Assessment of Highway Improvement and Congestion Pricing Strategies for a Medium-Sized City Network

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Abstract

This report evaluates traffic congestion and improvement strategies in a medium-sized city's arterial highway network using a static User-Equilibrium (UE) assignment model. The network comprises 24 nodes, 76 directed links, and 161.21×10^3 veh/hr of morning peak-hour demand. Three strategies are considered: (a) Scheme 1—expansion of congested links and construction of new connections, (b) Scheme 2—congestion pricing on the ten most congested links, and (c) a Combined strategy implementing both capacity improvements and tolls.

Results show that the baseline network exhibits severe congestion along the 1–3 and 21–24 corridors. Scheme 1 effectively reduces congestion, lowering total system travel time (TSTT) from 1118.23 to 1096.79 veh·min (–1.9%). Scheme 2 increases TSTT to 1147.17 veh·min (+2.6%), as tolling triggers inefficient rerouting. The Combined strategy performs better than pricing alone but still worse than pure expansion, producing a TSTT of 1125.28 veh·min (+0.6%). The findings suggest that structural capacity shortages dominate system performance, and supply-side improvements are more effective than pricing in this network.

1 Introduction

Congestion on urban freeway systems is a critical source of travel delay, fuel consumption, and environmental emissions. As demand increases, many medium-sized cities face chronic congestion during peak periods, especially along key arterial corridors. To mitigate such issues, transportation agencies typically consider supply-side strategies such as capacity expansion, and demand-side strategies such as congestion pricing.

This project evaluates two improvement schemes proposed for a medium-sized city's arterial highway network. The first scheme (Scheme 1) introduces capacity expansion on selected bottleneck links and constructs new road segments to provide alternative routes. The second scheme (Scheme 2) imposes congestion pricing on heavily loaded links. A combined strategy that integrates both capacity enhancement and pricing is also examined. The objectives of this study are to: (a) identify baseline bottlenecks using volume-to-capacity (v/c) ratios, (b) evaluate the performance impact of each scheme using a static UE assignment, (c) analyze how congestion patterns and flows change under different strategies, and (d) discuss the feasibility and effectiveness of the proposed schemes.

2 Network and Data

2.1 Highway network structure

The study network represents the arterial highway system of a medium-sized city. It contains 24 nodes and 76 directed links, including major urban corridors and intersections. Origin–destination (OD) zones are located at nodes 1, 2, 4, 5, 10, 11, 13, 14, 15, 19, 20, 21, 22, and 24. Morning peak-hour OD flows between these zones sum to 161.21×10^3 veh/hr.

Figure 1 provides an overview of the highway strategy network. Centroid nodes are highlighted and connected to the physical network by centroid connectors. This figure establishes the spatial context for the subsequent analysis.

