is along the line.

Future research could consider parking and ticket fares, the inconvenience of having to change modes, and the waiting time to be included as a generic cost added to the travel time on the transit line. The possibility of including park-and-ride facilities at only some stations, limiting the capacity of the parking lots, more detailed cost computations (e.g., precise calculations, inclusion of fuel cost in individual transport links), and a sensitivity analysis on the value of the generic cost would, if time allows, be interesting additions to the study.

[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

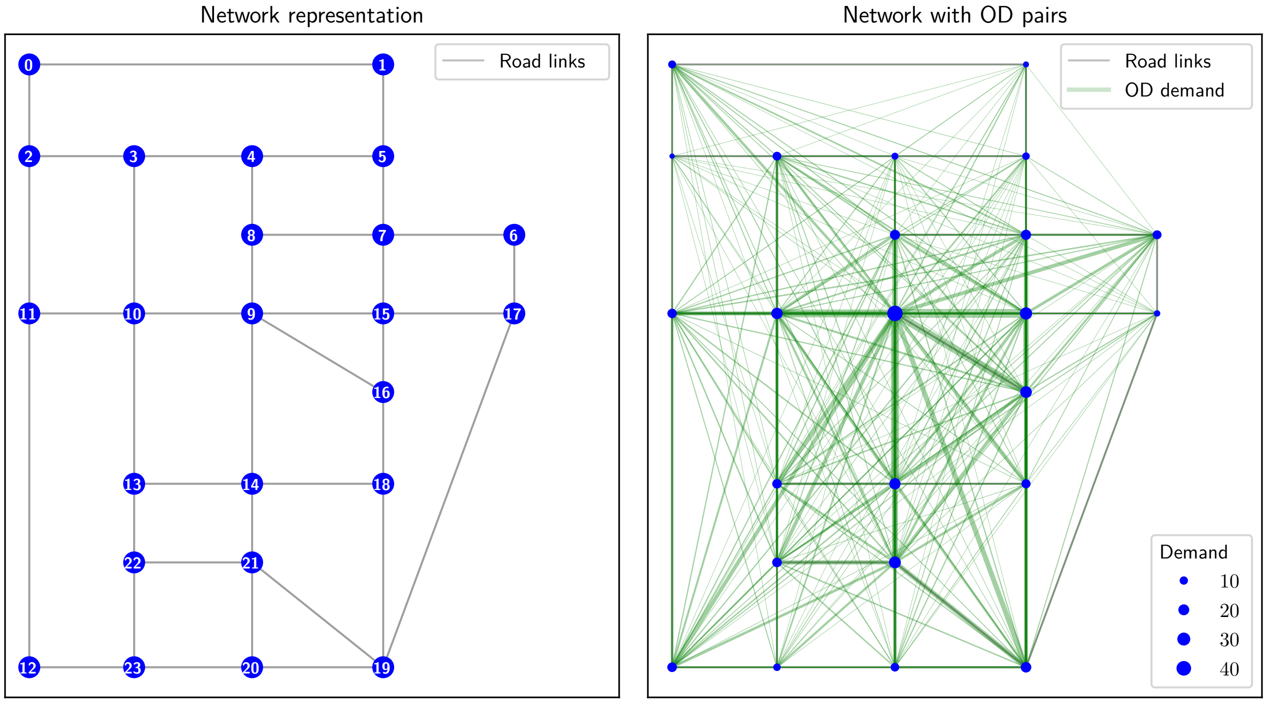
To study the impact of a light rail network and park-and-ride facilities, we compute the road link usage in three scenarios:

1. **Base** No light rail.

2. **Light Rail** Light rail can only be taken when both the origin and destination are served by the network, and no interface is possible between the two.

3. **P&R** Light rail can be taken when either the origin or the destination is served by the network.

We use the simplified network of Sioux Falls as a case study, given its place as a common benchmark in traffic engineering, and because computations run in reasonable time. Figure 3 presents the road network and the OD demand that form the base of our case study. We used the data provided for the assignment of the course; altough unsure of the unit of the demand, we assume it is in thousands of users.



