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Optimizing Bike Infrastructure for Sustainable Urban Mobility: A Joint Mode and Route Choice Equilibrium Approach

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Overview

Background:

- Planning agencies are increasingly being faced with the question of improving existing bicycle infrastructure to encourage cycling and reduce stress for cyclists within limited budgets.
- In this research, we focused on the **planning and improvement** of existing bicycle infrastructure within the context of sustainable transportation initiatives.
- Our research specifically focuses on three points:
  a) Evaluating the **impact of bike infrastructure improvements on** multiple modes of transportation, especially **automobile infrastructure** where existing car lanes are commonly repurposed for creating new bike lanes or protected lanes and
  b) Incorporating multiple objectives considered by bikers in their choice of routes including **safety stress** (in driving next to high-speed cars) and **travel times**.
  c) Investigating the **tradeoffs between bike infrastructure enhancement and reduced travel times** for car modes, emphasizing the need to ensure the availability of alternate transportation options.

Image sources: https://www.civilbeat.org/2023/12/building-a-bike-path-from-nanakuli-to-manoa-could-take-20-years/ and https://waba.org/advocacy/campaigns/create-the-silver-spring-circle/

- **Research question:** What are the optimal strategies for enhancing existing bicycle infrastructure in urban areas, considering the diverse transportation modes, with a particular focus on repurposing automobile infrastructure?

Literature Review

Bicycle Level of Service (BLOS):

- BLOS are used to quantify cyclists' experiences, integrated into the multimodal level of service in the Highway Capacity Manual. Factors influencing BLOS include automobile characteristics, quality of bike infrastructure, and other design features.
- Integrated into the multimodal level of service, with a higher BLOS indicating better suitability for cycling.
- Assessment factors include automobile characteristics, quality of bike infrastructure, and other design features.

Connectivity Measurement in Bicycle Networks:

- Flow-based centrality metrics used for connectivity assessment.
- Metrics include betweenness centrality, shortest cycle closeness centrality (SCC), all cycle betweenness centrality, etc.
- Network-edge effect observed, with central links having higher betweenness centrality.

Optimal Network Design for Bike Paths:

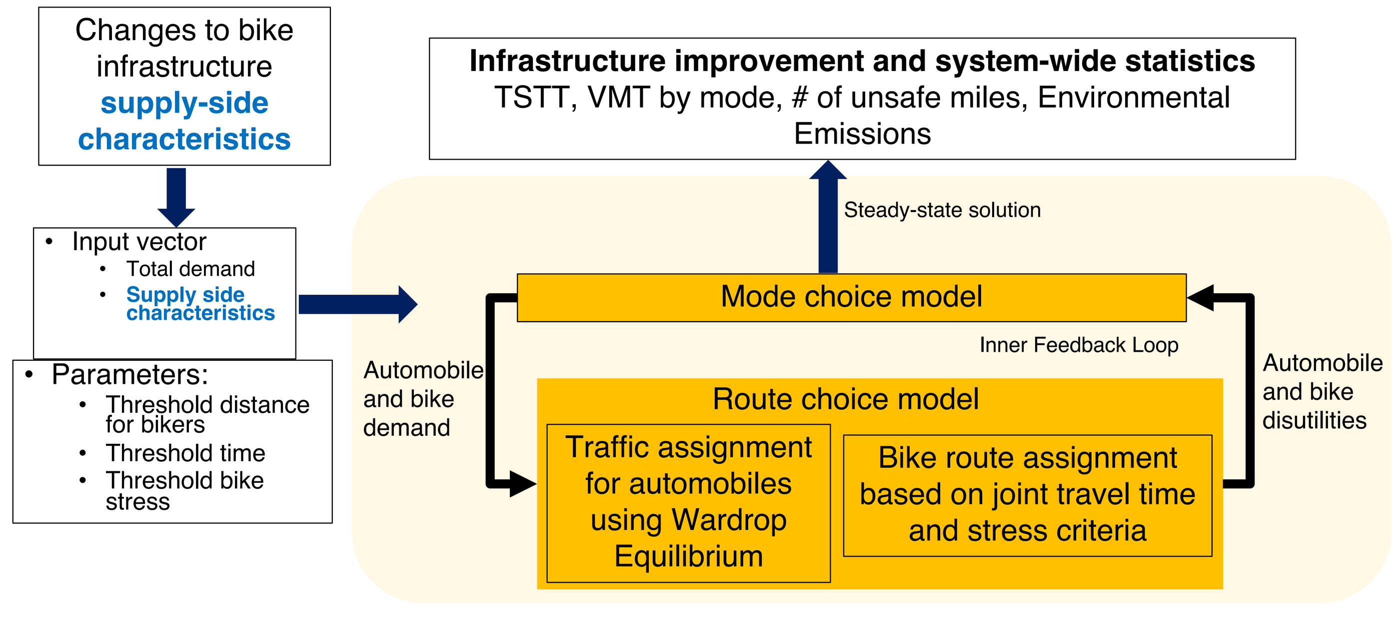
- Existing work address the challenge of optimal network design for bike paths located on or adjacent to roadways.
- Developed a mixed-integer nonlinear nonconvex model, reformulated and linearized into a mixed-integer linear program.
- Solved using a global optimization method and a metaheuristic approach.
- Limitations include a focus on bike paths, not bike lanes, and the route choice model being path-based which is not scalable.