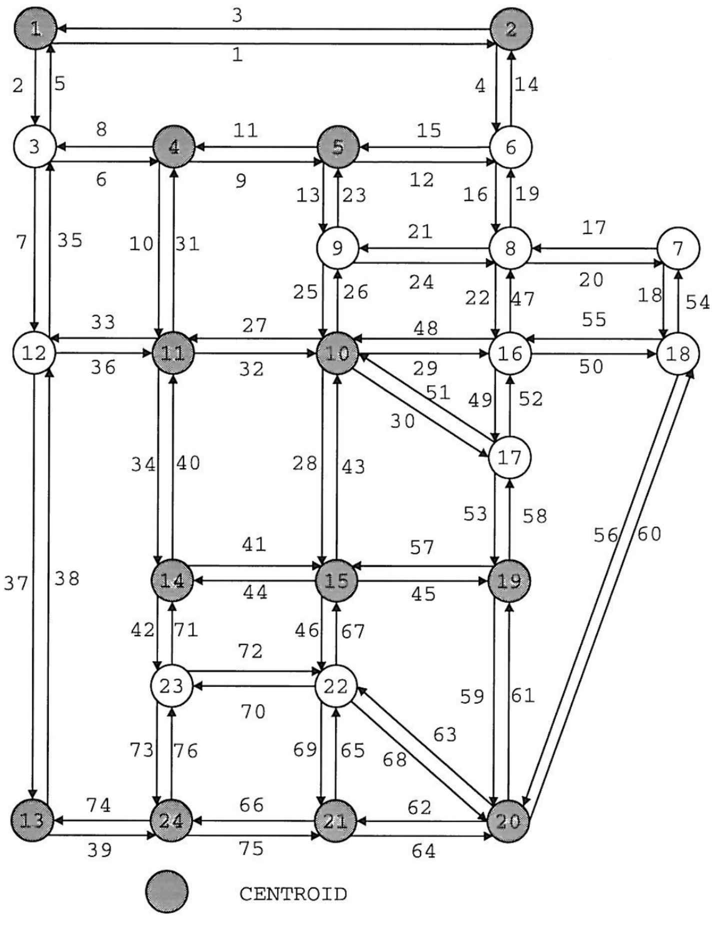

Figure 1: The highway strategy network of a medium-sized city. The network includes 24 nodes and 76 directed links, with centroid nodes shown in grey circles.

2.2 Candidate improvement projects

Candidate improvement projects, including potential new links and widening opportunities, are illustrated in Figure 2. Proposed new connections are shown as dashed arrows, while existing links eligible for capacity expansion are highlighted as solid arrows. This schematic serves as the basis for defining the design of Scheme 1 and the Combined scheme.

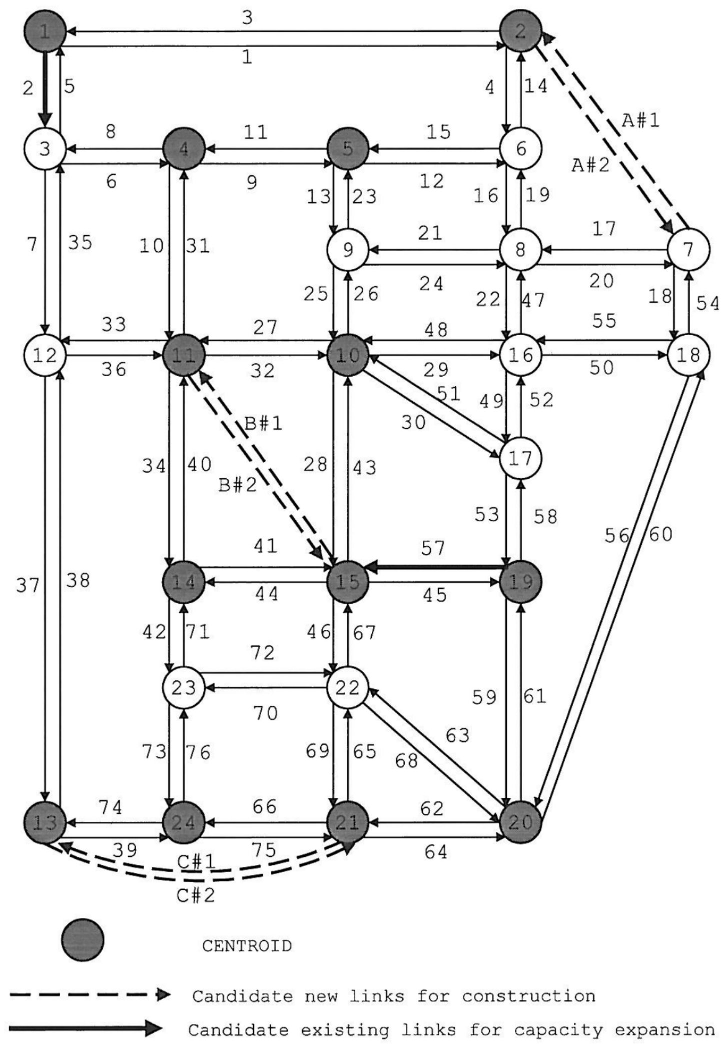

Figure 2: Locations of candidate highway improvement projects on the network. Dashed arrows represent proposed new links; solid highlighted arrows indicate links available for widening.

