Journal of Transport Geography 56 (2016) 110–119

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

The space race: A framework to evaluate the potential travel-time impacts of reallocating road space to bicycle facilities

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ARTICLE INFO

Article history:
Received 8 April 2016
Received in revised form 6 July 2016
Accepted 6 September 2016
Available online 16 September 2016

Keywords:
Active travel
Bicycle
Bike lane
Cycling
Network robustness index
Sustainability

ABSTRACT

When building a cycling network, planners have the option of constructing bicycle facilities at different design widths. However, increasing the width of bicycle facilities reduces lane space for motor vehicles, in turn impacting a road's level of service. Presently, no framework exists to systematically measure the potential travel time consequences of employing wider bicycle facilities on a road network. In this paper, we demonstrate how the Network Robustness Index (NRI) can be used to identify the bicycle facility design that limits traffic disruption for any road link in an urban network. To demonstrate the utility of the new approach, we use a theoretical, generalizable network and compare it against an approach used in current bike lane planning practice. The results show that if a planner is challenged to build a road network of wider bicycle facilities while at the same time minimizing potential impacts on motor vehicle traffic, their decision-making power improves when using the NRI to support this aim. If widely adopted, this new evaluation framework may lead to the development of better urban cycling networks that consist of wider bicycle facilities.

> "Separated bike lanes cannot be planned in a vacuum. Among the primary concerns when planning a separated facility is determining how much, if any, motor vehicle capacity might be removed due to an installation. The reduction could result from removing a lane of vehicular traffic or altering signal timing such that vehicular throughput is impacted. Many municipalities find the subject of reduced capacity politically challenging. Planners should engage in a comprehensive, multi-modal analysis of the costs and benefits of a separated bike lane in terms of mobility for all street users – cyclists, pedestrians, and transit users, in addition to motorists. Planners should take a flexible approach to separated bike lane construction and engage in robust before and after data collection in order to holistically evaluate how separated bike lanes can fit into a roadway network. Evaluation should include performing a traffic volume analysis, determining if a corridor has excess capacity, and evaluating whether a separated bike lane design will require removal of roadway capacity. Planning for high-quality separated bike lanes within a dynamic, constrained environment poses considerable challenges and requires careful consideration and analysis."
>
> [Federal Highway Administration (FHWA, 2015, p. 47)]

1. Introduction

Bicycle lanes come in many different sizes, and the road space required for each design varies. Bike signs and shared lane markings require no specific reallocation of road capacity to bikes while conventional lined bike lanes or wider European style bicycle facilities need some road space to implement. The lowest stress options are bicycle boulevards, buffered lanes, and separated bike lanes or cycle tracks, and these all may need as much as a full lane worth of capacity to employ (see Fig. 1 for examples of various designs). Currently, most North American city cycling networks are made up of bicycle facilities that take up very little road space. Signs, shared markings, and conventional lined bike lanes are employed across Canada and the US, but fewer cities employ wider, buffered, or physically separated bike lanes (NACTO, 2015a).

However, this trend is changing, and as the number of urban cyclists in North America continues to grow, more and more municipalities are adopting wider bike lanes as part of their city cycling networks.[1] To facilitate the transition from the current state of cycling infrastructure to city networks that employ wider bike lanes, planners require some method to evaluate the cost of narrowing or removing lanes to reallocate space to bikes. This need is echoed in the quote from the FHWA that opens this paper, one stating that determining the amount of

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[1] Over the past decade, at least 17 cities in the United States have incorporated a separated cycle track into their cycling network (NACTO, 2015a).

http://dx.doi.org/10.1016/j.jtrangeo.2016.09.004
0966-6923/

Fig. 1. Types of bicycle facilities common in North America: (A) shared markings, (B) conventional bike lane, (C) buffered bike lane, and (D) separated cycle track.

capacity necessary to install a bicycle facility should be one of a planner's primary concerns (FHWA, 2015, p. 47).

One possible approach to assist planners in this regard is to measure the travel time impact a loss of capacity has on the greater road network. Since, for the most part, bicycle facilities are incorporated into rather than added to a road network, a bike lane is in essence a road capacity loss for motor vehicles. Since the network's primary objective is to facilitate operation for the majority of traffic, motor vehicles, the potential travel time impact a bicycle facility may have is a good indicator of the amount of capacity a planner could conceivably reallocate to bikes. The information provided from evaluating the impact of capacity loss can then be used, along with other factors, to help select the bicycle facility design for a particular location, and communicate to the drivers of motor vehicles that their concerns have been addressed in that selection.

Unknown vehicular travel time impacts have limited planned wide bike lanes in the past. Complaints over traffic disruptions have, in at least one case, delayed the installation of wider lanes in a New York City neighborhood (Sadik-Khan, 2016), and in another, forced a separated bike lane's removal in Toronto (Alcoba, 2011). Moreover, these two examples are not likely isolated incidents, as the same FHWA quote above indicates that the need for capacity evaluations stems from many municipalities finding reduced road capacity for cars is politically challenging (FHWA, 2015, p. 47).

This paper proposes a new approach to evaluate the potential impact of reallocating road space to bicycle facilities. This framework is built on a foundation of a critical link analysis method called the Network Robustness Index (NRI), first developed by Scott et al. (2006). The NRI method can be used in conjunction with a software tool called the NRI Calculator to perform a sensitivity analysis of road capacity impacts, measuring each link's ability to accommodate wider cycling facilities without a considerable disruption to vehicular traffic. The following experiment applies this method to a hypothetical, generalizable example road network to test its ability to perform this type of analysis and demonstrate its potential to be applied in cycling network planning.

The remainder of this paper is structured as follows. Section 2 provides some background on cycling in North America and the trends that motivate this research. Section 3 offers a critique of the current framework in place to assist planners in selecting bike lane separation. Section 4 outlines the NRI, the proposed capacity sensitivity analysis framework, and the example network used to demonstrate the approach. Section 5 covers the application of the NRI to the network comparing results against current practice. The paper closes with a brief summary and possible future considerations.