Model elements	This Paper	*(10)*	*(19)*	*(16)*	*(15)*
1. Objective function	Min bike stress and cost	min cost	min cost	min cost	Phase 1: max cov; Phase 2: min cost
2. Coverage (100%)	Yes	No	Yes	Yes	Yes
3. OD connection distance	Shortest disutility	Shortest path * factor	Shortest path	Factor in route choice model	Function of several factors
4. Link connectivity	Full	Full	Partial	Partial	Full
5. Budget limit	Yes	No	Yes	Yes	Yes
6. Approach	Heuristic	MILP	MILP, GRASP	MILP, GRASP	MILP

Review of methods in the literature (adapted from Ospina et al., 2022)

Network Design Models

- We use models for **mode and route choices for travelers**, based on the four-step planning models commonly used for studying long-term traveler behavior.
- For mode choices, we focus on bicycles and single occupancy vehicles (SOV) as the two-mode alternatives (using a Binary Logit model for predictions)
- We assumes the availability of an origin-destination matrix from the trip distribution step.
- For route choice, we consider Wardrop equilibrium routes for automobiles and shortest utility route for bicycles.



Schematic of the model used for analysis

Methods and Analysis

Algorithm 1: Joint Mode and Route Choice Equilibrium:

Determine equilibrium flows for bikes and cars considering route choices and mode preferences.

Steps:

1. Initialize bike proportion and set the iteration number.
2. Iteratively compute demands, shortest paths for bikers, and equilibrium solutions for automobile traffic.
3. Calculate mode utilities, update bike proportions, and iterate to converge.
4. Outputs: Total system travel cost, vehicle miles traveled, and flows on each link.

Algorithm 2: Network Design For Bike Infrastructure Optimization

Identify links for improvement, considering stress reduction and budget constraints.

Steps:

1. Solve the base-case Total System Travel Cost (TSTC) using Algorithm 1.
2. Iterate through stress reductions on high-stress links and compute changes in TSTC.
3. Rank links by TSTC reductions, allocate budget and prioritize links for repair.
4. Outputs: Selected links for infrastructure repair.

Model Parameters

Bike design speed	15 mph
Bike distance threshold λ	6 miles
No. of feedback iterations	4
Base value of weight for bike stress relative to bike travel time ζ	3 min per stress unit
Alternative specific constant (ASC) for automobiles	-0.5
Reduction in car capacity for a unit reduction in bike stress level (ν)	50 veh
Infrastructure investment cost for a unit bike stress reduction per mile C	$10000/stress unit/mile
Investment Budget B	$250,000
Greedy GP solver desired convergence gap	1.00E-08
Greedy GP solver step size	0.5

Algorithm 1

Algorithm 1 Algorithm for Solving Joint Mode and Route Choice Equilibrium

Inputs: Supply side characteristics, total demand for each OD pair, Algorithm parameters. Initialize bike proportion p_{bike} at 10% for all OD pairs. Set iteration number $n = 1$

while Iteration number n < Maximum number of feedback iterations **do**
  Compute the demand for bike and auto modes
  Compute the shortest disutility path for bicyclists and load all bike demand on those paths.
  Compute the equilibrium solution to the static traffic assignment for automobile demand using the greedy-GP algorithm in Xie et al. (*27*).
  for Each OD pair $(r,s) \in Z^2$ **do**
    Compute U_{auto} and U_{bike} from the obtained solutions using Equations (6) and (7).
    Compute p_{bike} using Equation (5).
  $n \leftarrow n+1$

Outputs: Total system travel cost, total vehicles miles traveled, and automobile and bike flows on each link.

