ADDRESSING DRIVER CONCERNS: THE NETWORK ROBUSTNESS INDEX APPROACH TO PLANNING CITY CYCLING INFRASTUCTURE

ADDRESSING DRIVER CONCERNS: THE NETWORK ROBUSTNESS INDEX APPROACH TO PLANNING CITY CYCLING INFRASTUCTURE

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ABSTRACT

On congested North American urban road networks, driver concerns over increased travel time play a major role in whether or not cycling infrastructure is built. This fact is recognized by transportation planning agencies in Canada and the United States, including the Ministry of Transportation Ontario and the Federal Highway Administration. However, specific frameworks to address such driver concerns do not exist within the practice of urban planning nor the academic literature.

One potentially fruitful avenue is to explore the methods and tools of critical link analysis. One such avenue is provided by the Network Robustness Index (NRI) and the Network Robustness Index Calculator, as this method and tool indexes critical links through traffic simulation from least to most critical. The specific information that can be used to address driver concerns is found in the least critical links as these roadways have additional capacity, and therefore may be considered underutilized.

This thesis explores the use of the NRI as a framework for urban cycling infrastructure planning. Experiments on the utility of the NRI against common traffic and cycling planning tools are explored. The NRI Calculator's ability to perform full network scans for potential bike lane locations, least cost corridors, and full cycling networks consisting of different designs is tested throughout the chapters of this manuscript.

The findings suggest that the NRI framework can be integrated into a broader multi-criteria planning analysis of cycling infrastructure. The approach shows an improvement over current practice as a decision support tool in several ways, including: identifying the greatest number of least travel time cost locations for bike lanes, the least travel time cost corridor for a separated bike lane, and building a complete least travel time cost cycling network with different bike lane designs. Added into a planner's analysis either before beginning a multi-criteria analysis of suitable locations to narrow the bike lane location choice set or after a decision on a site has been made to facilitate implementation through communicable evidence in public consultation, this NRI approach to planning city cycling infrastructure may lead to more complete and better cycling networks in urban areas affected by driver concern.

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First and foremost I would like to thank my family who have stood by me and supported me throughout my entire life. And to all my friends and former teachers, know that you have each shaped me tremendously. To name each of you individually would cover as many pages as the body of this dissertation, but rest assured that I could not have accomplished anything without each and every one of you.

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PREFACE

This thesis dissertation consists of five chapters: an introduction, three research papers, and one conclusion. The first journal submission has been submitted for peer-review and has been revised and resubmitted for publication. That paper demonstrates the ability of the NRI to identify which separated bike lane routes are least costly for vehicle travel times. The second submission has been published in the Journal of Transport Geography. This paper uses the NRI in a sensitivity analysis to assist a planner in choosing the least disruptive type of bicycle facility for traffic on a road link. The third paper has recently been accepted for peer reviewed conference presentation and will soon be submitted to a journal and for publication consideration. This submission identifies prospective separated bike lane locations and measures the cost of a separated bike lane on the Toronto road network. The first two papers are methodological contributions to the cycling planning process and the third is an application of the NRI framework to a real world case study. The motivation behind each paper, to address the political challenges generated by driver concern, leads to a certain degree of overlap between each submission in their introduction and comparison against elements of common practice.

For each article, the first author reviewed the literature, conducted the NRI model estimation, interpreted the results, and wrote the initial manuscripts. Dr. Darren Scott co-authored each paper, contributing his guidance from concept to analysis to submission and revision. Dr. Scott is also the lead author of the group that developed the original NRI methodological tool. The three submissions that underpin this thesis are as follows:

Chapter 2:

Burke, C. and Scott, D.M. (2016). The Bicycle Path of Least Resistance: Building Separated Bike Lanes with the Car in Mind. *Computers Environment and Urban Systems*. Revised and Resubmitted.

Chapter 3:

Burke, C. and Scott, D.M. (2016). The space race: A framework to evaluate the potential travel-time impacts of reallocating road space to bicycle facilities. *Journal of Transport Geography,* 56, 110-119.

Chapter 4:

Burke, C. and Scott, D.M. (2016). How to find 'sensible locations' for separated bike lanes on a congested urban road network: A Toronto case study. *Transportation Research Board, 96th Annual Meeting.* Accepted for presentation.

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Chapter 1 Introduction

1.1 Justification of Research Topic

> ‘In order to implement suitable policies to attain various goals there is a need for an overall characterisation of road networks, to gain insight into their propensity to ‘malfunction’, the extent of the resulting consequences, the scope for mitigation measures, etc.”
>
> Katja Berdica (Berdica, 2002, p. 2)

In 2002, Katja Berdica put forward her case to examine the vulnerability of road networks. This contribution led many to develop the methodological tools needed to evaluate road links from a level of service perspective, measuring how reduced road capacity impacts network travel times overall. For Berdica, the ultimate goal of road vulnerability research is to use information on the level of service costs of road failure to “implement suitable policies”; an applied field that addressed potential vulnerabilities with policy action. Yet, in the more than decade and a half following her outline, much of the body of road vulnerability research has yet to transition from academic theory into planning practice.

The volume of research dedicated to building the methods that measure the potential costs of road capacity loss are extensive (Al-Deek and Emam, 2006; Chang, 2003; Grubesic et al, 2008; Jenelius et al, 2006; Jenelius, 2009; Jenelius and Matteson, 2012; Knoop, 2012; Scott et al, 2006; Snelder et al, 2008; Sohn, 2006; Suarez et al, 2005; Sullivan et al, 2010; Taylor et al, 2006; Taylor and

D'Este, 2007; Taylor, 2008; Taylor and Susilawati, 2012). Yet, studies that go one step further, to use those processes to address a specific policy goal, are more difficult to find (Anderson et al., 2011; Chang, 2003; De-Los Santos, et al., 2012; Erath et al., 2009; Novak et al, 2012; Zhu and Levinson, 2012). The most common suggestion for action is to apply the information generated by road vulnerability studies to prioritize road maintenance or new construction based on the consequence of the failure of a link in a road network (Berdica, 2002; Jenelius et al, 2006; Jenelius, 2009; Jenelius and Matteson, 2012; Scott et al, 2006; Taylor et al, 2006; Taylor and D'Este, 2007; Taylor, 2008; Taylor and Susilawati, 2012). However, this might not be the best use of those methodological tools from a policy perspective.

Priority maintenance of road, bridge, tunnel, and overpass repairs are already computed by engineering methods in units of structural integrity, tensile strength etc. (Hearn, 2000; Johnston, 2005). And although the consequence of failure calculated in level of service terms certainly can be used in conjunction with structural and other measures to generate a multi-criteria analysis priority framework, scheduling repairs based on the travel time cost would likely rank extremely low in weight relative to the human costs of a potential calamity.

Another commonly proposed strategy is to prioritize the construction of new transportation infrastructure that adds to the redundancy of the overall road network, thereby decreasing travel time costs should a critical link fail (Jenelius et al, 2006; Novak et al, 2012; Scott et al, 2006; Taylor, 2008; Jenelius, 2009;

Jenelius and Matteson, 2012). However, generating additional paths for traffic via new roads, bridges, tunnels, and overpasses for with the main purpose of achieving a fail-safe measure may not be the best coping strategy. This proposal is not just difficult for transportation authorities to justify from a budgetary standpoint, but also because those fail safes would have to remain closed lest they too become vulnerable should they be subject to induced traffic demand.

It seems that this potential application of road vulnerability research was poached by authors in this field from earlier studies that characterized the vulnerability of utility and communication networks (Aggarwal and Rai, 1981; Rose et al, 1997). Yet supply side additions that increase the robustness of utility or communication networks tend to be easier and less costly to erect, things like: individual towers, cable, pipelines, or distribution centers; not significant lengths of steel, concrete or asphalt that cannot be buried or place on top of buildings, significantly constrained by the natural and built environment. Moreover, unlike road networks subject to induced demand, those additions can be more easily controlled by a central authority as designated fail safes.

Road vulnerability research to this point in time has seemed like an extensive toolbox in search of projects that fit its applied policy roots. This thesis simply takes one of those methodological tools, the Network Robustness Index or NRI, an approach first developed by Scott et al. (2006), and applies it in a unique way. The NRI can be used to measure road network robustness and the absence thereof, but to be even more precise, it can be used to measure the flexibility of road capacity to overcome a loss. This research uses that notion of road network flexibility – the ability of a road network to cope with the loss of some level of capacity – and measures it in motor vehicle travel time to build new bicycle facility planning frameworks.

The impact of a road capacity loss or a reallocation of capacity from cars to bikes is theoretically and operationally the same. Therefore, the NRI approach can be used to evaluate the travel time cost of reallocating road network capacity from vehicles to bikes. Due to political challenges, changes in level of service for drivers after an installation directly impacts a planner's ability to complete a project (FHWA, 2015). By applying the NRI as a methodological tool in this way, the limitations of using a level of service metric to prioritize transportation infrastructure projects is overcome. Here, opposed to road maintenance or road construction, the unit of measurement and the action align.

1.2 Thesis Objectives and Research Questions

> "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)

The larger goal of this thesis is to address driver concerns within the greater framework of planning bicycle facilities and cycling networks. Most modern cycling planning techniques have rightly been built with the needs of cyclists rather than drivers at the center. The latest frameworks built to aid a planner developing a cycling network use multi-criteria analysis to account for a facility's impact on cyclist's safety, demand, and accessibility (Larsen et al., 2013; Lovelace et al., 2015). Geographers have contributed to multi-criteria planning methods by adding location specific variables like ride topology, junction density, and network centrality; to the decision-making process (Milakis and Athanasopoulos, 2014; Rybarczyk and Wu, 2010). Despite the fact that these recent techniques attempt to account for every factor in order to generate a comprehensive cycling planning framework, none of them have considered the role driver impacts can play as a barrier to implementation. However, recently the US Federal highway Administration has signaled to planners that political challenges from drivers are limiting the development of cycling networks across North America (FHWA, 2015). These drivers are concerned that a reduction in road capacity along their perhaps already congested commute will lead to increases in travel time.

The more specific goal of this thesis is to explore some potential opportunities where the NRI methodology can assist cycling planners to overcome those political barriers. The NRI provides a means to evaluate the potential travel time costs of bicycle facilities, one based on readily available data and one that produces an easily communicable metric to address the public. The use of the NRI in the context of cycling planning is wholly new. As a result some theoretical development of the NRI frameworks into cycling planning was unavoidable and necessary. Tests of the NRI's ability to generate actionable information for a cycling planner are the subject of the next two chapters, each chapter applying the NRI to a generalizable road network to address the following research questions:

1) If a planner has several parallel route options to generate a separated on-road bike path, which route is the least costly for driver travel times?

2) If a planner has several bicycle facility designs to choose from (ranging from narrow to wide), which locations can accommodate each type to generate the most robust urban cycling network possible?

The fourth chapter, motivated by the desire to move from the continued theoretical development of the NRI and road vulnerability research in general, applies the tool to Toronto's road network. This application uses the methodological development from the first two chapters to identify each potential cost free location for a bicycle facility on the road network and measure the possible travel time costs associated with a corridor targeted in Toronto's *Bike Master Plan* (City of Toronto, 2016). These two uses of the NRI approach – to identify locations and to measure bicycle facility costs – encompass the specific objectives of this research. The way those objectives are integrated into the larger thesis are detailed in the section below.

1.3 Dissertation Contents

Chapter 2 addresses the planning dilemma of choosing where to add a separated bike lane installation when several alternative routes exist, some more disruptive to vehicles than others. The framework proposed in this chapter uses the NRI to provide information on the potential travel time costs of separated bike lane routes, allowing planners to evaluate and choose the least disruptive one, should that be the goal. A hypothetical road network, widely generalizable, demonstrates how the method can be used to identify the least disruptive route for a bicycle facility.

Chapter 3 addresses a different planning dilemma. 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 altering the degree a road's level of service is impacted. Presently, no framework exists to systematically measure the potential travel time consequences of employing wider bicycle facilities to generate a robust cycling network. In this chapter, we demonstrate how the NRI can be used in a sensitivity analysis of road capacity flexibility to identify the bicycle facility design that limits traffic disruption for any link in a road network. To highlight the utility of the new approach as a methodological framework, again we use a hypothetical road network designed based on a generalizable theory of network hierarchy.