2. Motivation

Regardless of coverage, city cycling networks that consist mainly of road signs, shared markings, recreational paths, and conventional lined bike lanes may soon no longer be considered adequate in North America:

> "Many municipalities may already have a comprehensive network that – when mapped – appears to adequately cover a large area with multiple intersecting on-street bike lanes or sign-posted bike routes. However, if these facilities are inaccessible to cyclists seeking a low-stress experience then the network may not meet the needs of everyone… a [new] network might be overlaid on and around – or even replace – an existing bicycle network."
>
> [Federal Highway Administration (FHWA, 2015, p. 32)]

Shared markings and conventional bicycle lanes may have, in the past, met the needs of the cycling 1% that consider themselves "strong and fearless," but these facilities are viewed by the majority of cyclists as high-stress (Mekuria et al., 2012). Shared markings scored lowest in preference among both surveyed cyclists and drivers, each viewing this design as potentially dangerous to riders (Sanders, 2013). Conventional lined bicycle lanes are the most commonly employed bicycle facility across North America, but survey evidence shows that they fall short of the comfort provided by wider bicycle facility types. Sanders (2013) found that less than 50% of riders found lined lanes to be "moderately or very comfortable when cycling near drivers" on corridors with parking, although that estimate rises significantly on streets where parking is eliminated (p. 69). Broach et al. (2012) collected GPS evidence showing that lined lanes on arterial roads were preferred by cyclists only when no other lower traffic alternative was available (p. 1737). In addition to North American cites heavily relying on these designs in their cycling networks, many municipalities also include

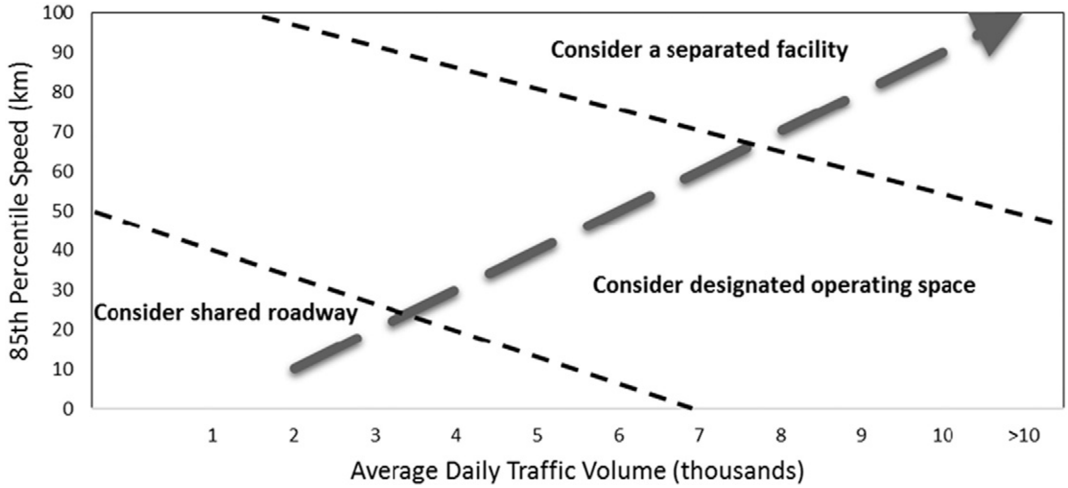

Fig. 2. Desirable bike facility pre-selection nomograph of two-lane, two-way roadways. A similar nomograph can be found in the "Ontario Traffic Manual Book 18: Cycling Facilities" (MTO, 2014, p. 30).

off-road bike paths as part of their total coverage. Recent research, however, indicates that cyclists strongly prefer separated on-road bike lanes over recreational paths (Nuworsoo and Cooper, 2013). Moreover, an earlier study found that even the highest quality off-road paths are used by utilitarian cyclists infrequently (Aultman-Hall et al., 1997).

The shortcomings of the widely employed bicycle facility types will be further exposed as the number of novice urban cyclists continue to grow. According to the 2014 American Community Survey, the number of new cyclists rose in the United States by an average of 63% since 2001, with medium and large size cites experiencing the greatest growth (League of American Bicyclists, 2015). From 1996 to 2006, Canada too saw a 42% rise in commuter cycling, overall maintaining a higher level of ridership per capita than the United States (Pucher et al., 2011). Both countries are bracing for the largest growing age group, 'Millennials' born after 1979, to continue to add to urban cycling's rise. The number of Millennial riders climbed 24% in the US National Household Survey in less than a decade from 2001 to 2009 (Davis et al., 2012). This surge in youth ridership seemingly will progress as nearly two thirds of young people polled in a recent survey prefer living in cities where car use is optional (Urban Land Institute, 2015).

Failing to recognize the oncoming confluence of city cycling growth and potentially inadequate facilities for the majority of that new cohort may result in a potential crisis for North American cities. While prior evidence suggests an inverse relationship between the volume of cyclists and the number of accidents on city streets (Jacobsen et al., 2009), this may not hold true if that increase is not accompanied by more and wider bicycle facilities that separate novice riders from traffic. Recently, cycling fatalities in the United States rose 16%, with 69% of those deaths occurring in urban areas (Williams, 2012). Overall, during the past four decades, fatal accidents have tripled for working age male cyclists (Vargo et al., 2015).

A number of cycling accidents and deaths in the 1960s and 1970s motivated nations like Denmark and the Netherlands to reevaluate their city cycling networks. This lead to the implementation of more robust city cycling networks comprised primarily of wider bicycle facilities that created greater separation between riders and drivers (Ligtermoet, 2006). These cities now comprise some of the highest standards for urban cycling in the world. A similar reevaluation in North America may soon be necessary.

Preventing that rethink, despite changing demographics, ridership, and attitudes, is that car culture remains ingrained in North America. Congestion free traffic and reliable car commutes remain important to the majority, and the challenge of reconciling this aim with building a low-stress cycling network may have limited the North American transition to some degree. To our knowledge, no framework currently exists to evaluate the costs of shifting road capacity from cars to bicycles measured by travel time impacts for motor vehicles. As a result of this lack of evidence, the decision to employ facilities of greater width may have been limited for fear of their potential impact. By using the Network Robustness Index (NRI), a method that can measure the potential travel time consequences of installing different bicycle facilities, planners may be able identify acceptable costs, and implement the widest facilities within the constraints entailed by working within a car culture.

3. Current practice

The "Ontario Traffic Manual Book 18: Cycling Facilities" (MTO, 2014) provides an illustration of one of the tools commonly used to select bicycle facilities in current practice worldwide. That illustration, recreated in Fig. 2, is called a nomograph, a "rule of thumb" used by Provincial Governments in Canada, Sustrans in the United Kingdom, CROW in the Netherlands, traffic authorities in Denmark, Australia, and New Zealand, with a similar variation found in planning guides in the US[2] (MTO, 2014). The nomograph advises that as speed and volume increase so too should the width of a bicycle facility increasing its separation between cyclists and traffic. For safety purposes, the reason behind this rule is intuitive, as more separation between cyclists and cars should reduce the frequency and severity of accidents.