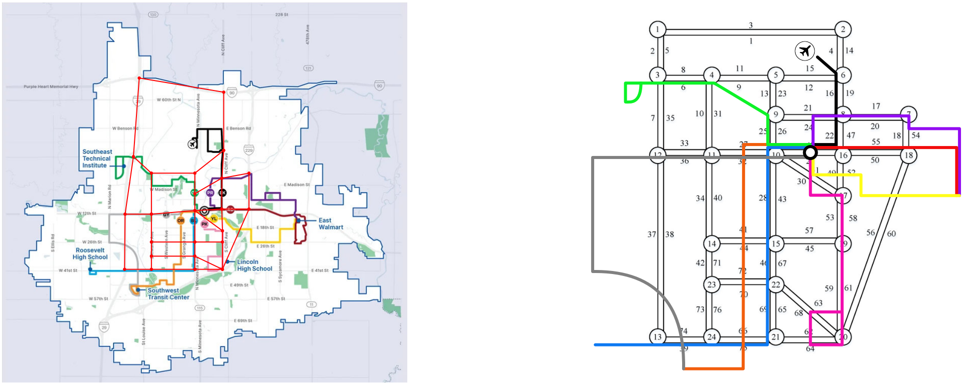
(a) Sioux Falls road network (simplified)

(b) OD pairs considered

Figure 3: Case study road network and demand

2.2 Defining the Light Rail Lines

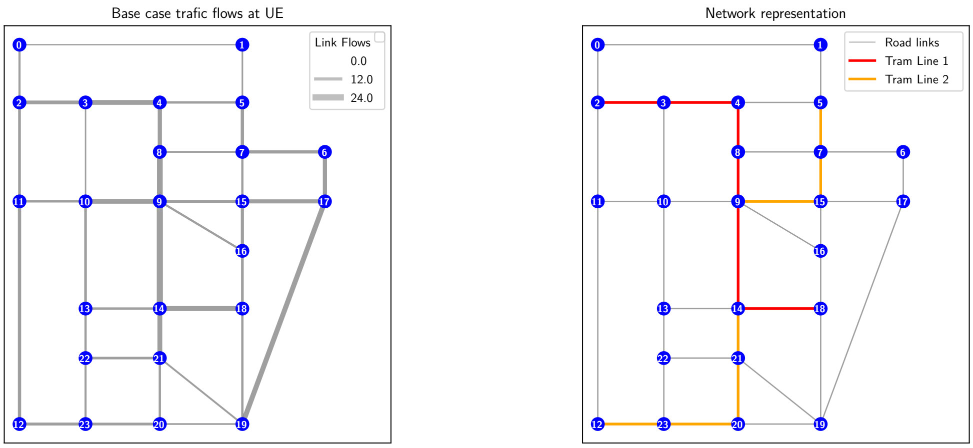
To define the light rail lines, we mapped the current Sioux Falls bus lines onto this network (see Figure 4). We then compared this network with the most heavily used links at user equilibrium (in the base scenario) to generate two light rail lines (see Figure 5).



(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

The travel times are then computed based on the distance between the nodes, as checked on Google Maps. A speed of 25 miles per hour was considered for the light rail, based on average speeds in light rail networks in the US[4]. The individual link travel times are reported in Appendix A.

2.3 Assumptions

The following simplifying assumptions are made :

- A traveler can only use one P&R (i.e., they only have one car, which they cannot take with them on public transport).
- The costs of using the light rail for part of the trip (waiting time at the station, time for parking and walking to the station, parking fee, etc.) are considered equivalent to the gain in comfort and in gas costs of using it, so we neglect them. The only cost considered is therefore the travel time on the light rail or on the road.
- The light rail is totally independent of road traffic, and as such 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

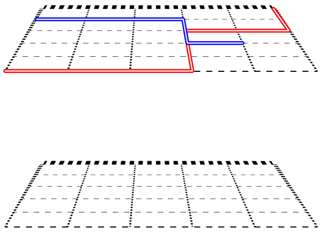
To model the road traffic, we use a Frank-Wolf optimization algorithm with the Bureau of Public Roads formula to compute road travel times (with parameters $\alpha = 0.15, \beta = 4$):

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

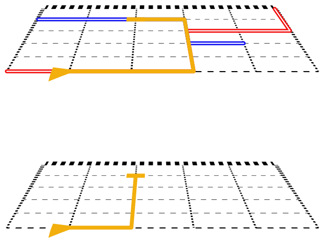
The t_0 and capacity parameters are link-specific. The travel time on the light rail network is considered to be constant. The shortest path is computed using Dijkstra's algorithm. To reduce computation time, we use the Python library `scipy` for this purpose.