Chapter 4 is motivated by the need to move the NRI methodological tool from theoretical development to policy application. Across North America, separated bike lanes have generated political challenges from drivers concerned that such facilities may increase their travel times. Toronto (Canada) is one such city where vocal complaints have limited the development of a separated bike lane network. To address these issues, we apply the theoretical frameworks developed in Chapters 2 and 3 to evaluate the travel time cost of installing separated bike lanes on the Toronto road network. The NRI approach is used to scan the network for costs and to evaluate the potential cost of adding a separated bike lane to a target corridor, the Bloor-Danforth, one where plans have encountered political opposition in the past.

The dissertation concludes in Chapter 5 with a discussion, an outline of contributions, and a limitation that may drive future research. The references from this chapter are also found at the conclusion of Chapter 5.

Chapter 2 The Bicycle Path of Least Resistance: Building Separated Bike Lanes with the Car in Mind

2.1 Introduction

By 2011, Toronto, Canada's largest city, the 4th largest in North America, had built less than half of the urban cycling network planned for in its 2001 Official Bike Plan (OMA, 2011). Much of the shortfall consisted of separated bike lanes that had been proposed but never built, reaching a tipping point in 2011 when no new additions were made and three kilometers were removed (Flack, 2011). The decision to remove bike lanes was particularly contentious amongst cyclists, justified by the City based on the possibility that they were increasing travel time for cars. The then Mayor of Toronto stated to the City Council, "over 15,000 commuters each day are suffering from longer travel times, for the sake of 600 additional cyclists," going on to state, "the City should remove the bike lanes as soon as possible and improve travel times for thousands of daily commuters" (ibid). However, rather than support these claims with data, when pressed, the Mayor predicated his stance on anecdotal evidence, "I've got a lot of people calling me, and they want to get rid of them and I do what the taxpayers want me to do" (Alcoba, 2011).

Torontonians or those familiar with Toronto politics may argue that the regression of the City's cycling network was the result of electing a Mayor particularly hostile towards urban cyclists. However, in fairness to that Administration, the City failed to develop the majority of its planned cycling infrastructure in the decade before the Mayor took office. This one instance then, where driver concerns went so far as to force the removal of a separated bike lane, serves to highlight a challenge that planners continue to face: in most North American cities the primacy of the car's role in urban transport is unquestioned by politicians elected and reelected by the car drivers that represent the majority of their constituents. However, for cycling and its associated benefits to grow, episodes like this that pit drivers against cyclists must be overcome by planners. Such incidents are so prevalent, that the Ontario Ministry of Transportation advocates developing cycling infrastructure by first, "building understanding and busting myths" of which, "the drivers versus cyclists myth is at the top of the list" (MTO, 2013, p. 28-29).

In Toronto, the notion that a separated bike lane increased travel time for drivers can be added to the list of myths. Not because it definitively did not impact car travel along that particular corridor, but because never at any stage was this outcome validated by more than the vocal concerns of an unknown number of drivers. This situation highlights the importance of evaluating the impact a separated bike lane may have on car traffic, a notion reinforced as proper practice by the Federal Highway Administration of the United States (FHWA) in the quote above that underpins this paper. In fact, it may be prudent planning to collect and analyze traffic data on not just one corridor but many prospective corridors, evaluating the suitability of each before a final decision to build is made. Such an evaluation would be similar in concept to an environmental impact assessment, except in this case it would identify the impact of a separated bike lane on cars. Unfortunately for planners, bike lane design guides (e.g., FHWA, 2015) present no specific instructions on how to perform such an evaluation. To address this need, we propose using the Network Robustness Index (NRI) for situating separated bike lanes. This method, developed by Scott et al. (2006), has yet to be applied in this context.

The following section describes the most common approach to corridor evaluation, the Volume/Capacity (V/C) ratio, and the most common approach to evaluating bike lanes, the nomograph. Each illustrates the limitation that local metrics have when planning a separated bike lane. Section 3 details the NRI and lays out some potential advantages that are highlighted by the application of both it and the V/C ratio on a theoretical road network. In Section 4, the NRI is applied to analyze multiple prospective corridors as a template for identifying the bicycle path of least resistance[1]. This is followed by a brief conclusion.

Once cycling corridors have been evaluated for their potential traffic impacts, such evidence can then be used to communicate a planner's decision to the general public even before a lane is ever built. The bicycle path of least

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[1] While the NRI is proposed in this paper as a method that can inform development of more robust urban cycling networks, the approach itself can be used to identify the impact of anything that requires a reallocation of road space away from cars. This includes bus rapid transit and light rail lanes as well as on-street parking, public space, and parklets.

resistance (politically, publically, and for traffic) may be that a planner recommends building a separated bike lane along the corridor that minimizes traffic disruption. When drivers question the impact of the newly added separated facility along their preferred corridor, those concerns can be addressed by established evidence that the choice of corridor was made with the interest of their travel times in mind. Hopefully by demonstrating to the car driven majority that every attempt to avoid disruption was made when planning a separated bike lane, fewer phone calls to halt or remove cycling infrastructure will be fielded by politicians.

This tact may prove more effective than the alternative approach, which in the past has been trying to persuade drivers that cycling infrastructure has an overall social or economic benefit. That type of shift in North American car culture has been difficult to cultivate, and likely has limited the expansion of cycling networks in the past[2]. Encouraging apathy by minimizing a bike lane's disruption for drivers may be more fruitful than galvanizing acceptance by impressing cycling benefits on them at the current time.

Despite the focus this study places on driver concerns, it is important to note that other extremely important issues such as safety, cycling demand, accessibility, economic development, and many other concerns should be taken into account when determining the final location of bike lanes. One particular

[2] An interesting article that highlights the extremely important role that driver concerns play in implementing bike lanes is Janette Sadik-Khan's (2016) oral history of her experience as New York City's Transportation Commissioner from 2007-2013.

concern of planners when locating bike lanes should be to identify areas of potential cycling demand. This is important due to the fact that the spatial distribution of short cycling trips differs from that of cars. New methods of evaluation have been recently established in this area and should be reviewed (Lovelace et al., 2015; Larsen et al., 2013). Furthermore, local site characteristics must also be accounted for, like shoulders, grade, parking, intersections, etc. A planner may choose to evaluate these issues first and target specific locations with the approach proposed in this study or vice versa. In short, planning the location of a separated bike lane is a complex process and this framework only addresses one component of a larger problem. We leave the decision on how to weigh all of these issues up to the planner.

Figures 2.1 and 2.2 highlight the ideal outcome of our approach – the identification of adequate capacity on a road network that can facilitate both car traffic and a separated bike lane.

Figure 2.1 Before a Separated Bike Lane on Cannon Street, Hamilton.

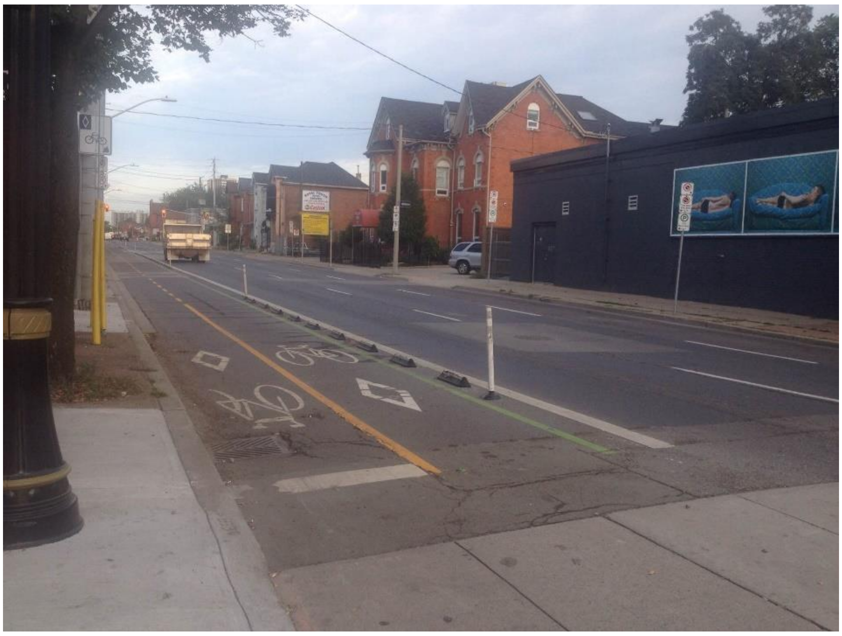

Figure 2.2 After a Separated Bike Lane on Cannon Street, Hamilton.

2.2 Background

Past studies have shown that utilitarian cyclists, like drivers, prefer the efficiency of designated on-road bike lanes as direct routes free from pedestrian traffic (Nuworsoo and Cooper, 2013; Aultman-Hall et al., 1997). When planning a separated bike lane that removes capacity from cars, the FHWA advises that a planner perform some type of a traffic analysis on the prospective road corridor. Using volume and capacity, a planner can determine the operational condition of a road, or its level of service (LOS). The most common way to measure LOS is to calculate a V/C ratio by dividing a road's traffic volume by its design capacity (Dheenadayalu et al., 2004). A ratio less than 0.85 indicates adequate capacity and congestion free vehicle flow along a corridor

(VTPI, 2016; FHWA, 2004). A ratio greater than 0.85 indicates a less stable traffic flow and some delay (ibid). A ratio of 1.0 or greater, where volume begins to exceed capacity, indicates unstable traffic flow, excessive delay, and queuing (ibid). Each of the above can be assigned a qualitative designation of LOS like "good", "fair", or "poor", to create a communicable metric; however, an estimate of travel times along a corridor cannot be directly expressed through the V/C ratio.

While the ratio is perhaps the simplest way for a planner to measure LOS, it is definitively not the proper tool to evaluate a location for a separated bike lane because it fails to measure the effect that a change in LOS on one corridor has on other corridors in a road network. Not accounting for such changes elsewhere is problematic, as the road network acts not in isolation but as a system. In a system, should a change in capacity on one corridor occur, traffic will inevitably reroute and reach a new equilibrium causing changes in volumes elsewhere. These 'spillover' effects limit the usefulness of the V/C ratio when planning a separated bike lane. Scott et al. (2006) caution that using the ratio to determine the consequence of capacity loss on a road network can lead to "limited, negligible, or even adverse system-wide effects." The authors further explain this potential result through the use of a simplified two-lane hypothetical network illustration (Scott et al., 2006, p. 217). Here we use a similar example, but instead apply it in the context of planning a separated bike lane.

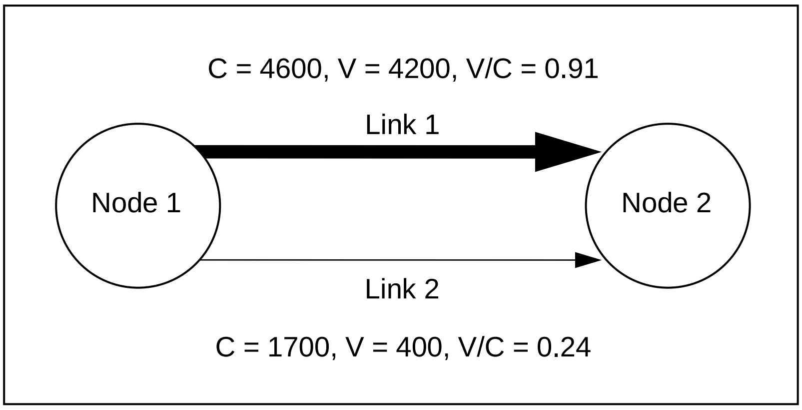

Figure 2.3. Example Problem of the V/C Ratio.

As shown in Figure 2.3, using a localized metric like the V/C ratio, a planner would determine that of the two network links, Link 2 would be the better choice for adding a separated bike lane. The reason for this is that Link 1 has a V/C ratio of 0.91, suggesting that reallocating a full lane away from cars would create considerable traffic congestion. However, when the network is viewed as a system rather than as links in isolation, either link could sustain a full lane capacity reduction. Regardless of which link the separated bike lane is placed on, following the establishment of a new traffic equilibrium each would still maintain a V/C ratio at or below 1.0. As much as 28% of the volume from Link 1 can be absorbed by Link 2 (up to 1300 vehicles) and all of Link 2's capacity can be reallocated from cars to bikes (Link 1 would absorb the volume of Link 2). Thus, in the case of this simplified network, when viewed as a system, the potential locations for siting a separated bike lane doubles.

This hypothetical example serves to highlight that the dynamics of a road network as a system are different from a road's LOS in isolation. Knowing that these conditions exist in reality may identify more corridors as suitable for separated bike lanes, or on the other side of the coin, highlight specific corridors that must be avoided because they have negative impacts on LOS elsewhere.