However, from the perspective of a planner whose primary concern may be facilitating car traffic, the direction of this rule is less intuitive: "Lane widths also affect highway level of service. Narrow lanes force drivers to operate their vehicles closer to each other laterally than they would normally desire" (AASHTO, 2011, p. 315). Since a road's level of service dictates traffic flow, and in cases where volume and speed are high (just the case where the nomograph advises more space to bikes), narrowing those lanes with a bicycle facility may lead to increased congestion on that corridor. Harvey (1992) surveyed 35 British traffic calming schemes and found that narrowing non-highway roads can reduce maximum speed by as much as 10 km/h, while a full-lane loss may slow traffic speeds by as much as 30 km/h. As a result, planners may be concerned that installing a wide bicycle facility that narrows or even removes a lane may have an adverse impact on travel time along that corridor. Since the nomograph acts against a planner's instinct to try to maintain level of service, planners may simply choose to employ narrower bicycle facilities than advised regardless of the nomograph's rule. Taking an instinctual "ad-hoc" approach to

[2] The United States AASHTO "Guide for the Development of Bicycle Facilities, 4th Edition" (AASHTO, 2012) uses the same information as Figure 2 as a facility type guide, but in table format (see Table 2–3 of the guide).

planning bike lanes is likely not uncommon (Rybarczyk and Wu, 2010). However, if the trend to adopt wider bicycle facilities into city cycling networks is to continue, a more sophisticated approach is needed.

The framework proposed herein differs from the nomograph because instead of using a "rule of thumb," it measures directly the potential impacts that different bicycle facility designs may have on roads across a city's network. The framework can be used to identify the locations where wider facilities have a limited impact on travel time, even on high volume links.

In the initial study of the NRI method, Scott et al. (2006) found that not all road capacity is created equally, and at some locations, a loss is more impactful than others. Sullivan et al. (2010) used a method similar to the NRI to discover that not only is the location of the loss important, but that even a fraction of capacity lost at a particularly vulnerable location may impact a network's operation greatly. This knowledge can therefore be used to identify the least disruptive locations and facilities to aid a planner in building a cycling network, avoiding the seeming contradiction that the nomograph entails.

4. Methodology

This section describes the Network Robustness Index (NRI) as a method and as a framework to assist bicycle facility and cycling network planning. We begin with a brief explanation of the calculations used by the NRI to measure travel time change following a road capacity reduction, and the software tool used to automate these computations across a road network. This is followed by an outline of how this framework can be used in a sensitivity analysis to evaluate the potential cost of installing different bicycle facilities on a roadway. Last, in this section, is a description of the theoretical road network data used to demonstrate the application of this approach.

4.1. Network Robustness Index and NRI calculator

The NRI was developed by Scott et al. (2006) to measure how critical a link is to overall traffic flow through a road network. While they defined the NRI of a link as the change in total travel time attributed to the rerouting of traffic through a network given the complete disruption or removal of that link – a 100% capacity loss – the NRI of a link can be calculated for any level of reduced capacity, as demonstrated in later work by Sullivan et al. (2010). In this paper, we formally generalize the NRI to denote this flexibility:

$$NRI_a^r = c_a^r - c \quad (1)$$

where NRI_a^r is the value of the index (change in system-wide travel time) for link a when its capacity is reduced by r, which is a value greater than 0%, but less than or equal to 100%; c is the system-wide travel time when all links in the network are operating at full capacity (i.e., *base case scenario*); and c_a^r is the system-wide travel time attributed to the reduced capacity on link a after traffic has reached a new equilibrium (i.e., *capacity reduction scenario*).

$$c = \sum_{i \in I} t_i x_i \quad (2)$$

where t_i and x_i are respectively the travel time and traffic flow across link i at equilibrium. I is the set of all links comprising the road network.

$$c_a^r = \sum_{i \in I/a} t_i^{a,r} x_i^{a,r} \quad (3)$$

where $t_i^{a,r}$ and $x_i^{a,r}$ are respectively the travel time and traffic flow across link i when link a's capacity has been reduced by r and all traffic has been rerouted through the network achieving a new equilibrium.

The key to deriving the NRI of a link is computing realistic link-level travel times and traffic flows as input to Eqs. (2) and (3). In practice, this is accomplished using a traffic assignment model, such as Wardrop's (1952) user equilibrium, which is used in this study. The input for such models are a topologically correct road network and an origin-destination (OD) matrix of vehicular trips for a given time interval, such as the morning peak period or a day.

To automate computation of the NRI for links in a road network, the NRI Calculator has been developed in TransCAD®, a powerful geographic information system (GIS) for transportation applications, using its native programming language Caliper Script. This software tool is designed for maximum flexibility. It first prompts the user for a traffic assignment model that is available within TransCAD®. Further, it allows the user to specify a capacity reduction value greater than 0%, but less than or equal to 100%. Using the input, the tool calculates iteratively the NRI for all links in a road network or a subset of links specified by the user through the tool. In total, the NRI Calculator runs the chosen traffic assignment model $n + 1$ times – once for the base case scenario (Eq. 2) and once for each link identified by the user as warranting investigation under a given capacity reduction scenario (Eq. 3).

The NRI Calculator outputs values in hours. However, the NRI can be measured in other units of time and can also be normalized by dividing the value by the total number of trips underlying its computation (i.e., the sum of all trips in the OD matrix). Mathematically, this expression of the NRI is defined as:

$$nNRI_a^r = \frac{c_a^r - c}{d} \quad (4)$$

where $nNRI_a^r$ is the normalized value of the NRI (change in system-wide travel time *per trip*) for link a when its capacity is reduced by r, and d is the total travel demand in the network. In this study, the NRI is measured in seconds per trip as we believe that it is easier to communicate the impact of a separated bike lane to drivers and passengers in terms of how it might impact them personally.

4.2. Sensitivity analysis framework

The average size of an urban lane in North America is between 9 and 12 ft. or 2.7 to 3.7 m, with the most common lane width being 12 ft. (AASHTO, 2011). Different options for bicycle facilities range in width from 4 to 15 ft. or 1.2 to 4.5 m (AASHTO, 2012; MTO, 2014). Arterial roads are frequently designated as bikeways (Region of Peel, 2013). A typical arterial road with two lanes in each direction is 48 ft. wide or approximately 14.6 m across. Local access, or residential roads of low volume, may also be designated as bikeways (Mekuria et al., 2012). These roads typically have one lane in each direction with a total width of approximately 18 to 24 ft., or 5.4 to 7.3 m to accommodate traffic. To implement a bicycle facility on these types of roads, certain minimum standards must be met to accommodate vehicular traffic. These minimum standards, along with a typical arterial bikeway configuration, are described below in the AASHTO guideline (2011, p. 316):

> "Although lane widths of 3.6 m [12 ft] are desirable on both rural and urban facilities, there are circumstances where lanes less than 3.6 m [12 ft] wide should be used. In urban areas where pedestrian crossings, right-of-way, or existing development become stringent controls, the use of 3.3-m [11-ft] lanes are acceptable. Lanes 3.0 m [10 ft] wide are acceptable on low-speed facilities, and lanes 2.7 m [9 ft] wide are appropriate on low-volume roads in rural and residential areas… In some instances, on multilane facilities in urban areas, narrower inside lanes may be utilized to permit wider outside lanes for bicycle use. In this situation, 3.0- to 3.3-m [10- to 11-ft] lanes are common on inside lanes with 3.6-m to 3.9-m [12- to 13-ft] lanes utilized on the outside lanes."