We stop the algorithm when the gap is smaller than 10^{-4}.

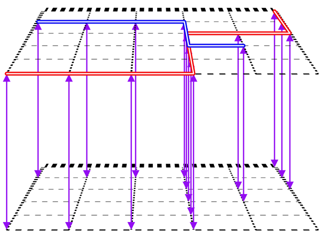
To model the light rail network, we consider a two-layer approach (Figure 6a), where the light rail is considered as an additional layer on top of the road network. In scenario **2. Light rail**, the two layers are not connected. When doing the all-or-nothing assignment, we compute, for the origin-destination (OD) pairs that can use the light rail, the travel time on both layers (Figure 6b). We then assign traffic to the layer where the travel time is the lowest.



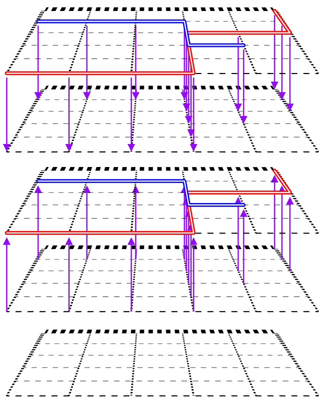
(a) The two layers



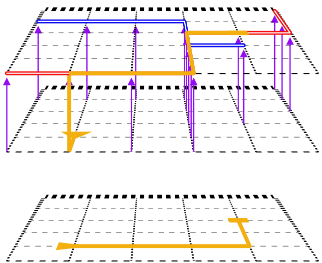
(b) A path on each layer



(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 the last scenario (**3. P&R**), we add connection links between the two layers (Figure 6c). With our assumptions, the connection links have no cost. However, travelers cannot use the tram network in the middle of the trip (see the definition of the scenario and the first assumption). As such, we consider three different graphs (see Figure 6d) on which we compute the shortest paths at each all-or-nothing assignment:

1. Onboarding graph: this graph consists of the two layers, with links only from the road layer to the tram layer. For the origin-destination pairs for which the destination is served by a tram station, we compute the shortest path on this graph, between the origin node on the road layer and the destination node on the tram layer.

2. Offboarding graph: this graph consists of the two layers, with links only from the tram layer to the road layer. For the origin-destination pairs for which the origin is served by a tram station, we compute the shortest path on this graph, between the origin node on the tram layer and the destination node on the road layer.

3. Road graph: this graph consists only of the road network. We compute the shortest path on this graph for all origin-destination.

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

In this section, we present graphical results for each scenario. The numerical values of the results are presented in Appendixes B and C.

3.1 Base scenario

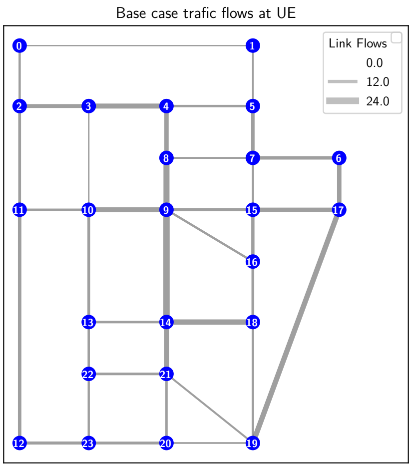
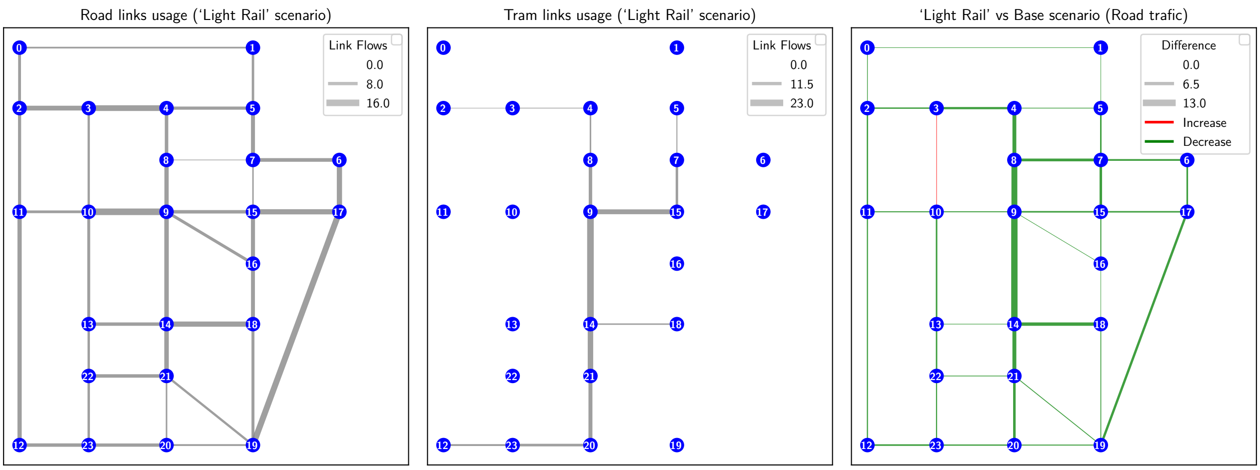