Link characteristics are provided in the project handout. For each link a, the free-flow travel time t_a^0 (minutes) and capacity c_a (in 10^3 veh/hr) are specified. The OD matrix provides peak-hour demands between the 14 centroid nodes.

3 Methodology

3.1 User-equilibrium model

Travelers are assumed to follow Wardrop's first principle: no user can reduce travel time by unilaterally changing routes. Route choice is modeled using a deterministic User-Equilibrium (UE) assignment with the standard Bureau of Public Roads (BPR) link performance function:

$$t_a(x_a) = t_a^0 \left[1 + 0.15 \left(\frac{x_a}{c_a}\right)^4\right], \tag{1}$$

where x_a is the flow on link a, t_a^0 is the free-flow time, and c_a is capacity.

3.2 Solution algorithm

The UE is solved using the method of successive averages (MSA). Starting from an all-or-nothing assignment based on free-flow times, link travel times are updated iteratively according to the BPR function. At each iteration, shortest paths are recomputed and new auxiliary flows are assigned. Let $x^{(k)}$ denote the flow at iteration k and $y^{(k)}$ the auxiliary flow obtained from the current travel times. The update formula is

$$x^{(k+1)} = x^{(k)} + \alpha_k \big(y^{(k)} - x^{(k)}\big), \qquad \alpha_k = \frac{1}{k+1}. \tag{2}$$

Iterations continue until the relative change in flows is less than 10^{-3}. Shortest paths are obtained using Dijkstra's algorithm on the directed network.

3.3 Performance measures

For each scenario, performance is evaluated using three main indicators. First, total system travel time (TSTT) is defined as

$$\text{TSTT} = \sum_a x_a t_a(x_a) \quad (\text{veh} \cdot \text{min}),$$

which aggregates congestion across the entire network. Second, the volume-to-capacity ratio $v/c = x_a/c_a$ is used to identify critical links. Third, links with $v/c \geq 0.90$ are classified as bottlenecks, and their distribution is examined spatially and across scenarios.

4 Scenario settings

This study considers four scenarios: the baseline network, two single-strategy schemes, and a combined scheme. Table 1 summarizes the characteristics of the four scenarios. Each scenario represents a different combination of supply- and demand-side strategies, including capacity expansion, construction of new links, and congestion pricing. The table clarifies the operational differences among the scenarios and highlights the specific interventions applied in each case.

As shown in Table 1, only Scheme 1 introduces physical capacity improvements, both by widening existing critical links (Link 2 and Link 57) and by adding two new connections (C#1 and C#2). These enhancements directly target the major structural bottlenecks

Table 1: Summary of model settings for the four policy scenarios.

Scenario	Description	Capacity expansion	New links	Tolling
Baseline	Existing network, no interventions	No	No	No
Scheme 1	Capacity expansion and new links	Link 2 (+4), Link 57 (+4)	C#1 (L77), C#2 (L78)	No
Scheme 2	Congestion pricing on top bottlenecks	No	No	Yes (10 links)
Combined	Capacity + new links + pricing	Link 2 (+4), Link 57 (+4)	L77, L78	Yes

identified in the baseline network. Scheme 2 relies solely on congestion pricing, applying tolls on the ten most congested links. The Combined scheme incorporates both sets of interventions. These differences in design have substantial implications for route choice behavior and systemwide performance, as discussed in later sections.

5 Baseline congestion analysis

Identification of baseline bottlenecks is essential for designing effective improvement strategies. Table 2 lists the Top 10 most congested links ranked by their volume-to-capacity (v/c) ratios in the baseline UE solution. These bottlenecks represent critical constraints on network performance and directly influence the selection of capacity expansion projects.