Given these constraints, Fig. 3 presents a few different bicycle facility installations that can be placed along a local access road. Fig. 4 illustrates some potential configurations that make adding several bicycle facility

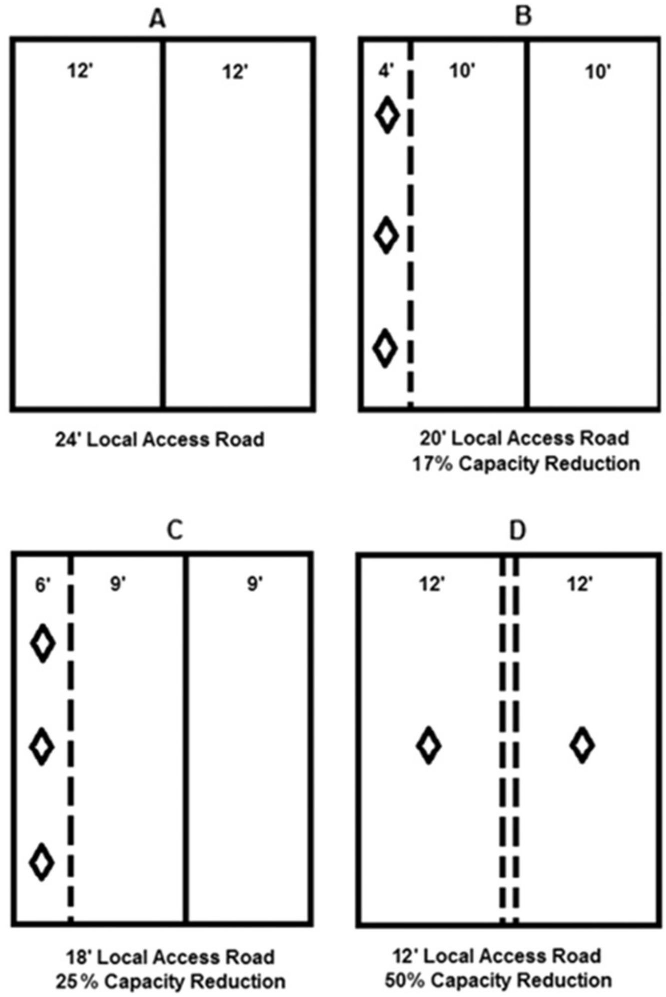

Fig. 3. Bicycle facility options for a one-lane, bidirectional urban local access road: (A) status quo, (B) conventional lined bike lane, (C) bike lane of greater width, and D) two-way bicycle boulevard.

types to a multilane arterial road possible. Option A in either figure represents the status quo.

In both figures, option B, shows the addition of a conventional 4 ft., 1.2 m, minimum AASHTO standard lined bike lane. For arterial roads, the four lanes are reconfigured to include two outward lanes of 12 ft. and two inward lanes of 10 ft. as described in the AASHTO guideline quote above. The lined bike lane installation reduces capacity by about 17% on the local access roads and 8% on arterials, narrowing total road space for motor vehicles on each by 4 ft. Option C illustrates a wider European style lined bike lane that provides riders with 6 ft. of space instead of 4 ft. This facility is less common in North America, but is frequently implemented in the Netherlands (CROW, 2007). Adding a 6 ft. facility still maintains AASHTO minimum lane widths equal to 9 ft. on local access roads and equal to or greater than 10 ft. on arterials. Wide lanes reduce road capacity by 25% on local roads and approximately 13% on arterials.

The third configuration in each figure is different for each road type. Fig. 3, option D, replicates a bicycle boulevard arrangement. A bicycle boulevard, also known as a greenway, neighborway, neighborhood bikeway or byway, is a local access road that is optimized for bicycle traffic by designating bicycles with the primary right of way (NACTO, 2015b). Bicycle boulevard roads remain two-way roads, but drivers can expect a higher volume of bicycle traffic on those streets and are expected to follow bikes (Mekuria et al., 2012). Although no capacity is actually lost, the cost of this type of configuration evaluated as a 50% reduction in road capacity. Out of all the facility design types, this is the most difficult to approximate. The 50% reduction is simply meant to reflect the instances where vehicles are following bikes. Since bicycle boulevards are not employed on arterials, Fig. 4, option D, employs an 8 ft, 2.4 m, buffered bike lane. Buffered bike lanes have a painted buffer that increases the width of the facility to provide additional separation between cyclists and car traffic. This alignment requires approximately a 17% reallocation of a road's total capacity to bikes.

The final option for arterial roads, E, is one that is commonly used to implement a separated bike lane or cycle track. Reducing a four-lane arterial to three lanes with a designated turning lane is commonly known as a ‘complete street’ conversion or a ‘road diet’ (Knapp and Rosales, 2007). This configuration is modeled by reducing road capacity by 25%, a full lane removal of a 4-lane arterial, although designating a left hand turning lane is used to limit some of the impact of a full lane reduction. It should be noted that roadway capacity actually loses a lane only when a separated bicycle facility is installed, therefore evaluating the other bike facility configurations by a small capacity reduction reflects increasingly narrow lanes. Beyond the evidence that narrow lanes have an impact on traffic speed, the effect of the degree of that narrowing on traffic flow has, to these authors' knowledge, yet to be validated. The observed impacts that different bike widths have on traffic speeds may be one area of future research that can validate this type of sensitivity analysis.

4.3. Network data

Computation of the NRI requires a topologically correct road network and an origin-destination matrix of vehicular trips (OD matrix). These inputs are used by the NRI Calculator to simulate traffic flows on the road network.