To complicate matters further, the most commonly used method for determining how much separation to provide between cars and bikes provides advice that seems to run counter to that of the V/C ratio. Shown in Figure 2.4, the nomograph, or a "rule of thumb" chart, is employed by governments in Canada, Sustrans in the United Kingdom, CROW in the Netherlands, and traffic authorities in Denmark, Australia, and New Zealand[3] (MTO, 2014). The nomograph shows that as a road's speed and volume increase so too should the width of a bicycle facility. For safety purposes, the reasoning behind this rule is readily apparent as more separation between cyclists and cars can help reduce the frequency and severity of accidents.

[3] The United States AASHTO "Guide for the Development of Bicycle Facilities, 4th Edition" (AASHTO, 2012) uses the same information as Figure 2.4 as a facility type guide, but in table format (see Table 2-3 of the guide).

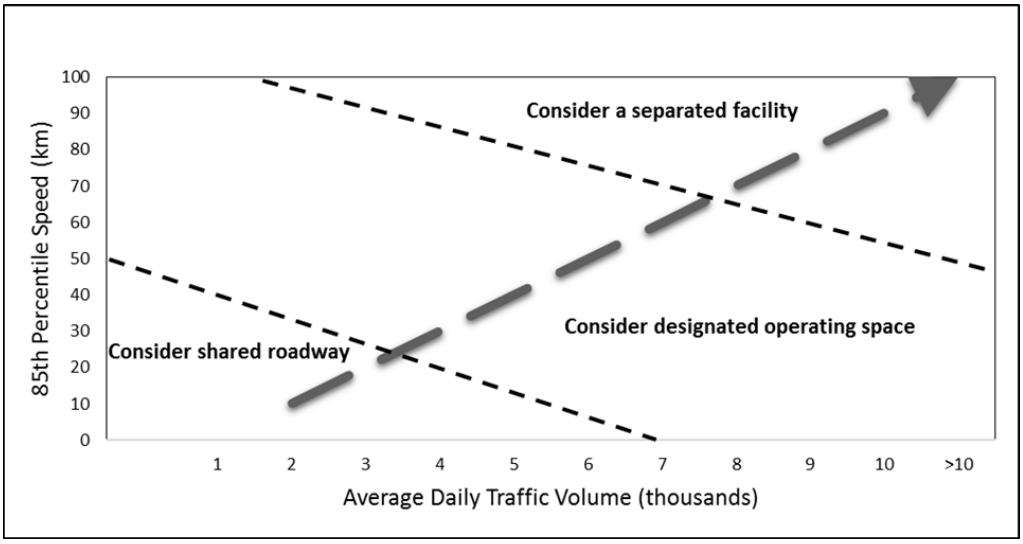

Figure 2.4. Desirable Bike Facility Nomograph (MTO, 2014, p. 30).

However, from the perspective of a traffic engineer using the V/C ratio in their evaluation of potential traffic flow impacts, this rule of thumb makes less sense. The reason for this is that as traffic volume increases in the numerator of the V/C ratio, any reduction in road capacity in the denominator may result in increased queuing and delay. In other words, even a portion of capacity on roads with significant speed and volume may be critical to facilitating traffic flow as even a small decrease in capacity may tip the balance of the V/C ratio. As a result, each additional meter of bike lane separation may move a road towards a lower level of service for cars, impacting traffic flow and travel time.

The NRI avoids the limitations of the V/C ratio's localized approach, guiding planners to roads where a loss of capacity has minimal impact on car travel times. This approach reassures planners that even though the capacity lost to bikes may appear to impact traffic flow on the road in question based on volume, capacity exists elsewhere in the network to mitigate the impact.

2.3 Methodology

2.3.1. Network Robustness Index

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:

$$NRI_a^r = c_a^r - c \tag{1}$$

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*).

$$c = \sum_{i \in I} t_i \, x_i \tag{2}$$

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.

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

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 (vehicle hours of travel or VHT). 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:

$$nNRI_a^r = \frac{c_a^r - c}{d} \tag{4}$$

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.

As formulated in this paper, the NRI approach does not take into account any of the other possible behavioral changes that may take place when a separate bike lane is added to a road network, including, but not limited to, a mode shift from cars to bikes for a number of travelers. Also, 'road diet' configurations can be used to mitigate potential travel time increases following a capacity loss (Knapp and Rosales, 2007). For reasons such as these, the changes in travel time predicted by the approach after capacity is reduced should be taken as high-end estimates.

Although the NRI is more complicated and computationally intensive than calculating a corridor's V/C ratio, it does have several distinct advantages that justify the additional effort. First, viewing a road network as a system affords planners a greater choice of suitable locations for building separated bike lanes. A corridor labelled by the V/C ratio as “poor” may indeed allow for a separated bike lane to be built when there are parallel options to absorb the displaced volume. On the other hand corridors with “good” LOS as determined by the V/C ratio may indeed have an impact on network operations should their capacities be reallocated away from cars. This is reinforced by the analysis below.

Second, the NRI’s ability to measure the impacts of different levels of capacity reduction on a link means that the approach can be used to test the consequences arising from different types of bike-lane designs. Bike lanes range from painted strips to single lane paths, and even a complete street retrofit; each requires distinct amounts of reallocated lane space. Such testing through the NRI method can aid planners not only in their location recommendation, but also their bike lane design choice.

Third, the NRI Calculator provides a full network scan of capacity reduction. Multiple road links can be tested for the suitability of a bike lane at once by measuring the impact of an addition across the network. By identifying several possible corridors that minimize traffic disruption, a planner can weigh the degree of potential traffic disruption against additional factors like a prospective corridor’s current cyclist demand, its connection to the greater cycling network, or even the types of businesses and scenery along its expanse.

Finally, the output of the NRI is measured not as a ratio but as change in travel time. The advantage of this is twofold. First, a planner can directly communicate potential travel time impacts to drivers in terms of total hours (VHT) or normalize values as minutes or seconds per trip. Second, in certain instances, capacity reduction may actually improve travel time. This phenomenon is called a Braess Paradox and can only be uncovered by simulating changes in travel time directly, not by calculating a V/C ratio. Uncovering a Braess Paradox is the ideal scenario for adding a separated bike lane to a road network, a scenario discussed in further detail below.

To illustrate some of the advantages of the NRI, both it and the V/C ratio are applied to the hypothetical road network shown in Figure 2.5. The V/C ratios calculated for each link comprising the network are compared against NRI values. The result is that the NRI identifies more suitable road links for a potential separated bike lane than the V/C ratio by treating the network as a complete system rather than as isolated corridors.

2.3.2 Hypothetical Network Data

The hypothetical test network used in this study was developed by Scott et al. (2006) to help demonstrate the utility of the NRI approach. The authors used Christaller's Central Place Theory (1966) and the rank-size rule as the basis for the network's design, making it generalizable and free of any bias that may come from designing a network with the forethought to achieve some desired result. Random links were removed from the network to simulate less than full connectivity. In the real world, this lack of connectivity can be the result of topography or land use that interrupts connectivity, such as rivers or parks[4].

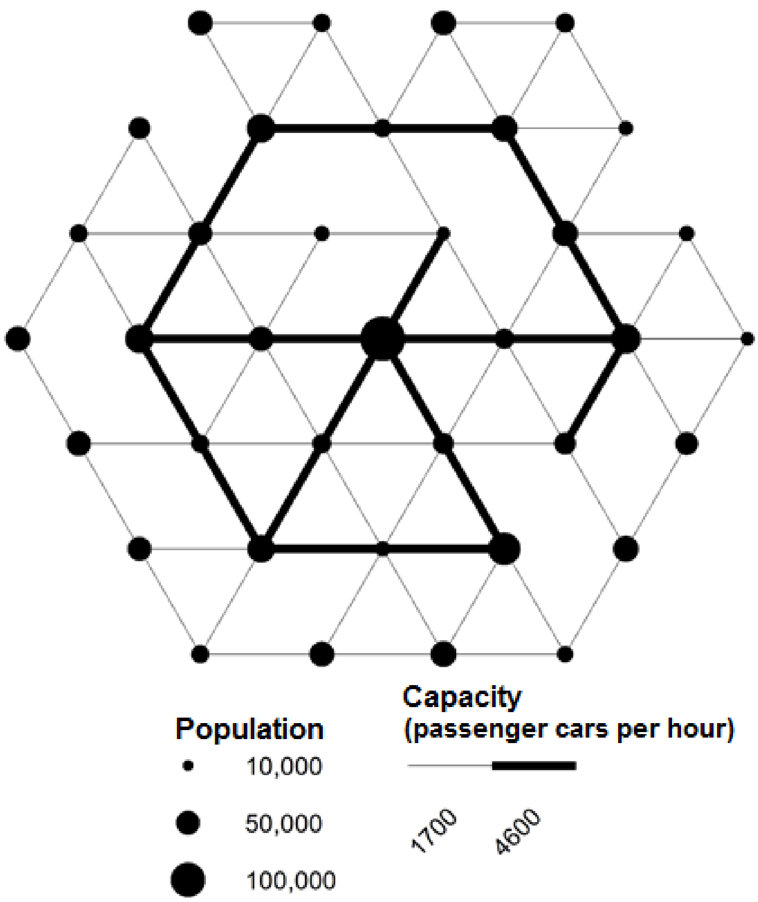

Figure 2.5. Hypothetical Road Network.

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

[4] For more detail about the network's design see page 220-221 of Scott et al., 2006.

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/hr to 50 km/hr to better represent typical speeds in an urban area. Link length was reduced from 50 km to 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:

$$T_{ij} = O_i \frac{W_j C_{ij}^{-\beta}}{\sum_{j=1}^{J} W_j C_{ij}^{-\beta}} \tag{4}$$

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 advantage of using hypothetical data (network and demand) based on a generalizable theory over a real-world case study is that the results of the demonstration can be used to highlight the NRI's application to any network.

The network is designed to be broadly representative; a chosen case study may possibly represent a unique scenario with results less likely to hold widely. This notion is reinforced by the network's developers, who state that "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).

2.3.3 Comparative Analysis of the NRI and V/C Ratio

To simulate the impact of a separated bike lane on each link of the road network, link capacity is reduced by 25% in the NRI Calculator. User equilibrium traffic assignment is chosen using the Bureau of Public Roads volume delay function and default values of alpha and beta – 0.15 and 4, respectively. A capacity reduction of 25% was chosen to replicate a reasonable approximation of the capacity required to facilitate a separated bike lane transition. A 25% reduction of lane capacity in a real-world example can be seen in the photographs shown in Figures 2.1 and 2.2.

Side by side, Table 2.1 records the results of the V/C ratio and NRI approaches. Figure 2.6 shows a scatterplot of each method's results. Cells in the table with negative values identify links where a 25% reduction in lane capacity for cars actually improves overall network travel times, a situation known as a Braess Paradox. Such instances occur when excess capacity on certain road links lead to suboptimal routing and bottlenecks elsewhere in the road network (Braess et al., 2005). Identifying such links is the best case scenario for a planner, where the results show that the addition of a separated bike lane for cyclists, also improves network travel times for drivers. Figures 2.7 and 2.8 map each link's V/C ratio and NRI value, respectively. Table 2.1 can be matched to these figures using Link ID, which is also shown next to each link on the maps.

Table 2.1. Comparison of V/C Ratios and NRI Values.