Figure 7: Base scenario trafic

Figure 7 presents the computed trafic flows in the base scenario. As we can see, line 1 runs along a corridor (nodes 2-3-4-8-9-14-18) with high trafic, while line 2 (nodes 12-23-20-21-14-9-15-7-5) runs on street with small to moderate trafic, except on its shared link with line 1. However, line 2 could take the trafic present on adjacent roads as well.

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

3.2 Light rail scenario



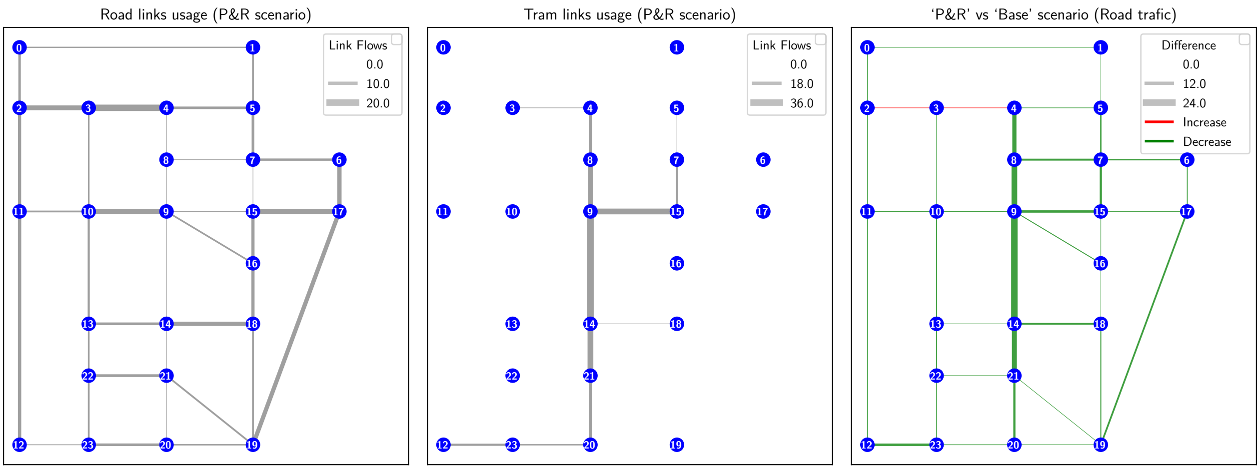
(a) Road traffic (b) Tram usage (c) Road traffic difference

Figure 8: 'Light rail' scenario results

In Figure 8, we present the effect of adding the two tram lines to the model, without park-and-ride facilities. The **total travel time** in this scenario is **43.5 [1000 user · h]**, a 40% improvement on the base scenario. As we can see on Figure 8b, the three most used tram links are between nodes 9 and 14 (desserved by both lines), between nodes 21 and 14 (on line 2) and between nodes 9 and 15 (also on line 2). As such, even if line 2 wasn't along the most used road links, it is this line that has the most crowded segments. The overlap between the two lines on the most used link is also good point for the design of the tram network.