The road network and data used in this study were first developed and used by Scott et al. (2006) to demonstrate the original NRI method. The authors used Christaller's Central Place Theory as the basis for the network's design, making it generalizable to real-world networks and free of any cognitive bias that may come from designing a network with the forethought of achieving some desired result. The central node in the network is linked to lesser nodes based on population and link capacity in a rank-size hierarchy. Random links are removed from the network to simulate less than full connectivity. In the real world, connectivity is frequently interrupted by natural features such as rivers and by land uses such as parks.[3] The advantage of using a network based on a generalizable theory over a real-world case study is that the experiment itself is computationally inexpensive and resulting model outputs may be more generalizable than a specific real-world case study. The modified network connecting neighborhoods of varying size via arterial and local access roads is familiar in physical space. The notion that a generalizable, sample road network can be developed for study is reinforced by the original network designers who state, “There is no evidence to suggest that the conclusions drawn from the use of such networks and OD flows will differ from those drawn from a real-world example.” (Scott et al., 2006, p. 220).

For this study, some elements of the original network described in Scott et al. (2006) were adjusted. The original network connected a system of settlements arranged in a hierarchy, meaning that link capacity and speed were developed to represent a regional-scale road network. For the current study, the highest capacity road links in the original network were lowered from a freeway capacity of 6900 to an arterial capacity of 4600, while all 1700 capacity links were left in place to represent local access roads. Capacity levels were derived from the “Highway Capacity Manual 2000” (TRB, 2000) and are expressed as the number of passenger cars per hour that can flow in each direction. Link speed was lowered from 100 km/h to 50 km/h to better represent typical speeds in an urban area. Link length was reduced from 50 km to

[3] For more detail about the network's design, see Scott et al. (2006, p. 220–221).

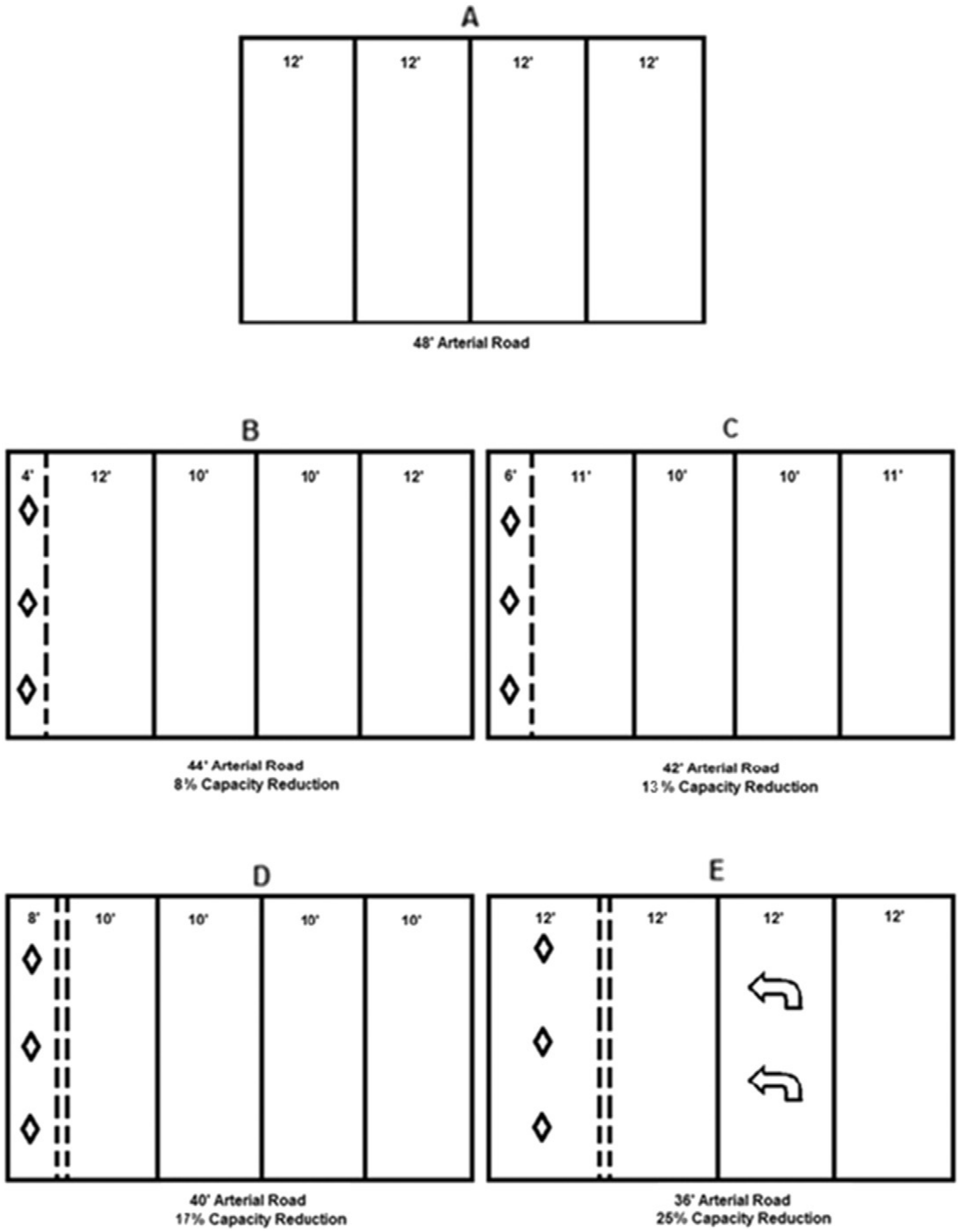

Fig. 4. Bicycle facility options for a two-lane, bidirectional urban arterial road: (A) status quo, (B) conventional lined bike lane, (C) bike lane of greater width, (D) buffered cycle track, and (E) separated cycle track.

5 km for the same reason. The population of each node was also adjusted by multiplying its value by 0.3 to better represent populations within an urban area, rather than a region. This change resulted in a total population of about 1.72 million people. Further, we assumed that each person made on average 2 car trips per day for a total of 3.43 million trips. As in Scott et al.'s (2006) original work, these trips were then distributed to destinations via the following production-constrained gravity model:

$$T_{ij} = O_i \frac{W_j C_{ij}^{-\beta}}{\sum_{j=1}^{J} W_j C_{ij}^{-\beta}} \tag{5}$$

where T_{ij} is the number of trips between origin i and destination j, O_i is the number of trips generated in origin i, W_j is the population of destination j, C_{ij} is the shortest path distance in kilometers separating origin i and destination j, and β is a measure of distance decay set at 1.1.

The theoretical road network and its population centers, which form the network nodes, are shown in Fig. 5.