Link ID	*V/C Ratio*	*NRI (sec/ trip)*	*Link ID*	*V/C Ratio*	*NRI (sec/ trip)*	*Link ID*	*V/C Ratio*	*NRI (sec/ trip)*
1	0.68	0.12	**26**	0.34	-0.12	**51**	1.18	0.96
2	1.21	3.3	**27**	1.16	1.68	**52**	1.65	10.2
3	1.58	12.96	**28**	1.04	3.06	**53**	0.87	0.54
4	1.29	8.58	**29**	1.13	1.08	**54**	0.24	-0.24
5	0.64	-0.12	**30**	0.93	0.72	**55**	1.48	3.54
6	1.79	10.14	**31**	1.09	1.38	**56**	0.70	-0.12
7	1.03	0.36	**32**	1.50	2.22	**57**	1.50	4.08
8	0.92	0.36	**33**	0.84	-0.06	**58**	1.26	3
9	1.7	7.5	**34**	1.12	2.04	**59**	0.86	0.42
10	1.77	7.02	**35**	1.56	4.38	**60**	0.98	0.48
11	0.77	0.66	**36**	0.77	0.6	**61**	0.64	-0.12
12	0.63	0.12	**37**	0.34	-0.18	**62**	1.12	2.7
13	1.12	0.96	**38**	1.08	1.98	**63**	1.05	2.88
14	1.12	1.86	**39**	0.99	2.04	**64**	0.38	0.12
15	1.14	1.2	**40**	1.01	0.18	**65**	0.60	0.24
16	1.60	6.9	**41**	0.97	1.56	**66**	1.50	3.72
17	0.95	1.8	**42**	1.49	3.18	**67**	1.75	31.26
18	0.73	-0.12	**43**	0.78	0.66	**68**	2.06	12.54
19	0.80	0.3	**44**	1.17	0.84	**69**	1.20	6.12
20	1.83	6.12	**45**	0.92	0.66	**70**	1.30	1.86
21	0.74	0.18	**46**	0.89	1.2	**71**	1.36	3.42
22	1.55	4.56	**47**	0.99	0.36	**72**	1.10	1.68
23	1.66	1.5	**48**	1.28	1.92	**73**	1.21	1.26
24	1.27	2.04	**49**	1.27	2.16	**74**	0.61	-0.12
25	1.17	5.34	**50**	1.36	3.42			

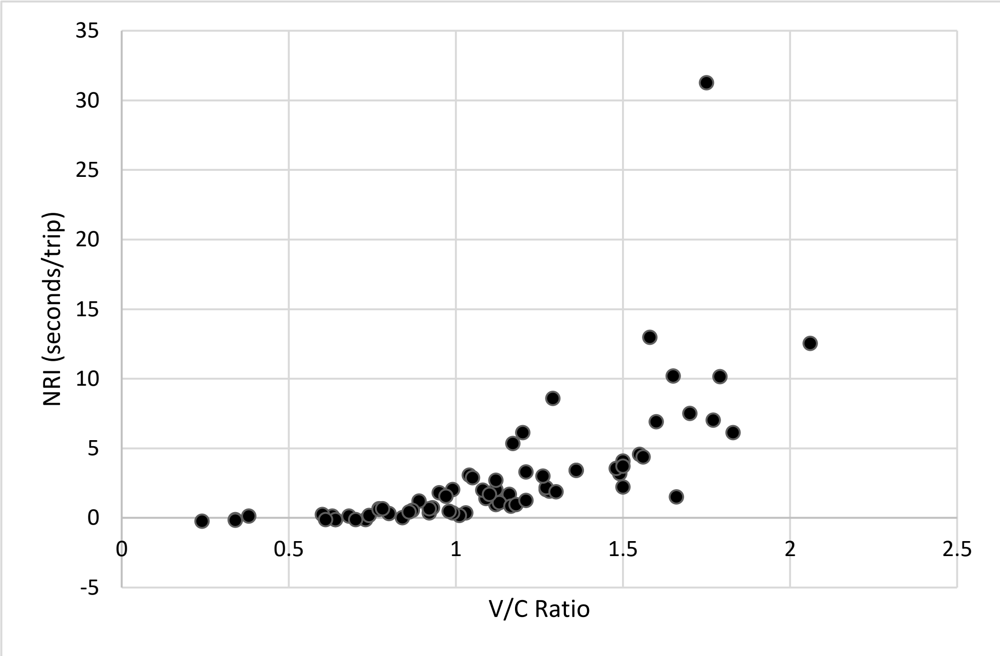

Figure 2.6. Relationship between the NRI and the V/C Ratio.

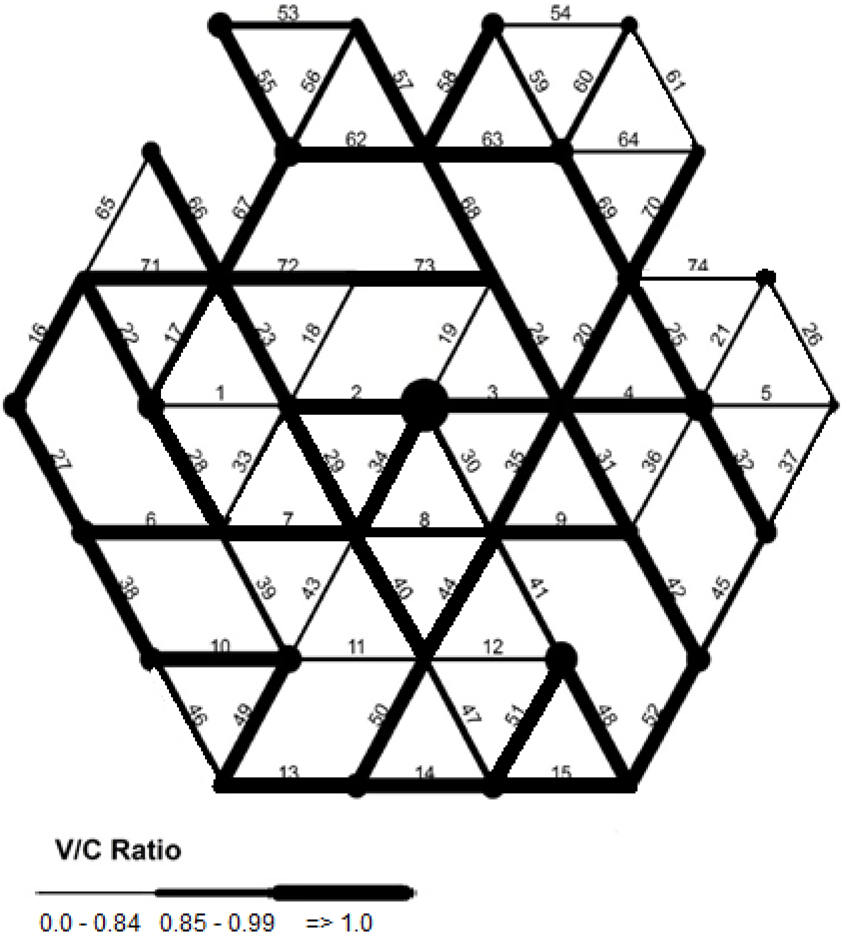

Figure 2.7. Map of V/C Ratios.

By calculating a V/C ratio for each link, 26% or 19 of 74 links result in a ratio of less than 0.85. These 19 links can be categorized as currently experiencing “good” LOS, illustrated in Figure 2.7 by thin black lines. By evaluating road links in this manner, a planner may consider each of these “good” LOS links a potentially suitable location for a separated bike lane. The other 55 links have ratios that exceed 0.85, shown in Figure 2.7 by thick black lines. If the possibility of negatively impacting car traffic along these roads factors into a planner’s decision to build a separated bike lane, many of the corridors in this network would be eliminated based on the V/C ratio. Finding many high V/C ratios on a network is likely not uncommon for planners in the real world. City networks are often congested, especially during peak periods. Planners faced with congested urban roads with V/C ratios exceeding 0.85 may conclude that they are without suitable options for siting a separated bike lane lest they further increase potential traffic delays on those corridors. The NRI approach, the results of which are mapped in Figure 2.8, and discussed in the following paragraphs, opens the network to greater opportunity, treating traffic as fluid and the road network as a system.

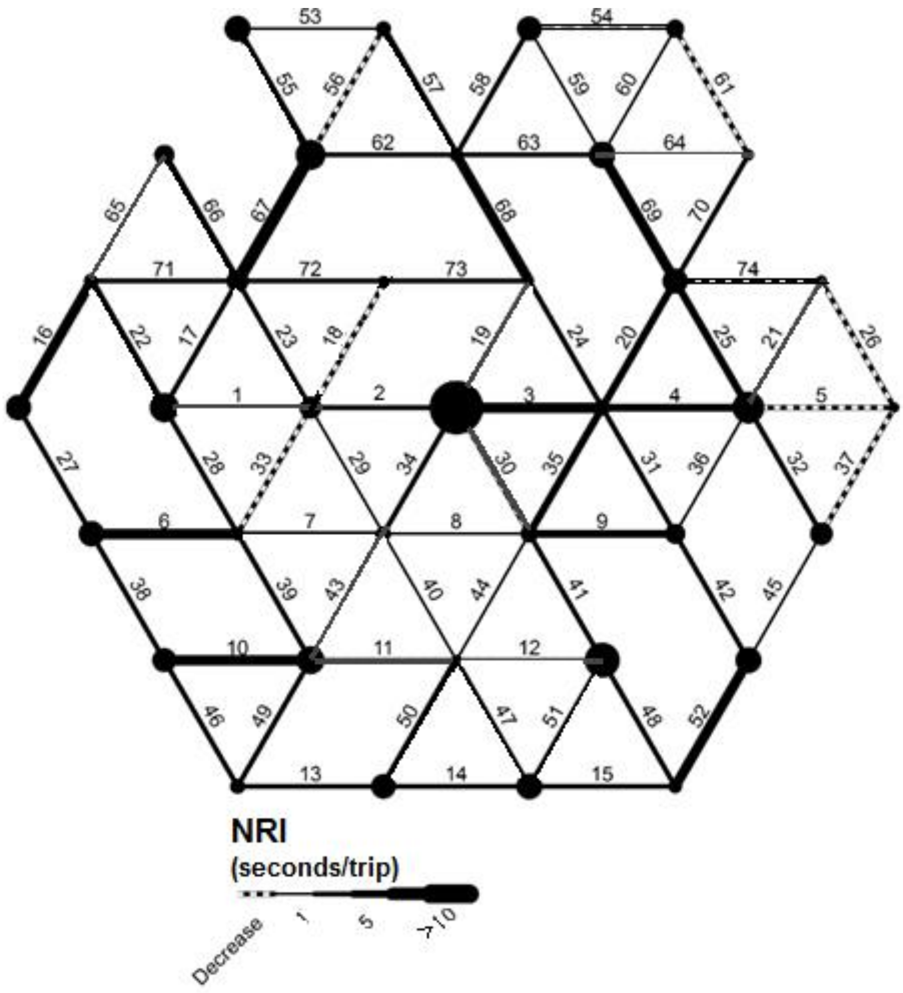

Figure 2.8. Map of NRI Values.

By using the NRI as an evaluation method, nearly half of the corridors, 39% or 29 of 74 links show less than a 1 second increase in travel time per trip when 25% of corridor capacity is reallocated to bikes. Moreover 12% or 9 of 74 links actually show improvement in network wide travel times for drivers when capacity is reduced – examples of Braess Paradoxes.

The NRI also identifies several links where a 25% reallocation of capacity results in a noticeable travel time increases despite V/C ratios less than 1.0. Links 41 and 46 both have ratios below 1.0; however, a 25% reduction of capacity on those links would increase travel time per trip by 1.56 and 1.2 seconds, respectively. Link 40 which has a V/C ratio of 1.01, a LOS that is considered "poor", results in an additional increase of only 0.18 seconds per trip when capacity is reallocated from cars to bikes. Another corridor where the application of each method's results differ greatly is Link 33. Although this link has a V/C ratio of nearly 0.84, a 25% reduction in capacity results in no change in system-wide travel time.

This comparative analysis highlights some of the differences and potential advantages of the NRI approach, especially the possibility of increasing the number of suitable corridors when planning the addition of a separated bike lane to a road network.

2.4 Findings

Using the NRI approach to evaluate potential impacts on car traffic, the following paragraphs discuss the results of corridor scenarios for siting a separated bike lane. For the demonstration, it is assumed that a planner aims to determine the least disruptive path for a separated bike lane that spans the network from the eastern-most node (connecting links 5, 26, and 37) to the western-most node (connecting links 16 and 27). To replicate a separated bike lane conversion, road capacity is reduced by 25% for all links forming potential separated bike paths (corridor scenarios). For each scenario, two traffic simulations are performed, one before (base case scenario) and one after the capacity reduction. The change in network travel time is calculating by subtracting the reduction scenario value from the base case scenario value. The potential path options are chosen in part based on the results of the full network scan shown in Figure 2.8. However, any number of potential corridors can be explored with this method and the corridor evaluations below are by no means exhaustive. The results of each corridor analysis is found in Table 2.2. Since Corridor 1 is the most innate choice, a direct east/west route connecting the two nodes across the network, it is used as the benchmark for evaluating other prospective corridors. Comparisons are mapped in Figure 2.9. Here the impact being assessed is car traffic, the metric is travel time, and since all links have the same distance, the number of links is a useful comparison from the perspective of cyclists.

Table 2.2 NRI Corridor Evaluation Results.