Table 2: Most congested baseline links (Top 10), motivating the selection of improvement projects.

Rank	Link ID	From→To	Flow (10^3 veh/hr)	Capacity	v/c	Description
1	2	1→3	10.55	9.01	1.17	Major N–S corridor
2	66	21→24	11.15	9.77	1.14	21–24 bottleneck
3	75	24→21	10.97	9.77	1.12	Reverse direction
4	34	11→14	10.84	9.75	1.11	E–W internal link
5	40	14→11	10.62	9.75	1.09	Reverse direction
6	14	6→2	10.36	9.92	1.04	Entry to major corridor
7	57	19→15	4.36	4.42	0.99	Minor bottleneck
8	39	13→24	9.44	10.18	0.93	Approaching centroid
9	19	8→6	8.84	9.80	0.90	Secondary congestion
10	74	24→13	9.40	11.38	0.83	Near centroid

As shown in Table 2, Link 2 (1→3) and the bidirectional 21–24 corridor (Links 66 and 75) are the most severe bottlenecks, operating well above their nominal capacity. Other links such as 11→14 (L34) and 14→11 (L40) also experience heavy congestion. These findings justify the choice of expanding Link 2 and Link 57 and constructing new links C#1 and C#2 under Scheme 1.

Figure 3 visualizes the v/c ratios of the Top 10 links. The figure confirms that several links operate close to or above saturation, with the highest v/c values clustered on the 1–3 and 21–24 corridors.

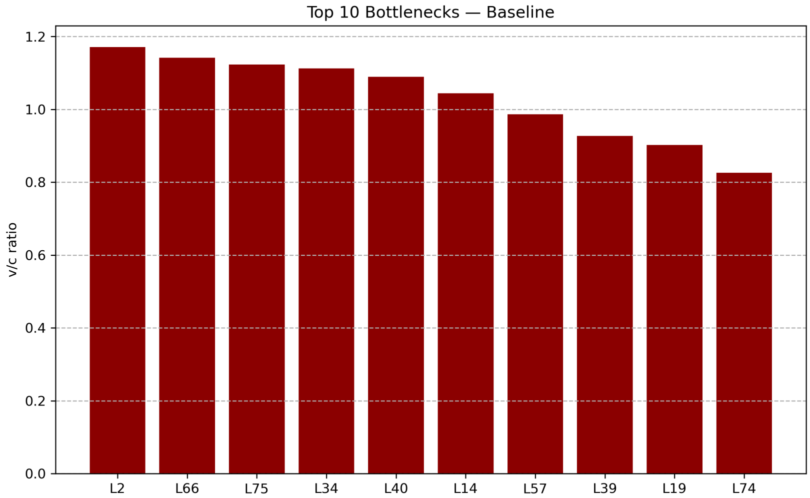

Figure 3: Top-10 most congested links in the baseline UE assignment, ranked by v/c ratio. Links 2, 66, and 75 form the most critical bottlenecks in the network.

To provide a systemwide view, Figure 4 shows the sorted v/c distribution for all links under each scenario. The baseline curve serves as a reference and will be compared with the modified scenarios in the next section.