5. Results and discussion

5.1. Complexity of planning a cycling network

Before proceeding with the proposed framework, it should be noted that before a final decision is made on the location or design of a bicycle facility and the development of a city cycling network, other considerations should be taken into account besides motor vehicle travel time. Despite the emphasis placed on driver concerns in this study, it is

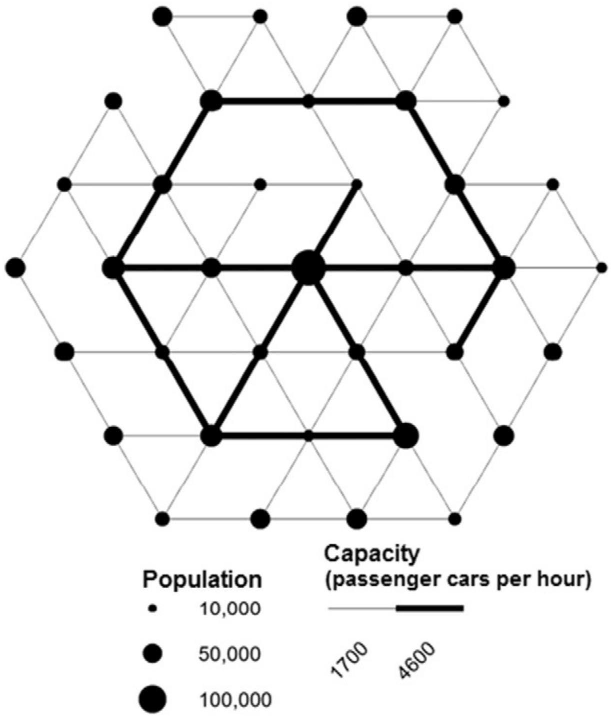

Fig. 5. The theoretical road network used to demonstrate the NRI approach.

important to note that other important issues, such as cyclist safety, cyclist demand, accessibility, and even the potential economic impacts of bicycle lanes, may all enter into consideration when developing a cycling network (see Lovelace et al. (2016) and Larsen et al. (2013) for some recent cycle-centric planning approaches). Moreover, geographic variables, such as ride difficulty, junction density, legibility, and centrality, may also be taken into account when determining suitable bike lane locations (see Rybarczyk and Wu (2010) and Milakis and Athanasopoulos (2014) for some recent geographic planning approaches). These issues are not addressed by this study, which is concerned with overcoming the specific barrier to implementation reduced motor vehicle capacity may cause, an issue highlighted by the FHWA. A planner may choose to evaluate these other concerns first in the planning process and then use the NRI method to evaluate specific links or facility designs, or instead use the proposed approach first for general road network information, evaluating what levels of capacity loss each link can sustain before motor vehicle travel time increases significantly.

5.2. Demonstrating the NRI approach

NRI values are calculated iteratively for each link in the entire road network using the NRI Calculator. As shown in Eq. (4), for this study, these values are adjusted by dividing them by number of motor vehicle trips (driver demand). For this network, a total of 3.43 million trips between origins and destinations are simulated. To evaluate the potential travel time costs of different bicycle facilities, a sensitivity analysis of road capacity reduction is performed, reducing capacity by 17%, 25%, and 50% on local access roads, and by 8%, 13%, 17%, and 25% on arterials. The results of this analysis are then used to assign each link a bicycle facility type.

A 2-second travel time increase threshold was chosen as the decision point to maintain the status quo on a link, leaving that link, in theory, undesignated, or in reality, potentially designated by signage or shared markings. In instances where the travel time cost of several facility types falls below the threshold, the widest type is chosen in order to facilitate the best network possible for cyclists. The 2-second limit was determined simply by using the mean value of each possible result based on the entire sensitivity analysis. Setting the status quo threshold is at the discretion of the planner and will likely be higher than 2 s. The threshold should reflect the increase that drivers are willing to accept, which can be informed by a planner's public consultation.

Some capacity reductions on certain links lower network trip travel time overall, known as a Braess Paradox (Braess et al., 2005). These Braess Paradox outcomes are identified in Tables 1 and 2 by their negative numbers. In the special case where a Braess Paradox occurs, the widest facility that triggers an overall improvement in travel time is chosen over a wider facility that may fall below the 2-second threshold. Tables 1 and 2 show the costs of implementing bicycle facilities of different widths for each road link in the network using the NRI approach.

Table 1
NRI values expressed as a change in seconds per trip for different bicycle facility types on local access roads.

Road ID	Conventional bike lane (−17%)	Wide bike lane (−25%)	Bicycle boulevard (−50%)	Recommended width (ft)
5	−0.1	−0.1	0.1	6
6	2.9	5.1	13.2	0
7	0.1	0.2	0.8	12
8	0.0	0.2	0.7	12
9	2.6	3.7	9.2	0
10	2.5	3.5	8.3	0
13	0.3	0.5	2.4	6
14	0.4	0.9	3.4	6
15	0.3	0.6	2.3	6
16	2.1	3.5	11.2	0
18	0.1	−0.1	0.3	6
20	1.9	3.0	7.1	4
21	0.0	0.1	0.4	4
22	1.3	2.3	5.6	4
23	0.7	0.7	1.7	12
24	0.6	1.0	3.6	6
26	0.0	0.0	0.0	12
27	0.5	0.8	4.0	6
29	0.2	0.5	1.2	12
31	0.3	0.7	2.2	6
32	0.9	1.1	1.6	12
33	0.0	0.0	0.3	6
35	1.3	2.2	5.9	4
37	−0.1	−0.1	−0.1	12
38	0.5	1.0	3.9	6
40	0.0	0.1	0.6	12
42	1.0	1.6	3.5	6
44	0.3	0.4	1.3	12
45	0.1	0.3	1.3	12
46	0.3	0.6	2.6	6
47	0.0	0.2	1.1	12
48	0.4	0.9	3.1	6
49	0.6	1.1	2.7	4
50	1.0	1.7	4.5	4
51	0.4	0.5	1.6	6
52	3.4	5.1	12.0	0
53	0.2	0.3	1.0	12
54	−0.1	−0.1	−0.1	12
55	1.1	1.8	4.0	6
56	−0.1	−0.1	0.4	6
57	1.5	2.0	5.0	6
58	0.7	1.5	3.7	6
59	0.0	0.2	1.0	12
60	0.1	0.2	0.8	12
61	0.0	−0.1	0.2	6
64	−0.1	0.0	0.1	12
65	−0.1	0.1	0.2	12
66	1.1	1.9	5.0	6
68	4.2	6.3	14.7	0
70	0.5	0.9	2.7	6
71	0.8	1.7	5.2	4
72	0.4	0.8	3.5	6
73	0.4	0.6	2.5	6
74	−0.1	−0.1	0.1	6

Table 2
NRI values expressed as a change in seconds per trip for different bicycle facility types on arterial roads.