Corridor	Evaluation Purpose	Link Path	Number of Links	NRI (hrs)	NRI (sec/trip)
1	Shortest path # 1	5, 4, 3, 2, 1, 16, 22	7	32,969	0.57
2	Shortest path # 2	5, 36, 9, 8, 7, 6, 27	7	20,049	0.34
3	Shortest path # 3	5, 4, 24, 73, 72, 71, 16	7	21,224	0.37
4	Avoid Links 4, 3, 2; Braess Paradox Link 1	5, 36, 9, 8, 29, 1, 22, 16	8	19,898	0.34
5	Braess Paradox Links 30, 1	5, 36, 9, 30, 2, 1, 22, 16	8	22,607	0.40
6	Avoid Links 22, 16	5, 36, 9, 8, 29, 1, 28, 6, 27	9	24,866	0.43
7	Braess Paradox Links 30, 33, 1	5, 36, 9, 30, 34, 7, 33, 1, 22, 16	10	23,823	0.41

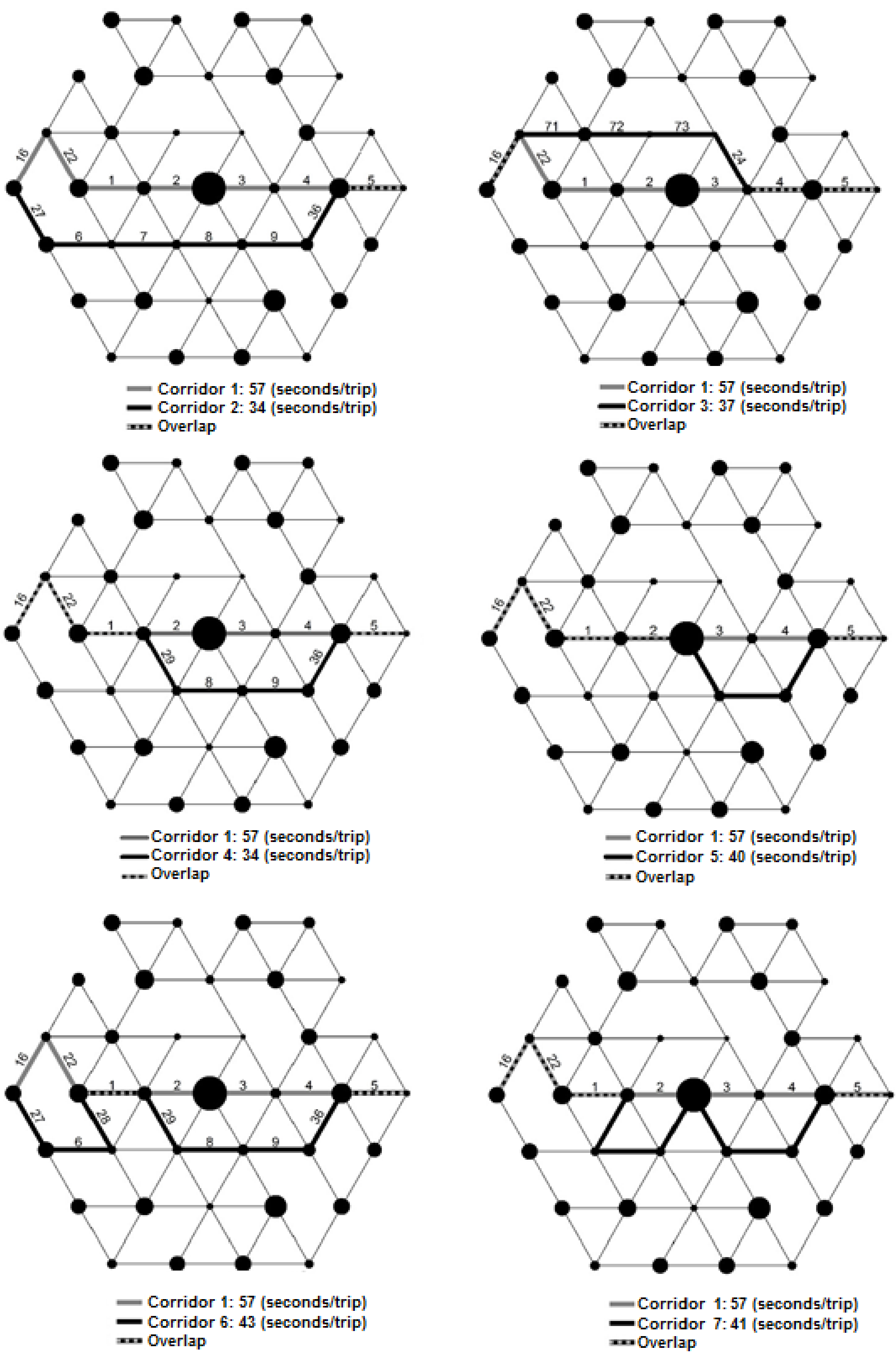

Figure 2.9. NRI Corridor Evaluation.

The first three potential corridors evaluated, Corridors 1, 2, and 3, are the shortest paths from east to west. Each of these corridors consist of seven connecting links spanning the network. The consequence of adding a separated bike lane to Corridor 1, intuitively the straightest most direct route east to west, is actually the highest cost route of all the potential options evaluated for their impacts on cars. Of the three shortest routes, none represents the actual least cost path for car traffic (as shown in Table 2.2, column 5, which records the total travel time increase each path creates in vehicle hours traveled or VHT). Corridor 2, however, is roughly equivalent to the least disruptive path (Corridor 4) and is one of the shortest paths for cyclists. Based on these results Corridor 2 may be the separated bike lane corridor of choice for the planner and represent 'the bicycle path of least resistance'.

Despite removing capacity on eight connecting road links rather than the seven required for the shortest path, Corridor 4 minimizes the total increase in travel time. The corridor detours slightly from the shortest path by one additional link. Detours like this have been found by previous research to be acceptable to cyclists who seek the greater safety afforded to them by separated bike lanes (Broach et al., 2012). Based solely on car travel times, this path may be the choice of a planner.

From the resulting NRI values of Corridors 5, 6 and 7, it appears that when more links are needed to form a separated bike lane (that is, as the length of a path increases), so too does travel time increase. This is intuitive, yet the fewest number of links is not necessarily the least disruptive choice either, illustrated by the comparison of Corridor 4's 8 link route to other shorter 7 link direct paths. Some additional prospective corridors were evaluated to test the network for potential travel time savings; none were fruitful.

Using the full scan from Figure 2.8 as a guide, Corridors 5 and 7 attempt to route the separated bike lane path through as many Braess Paradox links as possible. However, any gains from routing through such links were seemingly offset by the additional network capacity reallocated by the detours. As a result, detouring to capture Braess Paradox links should they be identified by a full network scan does not seem to be an optimal strategy when planning a separated bike lane route. Corridor 6 was tested as an alternate route to the western-most node, which is less connected and as a result has no direct path east to the rest of the road network. This choice is not a meaningful improvement over the three shortest paths, and is more disruptive to the network than any corridor save Corridor 1.

The NRI approach evaluates the potential travel time costs of routing a separated bike lane across a road network. The information generated can be used in conjunction with other cycling infrastructure considerations to help select the path that a separated bike lane will follow. Furthermore, a planner can convey to drivers the estimated cost of the separated bike lane on their travel through the communicable metric the normalized NRI value provides. At a minimum, this reassures drivers that their concerns are being taken into account in the planning process.

2.5 Conclusion

Planning a separated bike lane may be politically challenging. In Toronto, one separated bike lane was removed from the road network due to citizen complaints to the Mayor's Office. The primary concern of residents was that the reduction of capacity for cars increased travel times for drivers.

The Federal Highway Administration's "Separated Bike Lane and Planning Guide" (FHWA, 2015) advises a planner to evaluate a prospective corridor for bike lane suitability. Although no specific instruction is given, one common way a planner may evaluate potential locations is by calculating a V/C ratio to determine a corridor's level of service. An alternative approach is to view the road network as a system, and evaluate the traffic impact of a separated bike lane via change in system-wide travel time using the NRI. The analysis above has shown that the latter approach increases the number of potential suitable locations where a separated bike lane may be added.

Additionally, a planner can use the NRI to perform an impact assessment of prospective corridors and compare them based on travel time impacts for drivers. A planner can then use the evidence from this approach to communicate the minimally disruptive outcome to the general public. If the planner demonstrates such an impact on cars, fewer complaints may be made to politicians and more cycling infrastructure may be built by planners. It is the authors' hope that the NRI approach be adopted as common practice and lead to more robust urban cycling infrastructure worldwide. The next step is a real-world network application.

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Chapter 3 The Space Race: A Framework to Evaluate the Potential Travel-Time Impacts of Reallocating Road Space to Bicycle Facilities

3.1 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 Figure 3.1 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[5]. To facilitate the

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

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 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.

Figure 3.1 Bicycle Facility Types.

3.2 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 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., 2003), 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, 2014). 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.

3.3 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 Figure 3.2, 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[6] (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.

[6] The United States AASHTO "Guide for the Development of Bicycle Facilities, 4th Edition" (AASHTO, 2012) uses the same information as Figure 3.2 as a facility type guide, but in table format (see Table 2-3 of the guide).

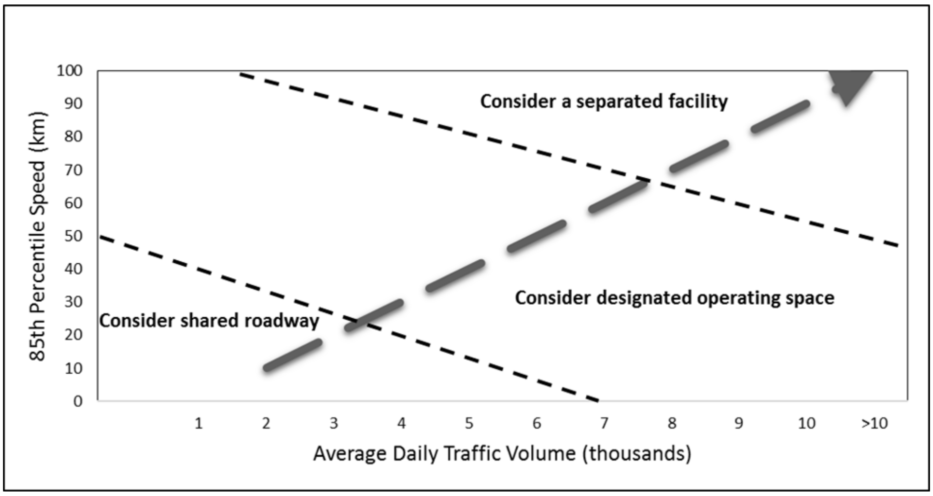

Figure 3.2 Nomogaph.

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 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.

3.4 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.

3.4.1 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:

$$NRI_a^r = c_a^r - c \tag{1}$$

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*).

$$c = \sum_{i \in I} t_i \, x_i \tag{2}$$

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.

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

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:

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

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.

3.4.2 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, Figure 3.3 presents a few different bicycle facility installations that can be placed along a local access road. Figure 3.4 illustrates some potential configurations that make adding several bicycle facility 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. Figure 3.3, 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, Figure 3.4, 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.