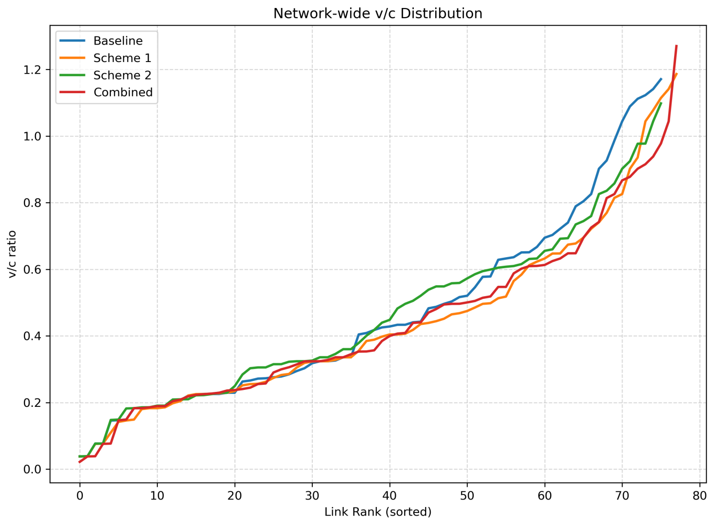

Figure 4: Network-wide sorted v/c distributions for all scenarios. The baseline curve highlights the upper tail of highly congested links, which Scheme 1 aims to relieve.

6 Scenario performance: system-level comparison

To compare the systemwide performance of the four scenarios, Table 3 reports the total system travel time (TSTT) and the change relative to the baseline. TSTT provides a comprehensive measure of aggregate delay and is therefore an appropriate metric for evaluating congestion mitigation strategies.

Table 3: Total system travel time comparison across all scenarios.

Scenario	TSTT (veh·min)	ΔTSTT vs baseline	Percentage change
Baseline	1118.23	–	–
Scheme 1	1096.79	−21.44	−1.9%
Scheme 2	1147.17	+28.94	+2.6%
Combined	1125.28	+7.05	+0.6%

Table 3 shows that Scheme 1 delivers the greatest reduction in TSTT, improving network performance by approximately 1.9%. Scheme 2 increases TSTT by 2.6%, indicating that pricing alone triggers inefficient rerouting and additional detour-based travel. The Combined scheme performs better than Scheme 2 but remains inferior to pure capacity expansion.

Figure 5 presents the absolute TSTT values for each scenario, while Figure 6 shows the corresponding changes relative to the baseline. These graphics complement Table 3 by making the relative magnitudes easier to visualise.

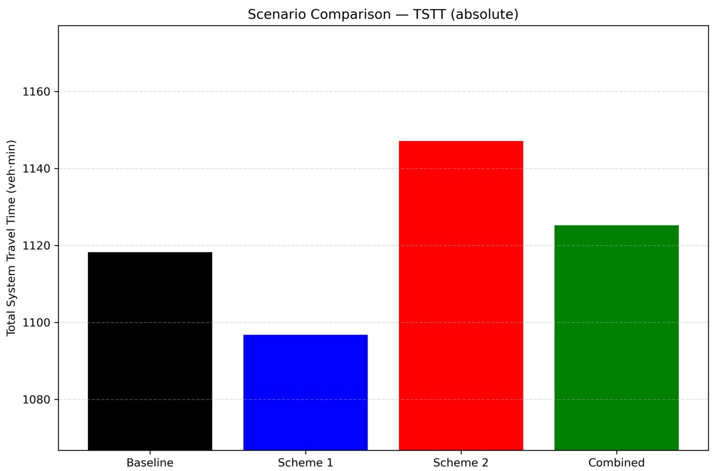

Figure 5: Total system travel time (TSTT) for all scenarios. Scheme 1 achieves the lowest TSTT, while Scheme 2 yields the highest.

Taken together, Table 3, Figure 5, and Figure 6 clearly indicate that capacity expansion and new links (Scheme 1) are the most effective option in this network, whereas pure congestion pricing (Scheme 2) is counter-productive. The Combined scheme lies between these two extremes.