Road ID	Conventional bike lane (−8.5%)	Wide bike lane (−12.5%)	Buffered bike lane (−17%)	Separated cycle track (−25%)	Recommended width (ft)
1	0.1	0.1	−0.1	0.0	12
2	0.3	0.3	0.6	0.9	12
3	1.2	1.7	2.8	3.9	0
4	0.9	1.1	1.7	2.6	8
11	−0.1	0.0	0.1	0.1	12
12	−0.1	−0.1	−0.1	0.0	12
17	0.1	0.1	0.2	0.3	12
19	0.0	0.0	0.0	0.1	12′
25	0.4	0.7	1.0	1.8	12
28	0.1	0.2	0.6	0.9	12
30	0.1	0.1	0.0	0.1	12
34	0.1	0.1	0.5	0.6	12
36	0.1	0.0	0.1	0.1	12
39	0.2	0.1	0.3	0.4	12′
41	0.0	0.2	0.3	0.4	12′
43	0.0	−0.1	0.0	0.0	12
62	0.2	0.3	0.5	0.9	12
63	0.1	0.3	0.5	0.9	12
67	3.1	4.0	6.4	9.3	0
69	0.5	0.6	1.2	1.7	12

The suggested facility type is mapped in Fig. 6 for each link labeled by their ID. This a map can be used by planners as a template to begin building a city cycling network should vehicular travel time increases play a role in the planning process.

As mentioned earlier, Braess Paradox links stand out as negative values. If the objective is to facilitate cycling while also minimizing disruption to motor vehicle traffic then identifying these links are the best possible result for a planner. Should driver concerns challenge an installation, placing facilities on these roads may be the easiest projects to implement and therefore may represent the initial seeds of building a larger cycling network. What is interesting is that within the NRI results some Braess Paradox links are triggered by a particular bicycle facility type. For example, on Links 18 and 61, a negative value only appears when a wider bicycle lane is employed. This may or may not reflect the reality of driver behavior as the traffic assignment model reallocates a precise amount of demand to alternative links when a specific proportion of capacity is reduced. This finding reflects the results of the Braess Paradox experiments of Yang and Bell (1998), who found that the phenomenon only occurs within a specific demand range, but, as discussed earlier, it is unknown whether or not increasingly narrow lanes trigger such demand shifts in reality.

Although reallocating capacity at most locations for any facility type increases travel time, using just a 2-second threshold affords a planner many options to implement the widest facilities possible without significant disruption. A total of 17 links or 31% of all local access roads can accommodate a bicycle boulevard. On those links, capacity can be reduced by 50% without exceeding the 2-second threshold. Additionally, another 17 links or 85% of all arterials can accommodate a separated bike lane. As for the links that the NRI approach suggests remain status quo, those links are critical to network traffic operation. On these roads even a fractional loss of capacity increases trip travel times significantly. For example, implementing a bicycle boulevard on Link 68 would result in a nearly 15 second increase in travel time across all trips. The reason for this link's criticality is readily apparent when viewed in Fig. 6, as link 68 provides the sole connection between several nodes. Moreover, some links are not critical to network operations across all facility types, but do exhibit a clear critical threshold between types that result in a significant increase as widths progress. For example, on Link 27,

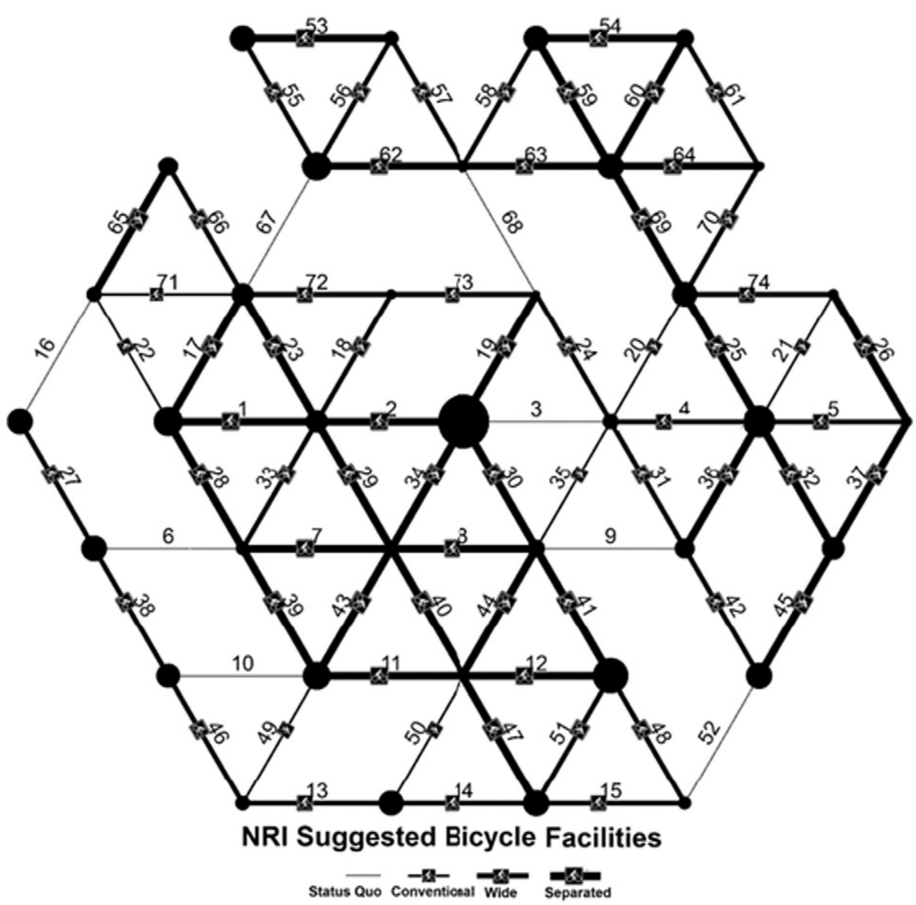

Fig. 6. Map of bicycle facility types that minimize disruption to level of service on each road link based on the NRI sensitivity approach.