Algorithm 2

Algorithm 2 Algorithm for Network Design For Bike Infrastructure Optimization

Inputs: Total budget (B), set of high-stress links where improvements are desired $A_{\text{high-stress}}$
Solve the base-case TSTC ($\text{TSTC}_{\text{base}}$) using Algorithm 1.

Compute TSTC reductions:
for Each link $(i,j) \in A_{\text{high-stress}}$ **do**
  for Stress reduction θ in $\{1, \min\{2, s_{ij}\}\}$ **do**
    Reduce the stress per mile from s_{ij} to $s_{ij} - \theta$.
    Reduce the capacity for the car lanes on the link from c_{ij} to $c_{ij} - \nu\theta$.
    Resolve the joint mode-and-route choice equilibrium using Algorithm 1.
    Compute changes in TSTC: $\Delta\text{TSTC}_{ij}^{\theta} = \text{TSTC}_{\text{base}} - \text{TSTC}_{\text{new}}$.
    Compute costs for reducing bike stress on this link $C_{ij}^{\theta} = \$C\theta l_{ij}$.
    Reset the stress and capacity.
Rank the links in the increasing order of $\text{TSTC}_{ij}^{\theta}$ in a priority queue. Set Remaining Budget= B
while Remaining Budget $\leq B$ **do**
  Pop the top-most link (i,j) from the priority queue with stress reduction as $\bar{\theta}$ resolving ties arbitrarily. Select the link for repair.
  Remaining Budget $\leftarrow$ Remaining Budget $- C_{ij}^{\bar{\theta}}$
Resolve the equilibrium using Algorithm 1 combining the stress reductions for all the selected links. Confirm as a proof of check that the obtained TSTC reductions relative to the base TSTC are higher than the highest value of $\text{TSTC}_{ij}^{\theta}$.
Output: Selected links for infrastructure repair

$$\text{TSTC} = \sum_{(i,j)\in A} x_{ij}^{\text{auto}} t_{ij}^{\text{auto}} + x_{ij}^{\text{bike}} \left((1-\zeta) t_{ij}^{\text{bike}} + \zeta s_{ij} l_{ij} \right)$$

$$U_{\text{auto}} = -0.025 \times \text{Auto Travel Time} - 0.00169 \times \text{Driving costs} + \text{alternative specific constant (ASC)}$$

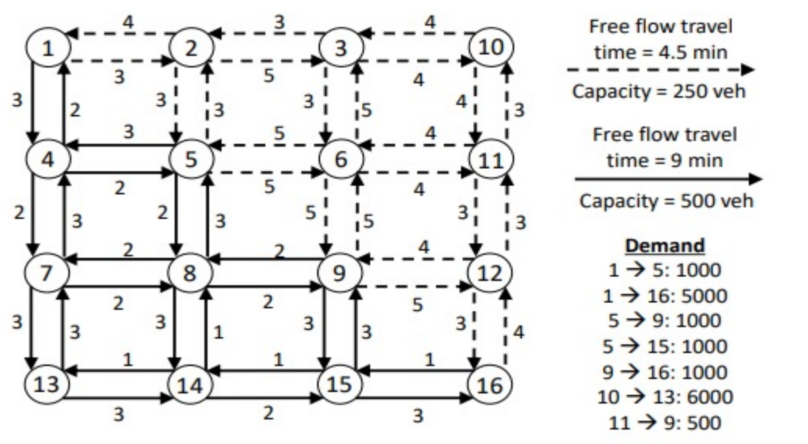
$$U_{\text{bike}} = -0.04584 \times \text{Bike Weighted Disutility}$$

Results and Conclusions

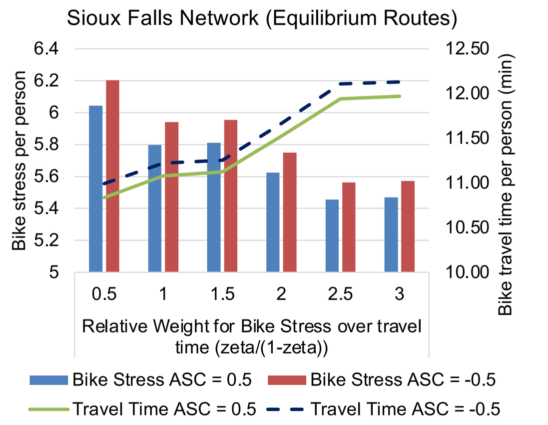
- Study demonstrates the network design formulation on two distinct test networks: a sixteen-node grid network and a Sioux Falls network. This captured the tradeoffs between different route choices
- Bike stress levels are randomly sampled within the range of -2 to +1 around the base stress levels using the equation below.