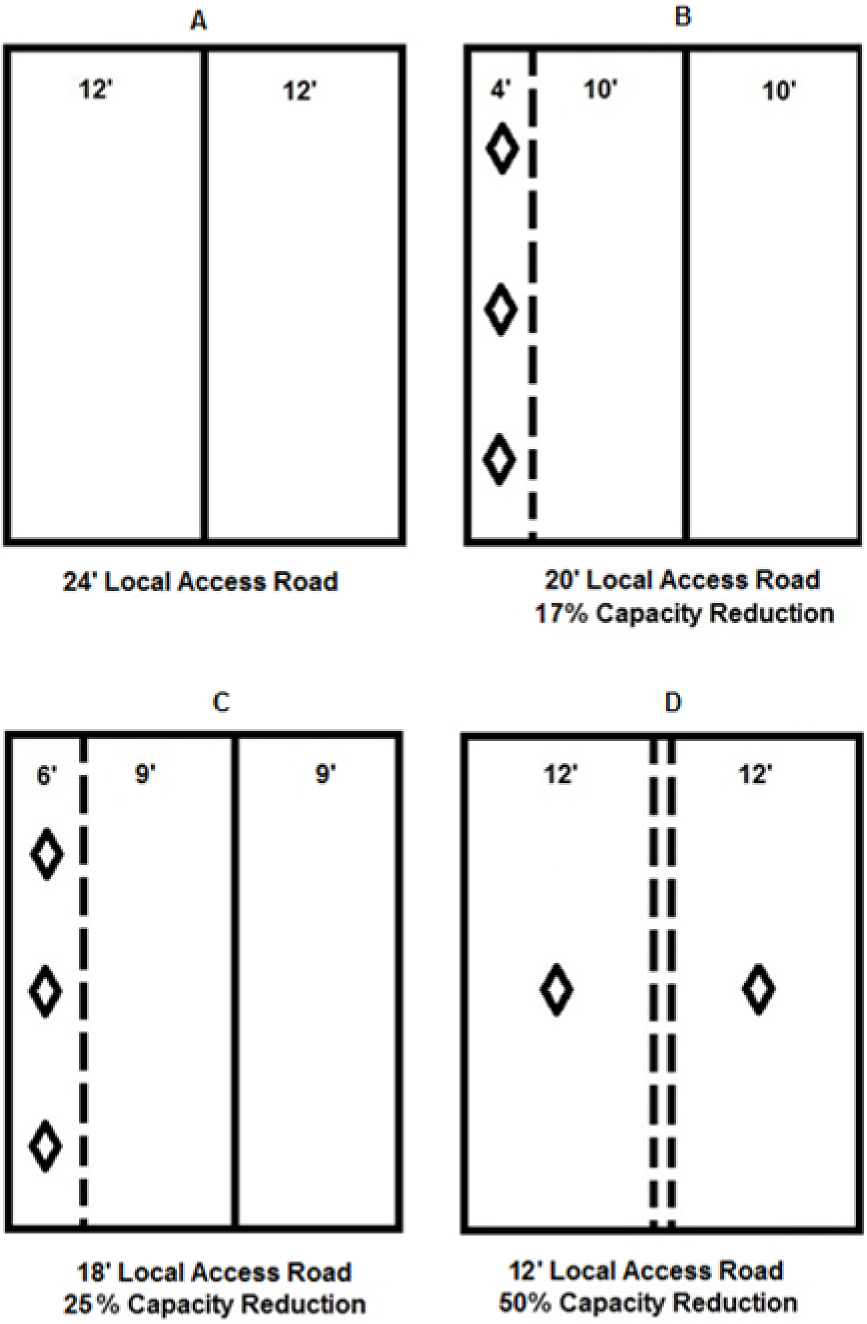

Figure 3.3 Facility Options (1 Lane Bidirectional).

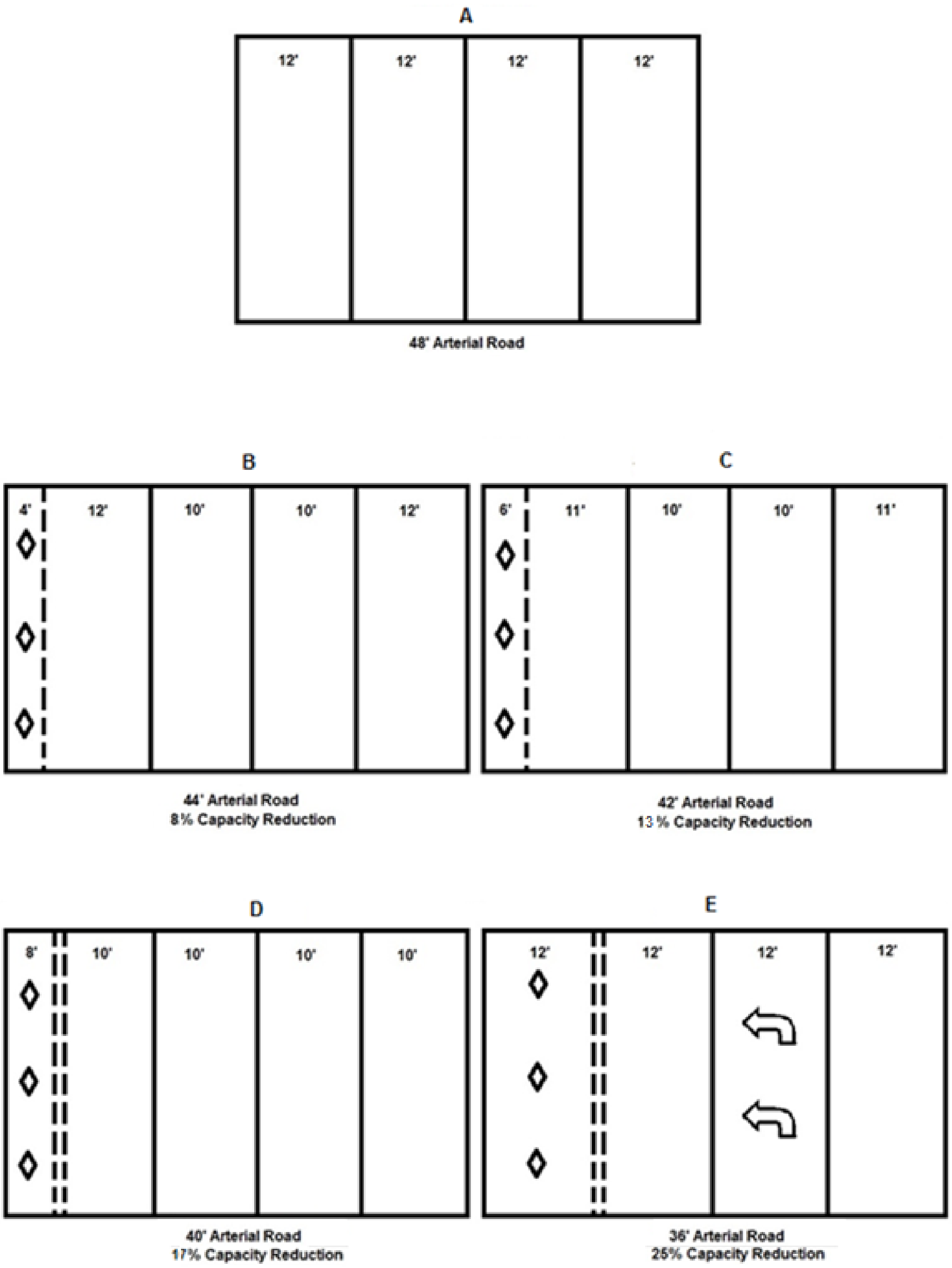

Figure 3.4 Facility Options (2 Lane Bidirectional).

3.4.3 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[7]. 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

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

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/hr to 50 km/hr to better represent typical speeds in an urban area. Link length was reduced from 50 km to 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 Figure 3.5.

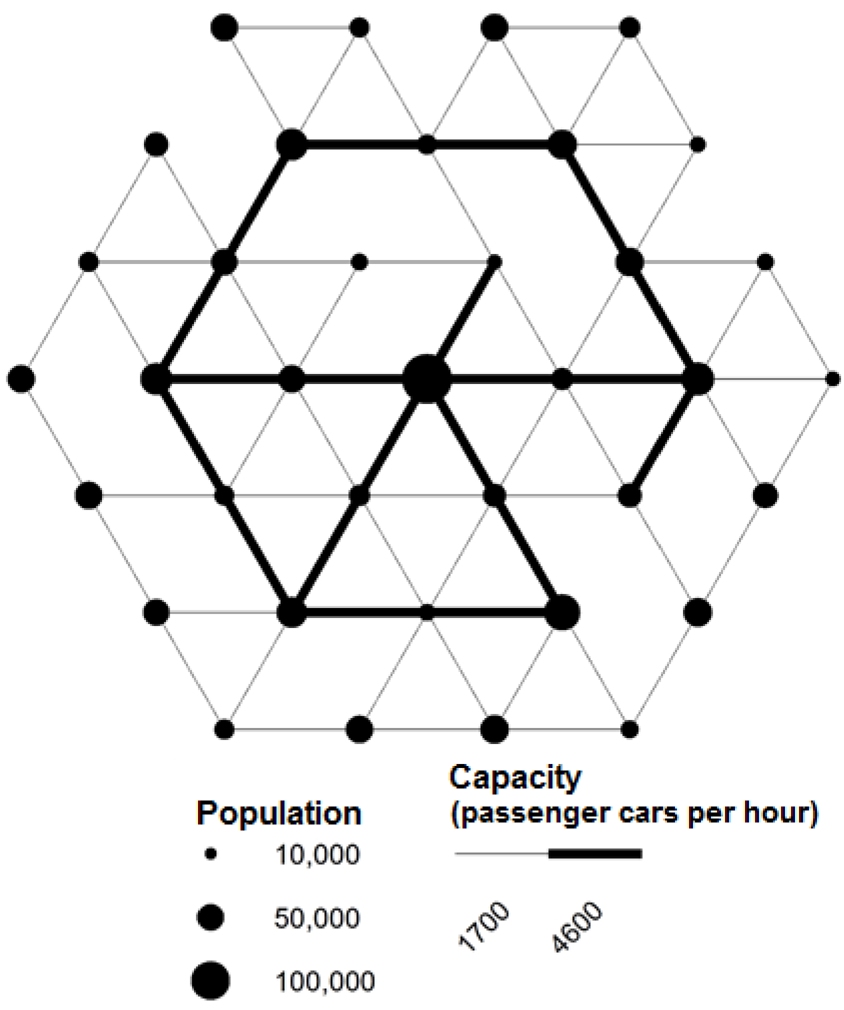

Figure 3.5 Theoretical Road Network.

3.5 Results and Discussion

3.5.1 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 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.

3.5.2 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 seconds. 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 3.1 and 3.2 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 3.1 and 3.2 show the costs of implementing bicycle facilities of different widths for each road link in the network using the NRI approach.

Table 3.1 NRI Values for Different Bicycle Facility Types (Local).

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 3.2 NRI for Different Bicycle Facility Types (Arterial).

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 Figure 3.6 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.

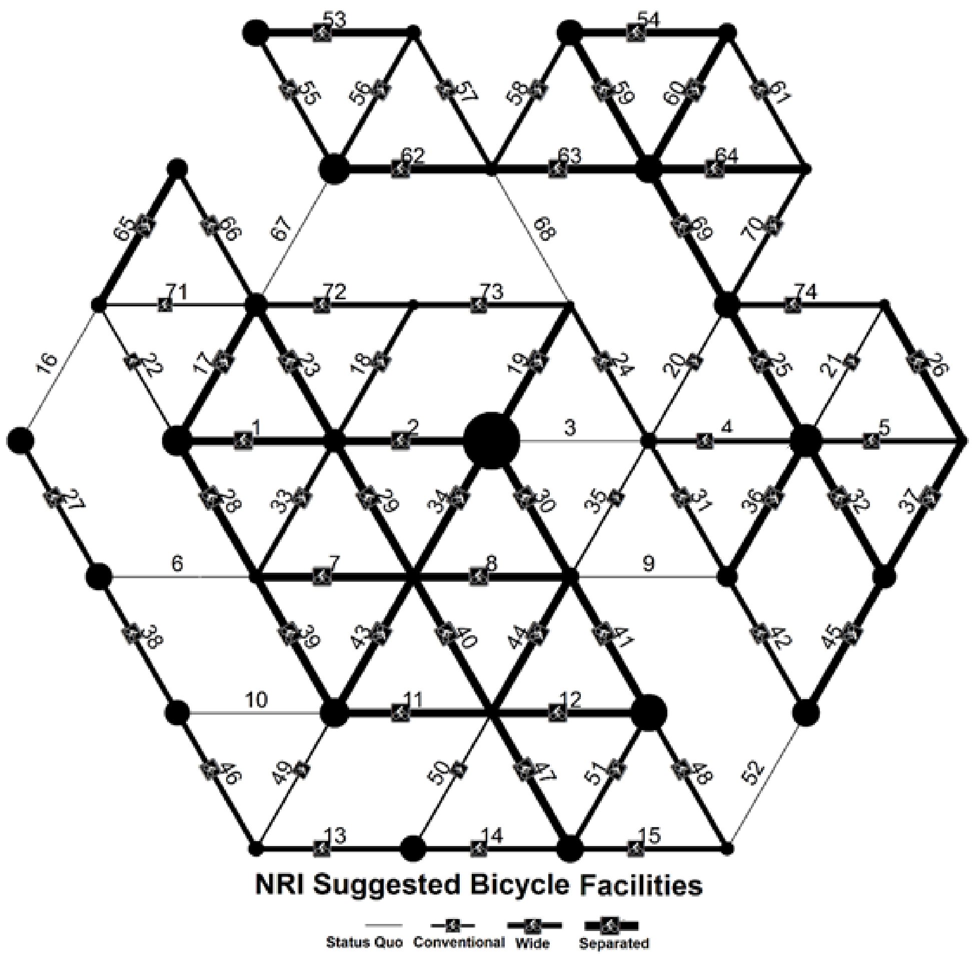

Figure 3.6 Map of NRI Suggested Facilities.

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 Figure 3.6, 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, employing a wide facility carries an estimated cost of less than 1 second per trip, but employing a bicycle boulevard increases that cost to 4 seconds 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.