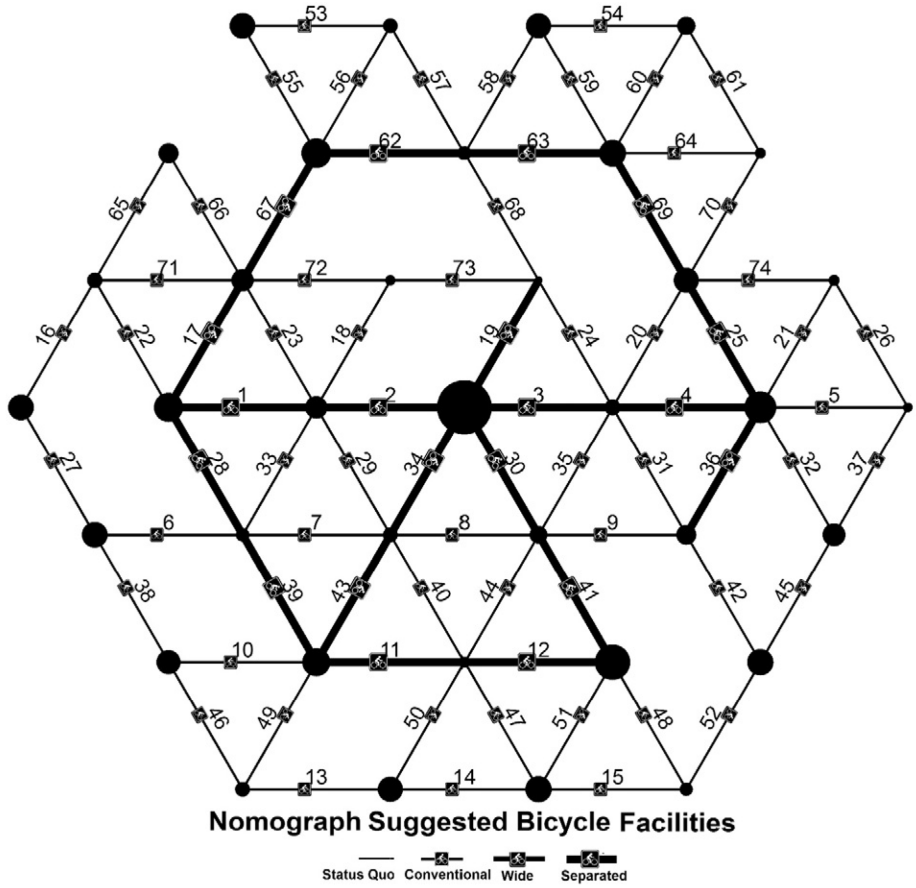

Fig. 7. Map of bicycle facility types chosen based on the nomograph rule of thumb.

employing a wide facility carries an estimated cost of less than 1 second per tip, but employing a bicycle boulevard increases that cost to 4 second per trip, a fourfold increase in travel time.

One caveat must be noted in relation to the results. The changes in travel times cannot be added together to produce an estimate of the impact of several bicycle facility installations added to the network at one time. These tables represent individual estimates of the cost of adding a bike lane of a particular width to a specific link. In other words, if several facilities are implemented at once, a new aggregate table would have to be generated where several link capacities are reduced at the same time. Such a table is created in the next sub-section to compare the travel time cost of creating a completely new cycling network based on the facilities the NRI approach suggests against the ones a planner would develop based on the advice of the nomograph.

5.3. Comparison between the NRI and nomograph

The following analysis compares the potential travel time impacts of using the NRI approach to the potential travel time impacts of the nomograph approach should a planner utilize either to implement a complete network all at once. Fig. 6 in the previous subsection depicts the choices suggested by the NRI approach while Fig. 7 follows the nomograph's "rule of thumb." Using the nomograph, all high volume, 4-lane arterial links are assigned separated facilities and all lower volume, 2-lane local roads are assigned conventional lined bicycle lanes to complete the cycling network. There are no status quo roads since those would be reserved for roads of lower speed and volume than the example network contains. This lack of diversity in bike facility options and lack of flexibility in cycling network design reflects the current state of the practice.

Table 3
Comparison of level of service costs in minutes attributed to the complete cycling network shown in Figs. 6 and 7.

Evaluation	NRI approach	Nomograph approach
Total travel time, complete road network	181,397,334 min	181,397,334 min
Total travel time, complete cycling network	244,268,040 min	246,977,298 min
Difference between scenarios	62,870,706 min	65,579,964 min
Total change in per trip travel time	18 min	19 min

To measure the travel time impact of each approach, we simulate a Wardrop's User Equilibrium traffic assignment for each design, reducing capacity on each link by the amount required by the facility type each method recommends. The results are compared in Table 3. Should a planner adopt the NRI approach to build a complete network, one consisting mostly of wide and separated facilities, the resulting impact on motor vehicle travel time is reduced 1 full minute per trip compared to the nomograph. Should a delay cost of 13 cents per minute (Litman, 2009) be applied, the NRI's complete cycling network represents a daily delay savings of approximately $447,134 over the nomograph. Although the NRI approach has some gaps in bicycle facilities on links critical to network traffic operation, overall many facility widths meet or exceed that suggested by the nomograph, especially on 2-lane local roads. Furthermore, the compromise that these gaps in the cycling network represent may help alleviate some driver concerns that may act as a barrier to implementing the rest of the cycling network.

6. Conclusion

As the number of novice urban cyclists grow in North America, municipalities must rethink their current city cycling networks and focus on building low-stress connections through wider bicycle facilities. In the past, choices of where to place different bicycle facility types were simplistic or potentially ad hoc. In this demonstration, the NRI approach to planning bicycle facilities provides information that can help planners selecting wider bicycle facilities and build city cycling networks around them. This approach uses the change in motor vehicle travel time to measure the different levels of capacity loss different bicycle facility options may need for installation. Using motor vehicle travel time as an indicator may also help overcome some of the political barriers to implementing wider bicycle lanes. Furthermore, the demonstration has shown that if the NRI approach is used to build a complete cycling network, that network has a lower impact on vehicular traffic than one common approach in current practice.

Again to reiterate, this approach to cycling planning only fills just one potential gap in the planning process. To adequately develop a city cycling network that fits the needs of all users, many factors can be used to assist planners in their final choices of bicycle facility type and cycling network design. Our framework best serves the potential gap in process between planning bicycle facilities and implementing them where driver concerns may potentially derail action. The NRI estimates of travel time costs, normalized per trip, provides planners with a communicable metric that may be used to facilitate discussion with drivers.

A proposed next step should be to validate the NRI estimates on real-world bike facility installations. Planners could apply the framework to their own road network data, select a facility type and location and then compare the potential estimated impacts of a facility against real-world observations of changes in traffic behavior and travel time.

Acknowledgements

This work was supported by the Social Sciences and Humanities Research Council of Canada (Grant Number 752-2015-1584) and the Natural Sciences and Engineering Research Council of Canada (Grant Number RGPIN-2016-06153). We would like to thank three anonymous reviewers for providing insightful comments to improve our paper.

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