As we can see in Figure 8c, the addition of the tram line reduces road usage on nearly all route links. The route link between node 3 and node 10 is the only one which sees an increase in traffic, but of very limited size (less than 1%). The best improvements are in the central district, along line 1 (along nodes 8-9-14-18). We also see improvements between nodes 7 and 8 altough those are not desserved directly by a tram line, but also on link 17-19 even though it is not connected to the light rail network. As such, we see that the development of public transport can have positive impact on the congestion in the whole road network and not only in the surrondings of the new public transport.

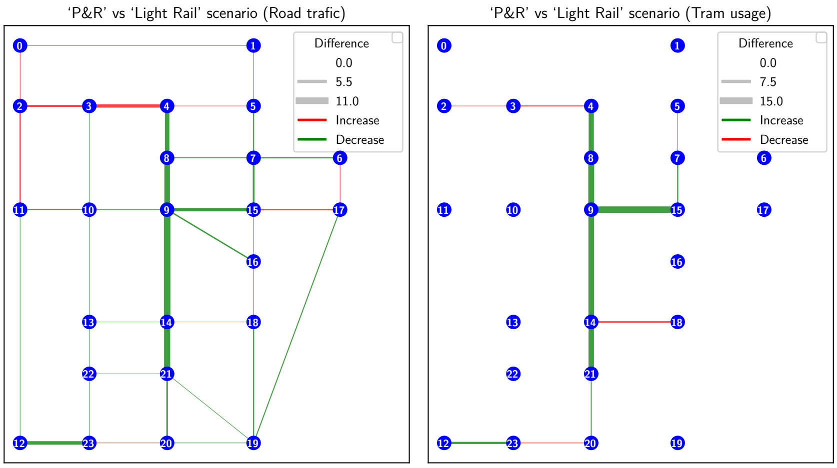
3.3 P&R scenario



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

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

The results of adding a lightrail network with park-and-ride facilities at each station are shown in Figure 9. The **total travel time** in this scenario is **38.1 [1000 user · h]**, the best of all three scenarii. Additionnally, there is a good impact on most links. The improvement is even better in this scenario than in the previous scenario in the central links. However, some links see an increase in traffic even if they are served by a lightrail line (along nodes 2-3-4). Looking at the precise results in Appendix B, we understand this is due to the travel time in the Light Rail not being competitive. Now that the users can take their car up to node 4, there is no more usage of the tram on these links.



(a) Road traffic difference

(b) Tram usage difference

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

Comparing adding a light rail network with or without Park-and-ride facilities (Figure 10), we can see 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 trafic 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 to do more impact with less money. Figure 10 is particularly useful to design usefull stations where to add Park-and-ride facilities : we would suggest nodes 4, 14, 15 and 21. We would also recommand to study a reduced network without tram lines beyond these nodes, to reduce overall cost.

4 Conclusion

This study studied the impact of adding a Light Rail network on the city of Sioux Falls, and whether adding Park-and-Ride facilities at the stations would increase its impact. We showed that Park-and-Ride facilities helped improving the performance of the system (in terms of total travel time), while additionally suggesting they could help make a smaller network as efficient if not more efficient. We identify next steps in the analysis : reducing the number of stations with P&R (we propose nodes 4, 14, 15 and 21) and reducing the network length to the central core. Studying these new scenarios could help provide the best light rail network at a good price over quality ratio.

Also, the precision of our analysis could be strenghtened in multiple ways. In this study, we made the assumption that we could neglect any other factor than the travel time, and we even did not take into account the waiting time or the cost of transfers. This was strong assumptions, and by adding costs to the on-boarding and off-boarding links, as well as dividing the tram network according to the lines and adding transfer links between them, we could model it better. Adding capacity constraints to the light rail is another step that could be taken to identify headway and capacity requirements, which would guide the rolling stock invesment cost.

Finally, modelling mode choice is a complex phenomenon, and assuming users always take the best choice according to our modelling could be a very strong assumption. Logit models, for example could be a better option.

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.

Any code and results produced for this project are availlable on Github : `https://github.com/merlebleue/CIVIL-477-Transport-Networks---End-project`

Appendixes

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