3.5.3 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. Figure 3.6 in the previous subsection depicts the choices suggested by the NRI approach while Figure 3.7 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.

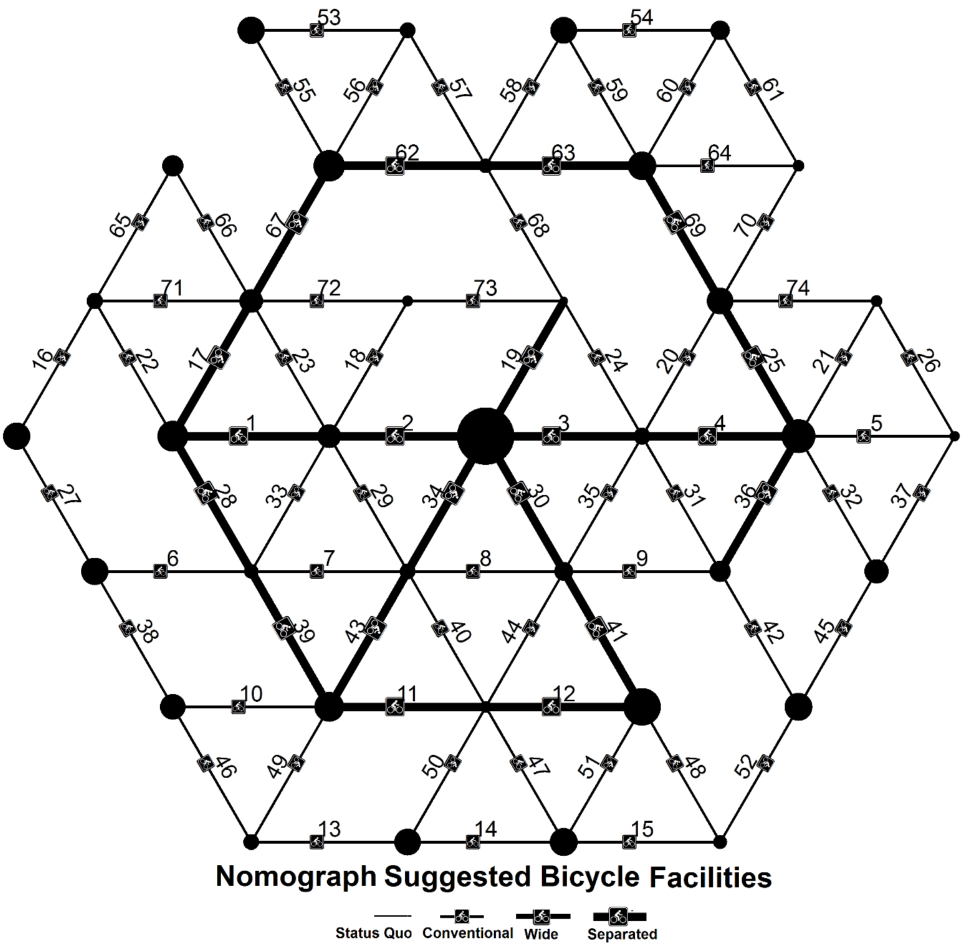

Figure 3.7. Map of Nomograph Suggested Facilities.

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 3.3. 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.

Table 3.3 Comparison of LOS Costs.

Evaluation	**NRI Approach**	**Nomograph Approach**
Travel time, complete network	181,397,334 min	181,397,334 min
Travel time, 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

3.6 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.

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Chapter 4 Identifying 'Sensible Locations' for Separated Bike Lanes on a Congested Urban Road Network: A Toronto Case Study

4.1 Introduction

> "My number one priority is tackling traffic and transit congestion. Adding separated bike lanes in sensible locations will give cyclists more alternatives to get around the city quickly and more safely."
>
> Toronto Mayor John Tory (Tory, 2014)

In the minds of the drivers commuting across congested urban road networks every weekday, 'sensible locations' to remove capacity from their preferred routes likely do not exist. At the same time, installing a separated bike lane on a roadway often requires a full lane of capacity to implement, physically separating cyclists traveling in both directions from other road traffic (see Figure 4.1). As a result, driver concerns over increasing urban travel times and the development of low-stress cycling networks are frequently at odds, a conflict which has fostered political challenges to cycling plans across North America (FHWA, 2015, p. 47). Recognition that those challenges exist has lead the Federal Highway Administration of the United States to urge planners to incorporate road capacity evaluations as part of their overall separated bike lane plans (ibid). However, despite this recognition, a useful framework to evaluate the impact of reallocating road capacity to bikes has yet to emerge from the planning guidelines.

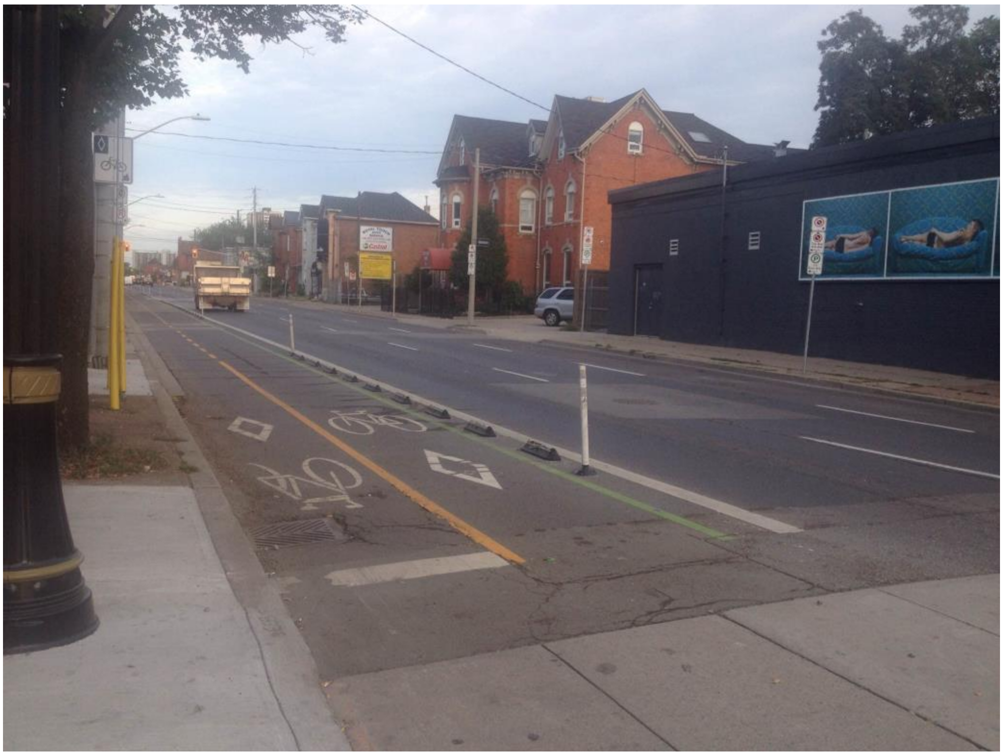

Figure 4.1 Separated Bike Lane, Cannon Street.

When current Mayor of Toronto, John Tory, precedes his commitment to separated bike lanes by stating that his first priority is tackling traffic congestion, we know that in Toronto, like many North American municipalities, driver concerns will play a role in his support of those facilities. For politicians, drivers make up the majority of their constituents, and therefore driver concerns often can define what is considered ‘sensible’ when public resources are allocated to bikes.

To assist a planning professional working within an environment of political constraint, we propose a new addition to cycling planning: a capacity evaluation that measures the potential travel time cost of a separated bike lane. This approach, borrowed from the literature concerning critical link analysis, is known as the Network Robustness Index or NRI, a method first developed by Scott et al. (2006). The NRI approach uses TransCAD®, a transportation GIS, and a Caliper Script® toolkit to measure the impact on vehicular travel time attributed to reducing a road's capacity. Using traffic simulations, the tool first calculates travel time for a network at full road capacity, then recalculates a new travel time after some or all of the capacity from a link has been removed. The process is then repeated by the Caliper Script® toolkit, again and again, until a capacity loss cost estimate is produced for each link in the road network (the method and the toolkit are described in detail in Section 4.2).

In the past, a variation of the NRI has been used in planning to prioritize highway construction projects in Vermont (Novak et al., 2012). However, this approach has not yet been directed towards cycling plans as part of a real-world case study. Fortunately though, because installing a separated bike lane is theoretically and operationally similar to removing a lane of capacity for motor vehicle traffic, the NRI approach may be used to measure the potential travel time impact of a separated bike lane. Once that cost is understood, planners can then evaluate which locations are 'sensible' should that concept's meaning be subject to the politics of driver concern.

It should be pointed out before continuing with this approach that the entire process of cycling planning is more complex than just accounting for a facility's impact on vehicular travel time. However, one must recognize that those impacts often do play a role in whether or not a facility is built. Therefore, by integrating the NRI approach into a larger cycling planning framework, a planner is provided more information to improve decision making and address driver concerns moving forward. That integration can be achieved in at least two ways.

First, a planner can begin by using the NRI toolkit to perform a full network scan, measuring the potential travel time impact a one-lane loss has on each road link to identify all the locations where costs are considered acceptable. In theory, since bicycle travel is only prohibited on highways, every road in the network could possibly act as the location of a cycling facility. This option presents one of many ways to narrow the entire network to fewer possibilities, especially if driver concerns have limited development in the past. After the full scan, further analysis of the remaining locations can take into account many other criteria in order to prioritize projects for installation.

Another potential fit is to begin a separated bike lane plan with an in-depth analysis of a target location, then afterwards measure the potential cost of installing a separated bike lane along that corridor. Using the NRI as a final step between planning and implementation allows for the initial selection process to be made based on cyclists' needs and other site specific attributes in absence of driver concerns, but still provides a planner the ability to address those possible challenges should they arise.

The aim of this study is to demonstrate both potential uses of the NRI as a technique to evaluate the travel time cost of installing separated bike lanes. First, the toolkit is used to conduct a full scan of the Toronto road network, identifying each link where a one-lane removal is free of negative travel time consequence. Conversely, this analysis also identifies locations where a one-lane loss does impact driver travel time. Both of these results are mapped for display. Second, the NRI approach is used to measure the potential cost of adding a separated bike lane across a target corridor, the Bloor-Danforth. Recently, part of this corridor was chosen by the City of Toronto for a separated bike lane pilot project in its *2016 Bike Master Plan* (City of Toronto, 2016a). To produce a cost estimate of the entire corridor, one lane of capacity is removed from each road link along it at once, rather than use the toolkit to iteratively remove capacity from each individual link. This aggregate corridor approach measures the cost of adding a separated bike lane to the whole stretch of road at once.

The remainder of this paper is structured as follows. Section 2 provides a brief background regarding the political challenges separated bike lane installations have created in Toronto, experiences that, in part, motivate our selection of the City as a case study. Section 3 describes some of the most recent cycling planning considerations with special focus on a common rule presented in planning guides to select bicycle facilities based on a road’s traffic speed and volume. In this section, a critical review of this rule illustrates the potential for a new approach to balance bicycle facility and traffic planning needs with the NRI. Section 4 provides a synopsis of the data and methods used in this study. This includes a description of the Toronto road network trip data, the NRI methodology, and the different road configurations possible following a one-lane loss on an arterial road link. Section 5 is separated into two subsections, each demonstrating a way to incorporate the NRI as a method of evaluation into the cycling planning process. Section 6 offers a brief summary and suggestions for future research.

4.2 Background

The *Deputy Mayor's Roundtable on Traffic Congestion* estimates that the average commute for Toronto office workers is 42 minutes and that on average Toronto commuters as a whole spend one additional day each week stuck in traffic (City of Toronto, 2014). Congested travel speeds in Toronto's urban core and the nearby surrounding suburbs can fall to as low as 40 km/h on average during peak periods (Sweet et al., 2015). Overall, the traffic congestion problem in the region is estimated to cost the regional economy at least $6 billion dollars (Canadian) each year (C.D. Howe Institute, 2013).

Frustration over traffic congestion has slowed the growth of Toronto's urban cycling network, where opposition to separated bike lanes has been particularly limiting. The City's current network consists of just 15.1 km of separated bike lanes (City of Toronto, 2016b). New York City, on the other hand, has installed 110 km of separated bike lanes – 22.5 km of which will be added in 2016 (New York City Department of Transportation, 2016). At times Toronto City Councilors have called separated bike lane plans "controversial" and characterized the City's past experience with implementing them a "disaster" (Grant, 2012). Perhaps the most clear political opposition to urban bike lanes came from former Toronto Mayor Rob Ford, who once stated that "Roads are built for buses, cars and trucks. Not for people on bikes" (Mahoney, 2010). In 2011, Ford successfully spearheaded the removal of a separated bike lane from downtown, citing driver complaints over perceived travel time increases along the corridor (Flack, 2011).