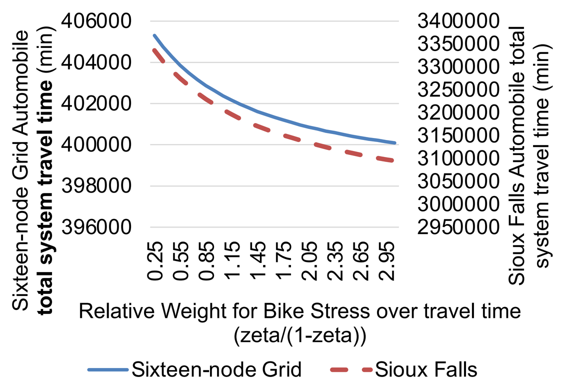
Actual stress level (s_{ij}) = Base stress level − Stress reduction due to separated lanes and buffer)

- An increase in the preference for the safety parameter (ζ) results in an expected increase in travel time for cyclists. This aligns with the idea that **prioritizing routes with lower bike stress often leads to the selection of routes with higher travel t**imes.
- The plot of Total System Travel Time (TSTT) for cars reveals a reduction in bike stress leading to an increase in TSTT for cars, showcasing an interplay between bike stress and car travel times.

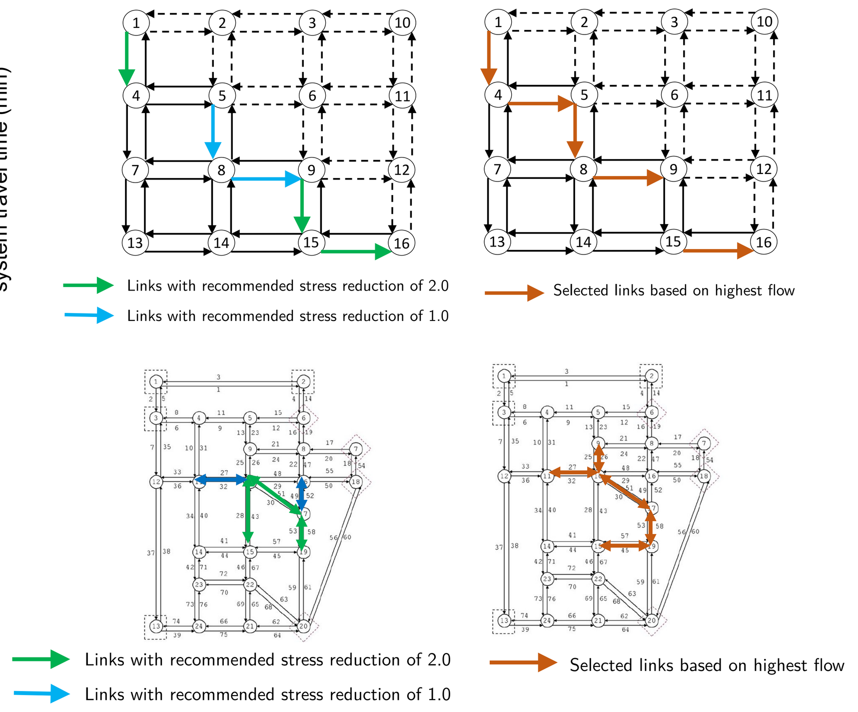


Base supply-side characteristics for the Sixteen Node Network. The values for each link indicate the approximate measure of bike stress





- **An increase in the weight assigned to bike stress** increases the percentage of travelers choosing to bike, leading to a proportional decrease in per person travel time for those using cars and a **decrease in automobile total system travel time**.
- We also observe that accounting for bike stress and interaction between mode and route choice of travelers, we get different predictions in the selection of links than the highest betweenness-centrality method in Vybornova et al. (2022).



Comparison of top 5 selected links for improvements based on (a) network design method and (b) highest betweenness-centrality method

- **Conclusions and Ongoing Work**:
  - The study contributed to bike infrastructure planning through a modeling framework, addressing equilibrium-based network design alongside mode and route choice models.
  - For the final solution we suggested a network design approach that considers stress reduction for all links, providing a valuable ranking framework for fixing bike infrastructure.
  - Future work is recommended to refine the approach by incorporating transit as a mode and using real-world data, calibrating model parameters, and considering the distribution of weight parameters for bike stress.

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