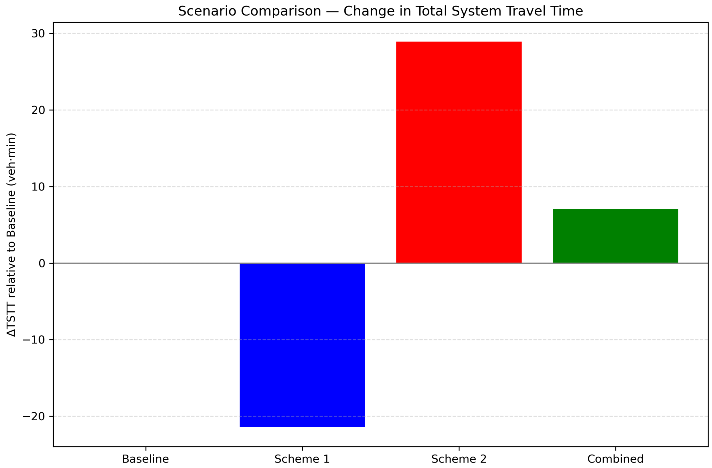

Figure 6: Change in TSTT relative to the baseline for all scenarios. Scheme 1 reduces TSTT by about 21 veh·min, whereas Scheme 2 increases TSTT by almost 29 veh·min.

7 Flow redistribution and role of new links

Beyond aggregate performance, it is important to understand how flows are redistributed by each strategy. Figure 7 shows the link flow differences relative to the baseline for the original 76 links. Scheme 1 and the Combined scheme create larger shifts on several key corridors—particularly around links 20–45 and 65–75—reflecting the use of the new and expanded capacity. Scheme 2 exhibits smaller but systematic flow reductions on tolled links, accompanied by increases on adjacent alternative routes.

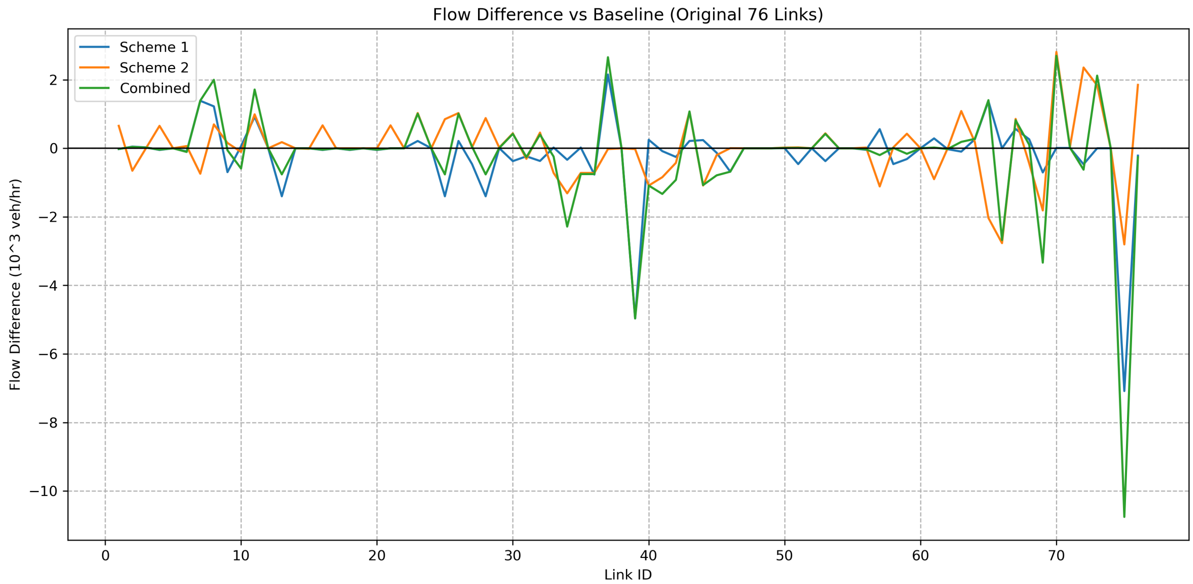

Figure 7: Flow differences relative to the baseline for the original 76 links under Scheme 1, Scheme 2, and the Combined scheme. Scheme 1 and the Combined scheme redistribute flows on major corridors, while Scheme 2 induces local detours from tolled links.

Figure 8 focuses on the two newly constructed links C#1 (L77) and C#2 (L78). Both links attract substantial traffic, and C#1 operates above its nominal capacity in both Scheme 1 and the Combined scheme. This confirms that the new connections fill an important gap in the original network and play a central role in relieving congestion on the 21–24 corridor.

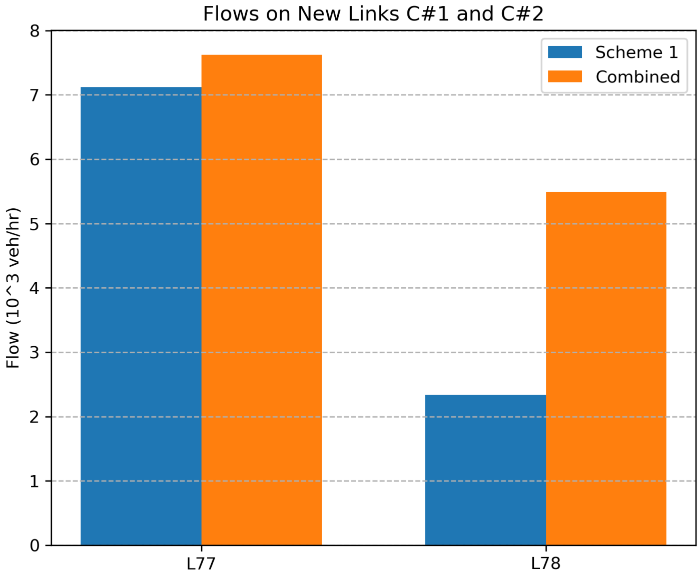

Figure 8: Flows on newly constructed links C#1 (L77) and C#2 (L78) under Scheme 1 and the Combined scheme. High flows on these links indicate that the new connections are heavily used and become important components of the network.

Comparing Figure 7 and Figure 8 with the v/c distributions in Figure 4 shows that Scheme 1 not only reduces congestion on existing bottlenecks but also effectively integrates the new links into the route choice pattern. The Combined scheme, however, partially undermines these benefits by applying tolls that distort route choice and limit full utilisation of the added capacity.

8 Conclusions and recommendations

The analysis indicates that the study network suffers from structural congestion on Link 2 (1→3) and the 21–24 corridor. The following conclusions can be drawn. First, Scheme 1 (capacity expansion plus new links) is the most effective strategy, reducing TSTT by 1.9% and lowering v/c ratios on critical links. Second, Scheme 2 (congestion pricing) is counter-productive in this context, increasing TSTT by 2.6% due to inefficient rerouting and additional detours. Third, the Combined scheme performs better than tolling alone but worse than pure capacity expansion, indicating that tolls partially offset the benefits of added capacity.

For this particular network and demand level, supply-side improvements should be prioritised. In practice, this means widening Link 2 and Link 57 and constructing links

C#1 and C#2. Future work may consider refined pricing designs, such as cordon pricing or time-varying tolls, implemented in combination with expanded capacity and improved alternative routes. Such extensions could provide a more balanced integration of demand management and infrastructure enhancement.

Appendix Code Repository and Project Structure

This appendix documents the external code repository used in the development of this project. All scripts, data-processing routines, network input readers, UE solvers, and plotting utilities are maintained in a publicly accessible GitHub project.

The full project repository is hosted at:

https://github.com/Jackie-ZHU-cloud/civil5610project-ZHU-Jiaqi

The repository contains the complete source code used to reproduce all analysis, including:

- Python scripts for network reading, UE computation, scenario processing, and figure generation.
- Input datasets required for the baseline and scenario evaluations.
- Auto-run controller script `runthemodel.py`, which executes the entire pipeline sequentially.
- All network plots, v/c analyses, TSTT comparison graphs, and flow difference visualisations.
- Documentation and development notes tracking the progress of the project.