While former Mayor Ford embodies Toronto's political opposition to on-road bicycle facilities, one particular arterial corridor stands as the culmination of the political stagnation that opponents have created in the City over time. The Bloor-Danforth corridor has been discussed as a possible target for a separated bike lane in Toronto City Hall for an incredible 40 years (see Figure 4.2). The first studies began in 1976, then again in 1992, 2010, and 2013. Yet by the end of 2015, no definitive action had been taken (Davis, 2016). However, in 2016, a small section of the Bloor-Danforth corridor was selected as a separated bike lane pilot project (CBC, 2016). Should the results of this pilot prove 'sensible' to drivers and current Mayor, John Tory, the addition represents a tremendous opportunity to develop a low stress urban cycling network in Toronto. However, given that separated bike lanes have not survived political challenges in the past, every possible analysis of the potential impact a separated bike lane may have on corridor traffic is important to the project's future. The potential costs of adding a separated bike lane across the Bloor-Danforth corridor are explored in Section 5.2.

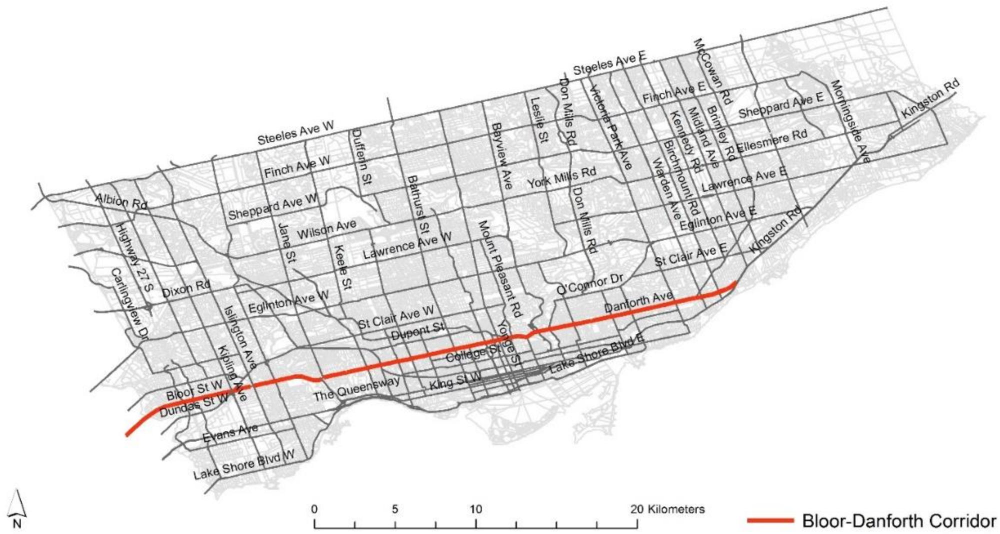

Figure 4.2 The Bloor-Danforth Corridor.

4.3 Literature Review

Most cycling planning frameworks have rightly been built with the needs of cyclists at the center. The latest techniques to aid a planner developing a cycling network use multi-criteria analysis to account for a facility's impact on cyclist's safety, demand, and accessibility (Lovelace et al., 2015; Larsen et al., 2013). Geographers have contributed to multi-criteria planning methods by adding location specific variables like ride topology, junction density, and network centrality; to the decision-making process (Rybarczyk and Wu, 2010; Milakis and Athanasopoulos, 2014). Despite the fact that these recent techniques attempt to account for every factor in order to generate a comprehensive cycling planning framework, none of them consider the role driver impacts can play as a barrier to implementation.

In its recent guide, the Federal Highway Administration recognizes that evaluating road capacity for all users should be a “top priority” for planners, one driven by the political challenges separated bike lanes have created in many cities in North America (FHWA, 2015, p. 47). However, the only specific direction that many authorities’ guidelines offer a planner relative to vehicle traffic is a simple ‘rule of thumb’ chart used to select the type of bicycle facility to employ. This chart, shown in Figure 4.3, appears in transport authority manuals in Canada, Denmark, Australia, and New Zealand, as well as in guides from agencies like Sustrans in the United Kingdom and CROW in the Netherlands (MTO, 2014, p. 30). The American Association of State Highway and Transportation Officials use similar rules for facility guidance, but present them in table rather than chart format (AASHTO, 2012, Table 2-3).

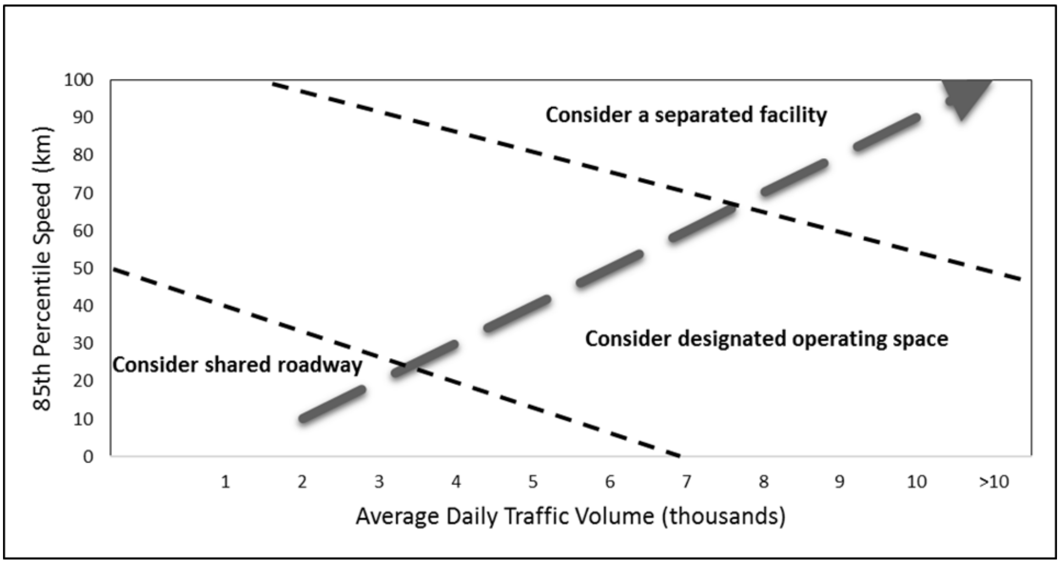

Figure 4.3 Nomograph.

The chart uses a road's 85th percentile speed and daily traffic volume to guide a planner to choose between varying degrees of bicycle facility width. Higher speeds and higher volumes dictate the provision of more space between cyclists and traffic, while lower order roads demand less separation. When cyclists' safety is the main objective, this rule makes perfect sense. As traffic speed and volume rise, more separation between traffic and cyclists should reduce the frequency and severity of accidents. Cyclists' safety should be paramount. However, this objective is often tempered by the goal of eliminating congestion and maintaining adequate traffic flow. Faced with these seemingly conflicting aims, a planner may purposely avoid reallocating significant capacity away from traffic on congested high volume roads regardless of the rule for fear of the potential travel time consequences.

However, what the original Network Robustness Index (NRI) study conducted by Scott et al. (2006) found was that road capacity loss does not necessarily result in equal consequences. Viewing a corridor in isolation, a significant removal of road capacity from a high volume link may appear counter-intuitive. However, this perspective does not account for the potential of the road network to act as a system. Traffic is fluid and can reroute onto additional roads when faced with a change in network capacity. This flexibility can either increase network travel time, should that rerouting lead to further congestion; create no impact, should capacity on parallel routes absorb additional volume; or in the case of a Braess Paradox, improve network travel time overall, should rerouting alleviate bottlenecks elsewhere (Braess et al., 2005). As a result of these potential outcomes, the NRI approach can be used to identify 'sensible locations' for separated bike lanes, even on roads where traffic volume is high.

The Scott et al. (2006) NRI study indexed results by listing them from greatest impact to least impact. Those authors were primarily concerned with a road's criticality in case of its failure due to extreme weather or a deliberate attack. The novelty of applying this approach to cycling planning stems from the value created by knowledge of the least impactful locations. Roads with enough connected capacity to allow for a low consequence or even consequence free capacity reduction can be used in this context for some purposeful advantage – installing separated bike lanes[8]. These low-cost locations are ones

[8] We use the NRI approach to identify roads where capacity can be reduced with little impact to aid planners in separated bike lane installations. However, this method can be used to help evaluate the impact of any reallocation of road capacity away from motor vehicles, including LRT, BRT, or street pedestrianization.

where the dual priorities of traffic flow and cyclist safety especially align. As a result, they may provide the best opportunity for easy implementation as the seeds of a planner's larger cycling network.

4.4 Data and Methods

4.4.1 Toronto Road Network and Trip Data

To conduct a NRI evaluation of a road network, an analyst must have access to a transportation GIS with the ability to perform traffic simulations. This study uses the latest TransCAD® software to conduct congested traffic simulations using a Wardrop (1952) User Equilibrium traffic assignment algorithm. Performing these simulations in the GIS requires two key inputs: a network file and an origin-destination (OD) matrix of flows between the traffic sources and sinks within the study area.

A network file of the Greater Toronto and Hamilton Area (GTHA) was obtained from Desktop Mapping Technologies Inc. (DMTI®). To the base network file, we added an attribute for design capacity based on the guidance of the Highway Capacity Manual 2000 (TRB, 2000). Additionally, centroids were added to the network file to correspond with the center points of the 5253 GTHA traffic analysis zones used by the OD matrix as units of geography.

The OD matrix itself was created from data obtained through the 2006 Transportation Tomorrow Survey (TTS), a travel diary survey of household travel patterns in the Greater Toronto and Hamilton Area. In the survey, 5% of the population within each GTHA zone is asked to provide information on each trip made by every person 11 years or older in the household for the previous day. Since a quarter of daily trips occur during the peak morning commute from 6 am to 9 am (Data Management Group, 2014), this study uses the respondents' trips over that peak period and uses a weighted average to create the one peak hour OD matrix used in the traffic simulations. Lastly, to account for commercial vehicles which are not included in the survey, a ratio of 1 truck to every 27 cars was added to the peak period OD matrix. This corresponds to the ratio of cars to trucks on the road found by Statistics Canada in a recent study (Statistics Canada, 2009).

4.4.2 NRI Methodology

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:

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

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*).

$$c = \sum_{i \in I} t_i \, x_i \tag{2}$$

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.

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

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, a toolkit called 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 as an aggregate travel time for all trips in the network. However, the NRI can be measured in other units of time and can also be normalized to better communicate the estimate to the general public. Normalization in this study is achieved by dividing the NRI value by the number of trips on the link where the capacity removal occurs (i.e., the road where the separated bike lane would be implemented). While the total change in travel time measured by the NRI is a network measure, this normalized value represents the potential cost on drivers at the epicenter of impact. Therefore, this normalized value likely represents the maximum cost of a capacity removal on driver travel time, should delay be assumed to be felt greatest at the location of the loss.

Mathematically, this expression of the normalized NRI is defined as:

$$nNRI_a^r = \frac{c_a^r - c}{d_a} \qquad (4)$$

where $nNRI_a^r$ is the normalized value of the NRI (change in system-wide travel time *per link trip*) for link a when its capacity is reduced by r, and d_a is the total travel demand on link a. 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.

4.4.3 Installing a Separated Bike Lane

The level of reduction set for removal in the NRI Calculator is based on the percentage of road capacity that equals a loss of one lane, or otherwise the amount needed to install a separated bike lane. Arterial roads within the Toronto road network with posted speeds of 60 km/h or less, range between 2 and 7 lanes in number. Reallocating a lane to a separated bike lane on a 2-lane arterial (one lane in each direction), would either convert that road to unidirectional or impact parking. These types of changes are not modeled in this study. Arterials with more than 2 lanes, however, can still maintain reduced flow in both directions. Assuming that each lane is set at a standard North American width of 12 feet or 3.7 meters (AASHTO, 2011), links that consist of seven lanes of traffic would require a 14% reduction to dedicate one of those seven lanes completely to bikes. To approximate the impact of installing a separated bike lane, 6-lane arterials are reduced by 17%, 5-lane by 20%, 4-lane by 25%, and 3-lane arterials are reduced by 33% in the NRI Calculator. When the number of lanes in each direction becomes uneven, the total impact of the capacity loss will be felt by drivers traveling in the direction of that loss. Figure 4.5 visualizes these changes to arterial roads with differing numbers of lanes.

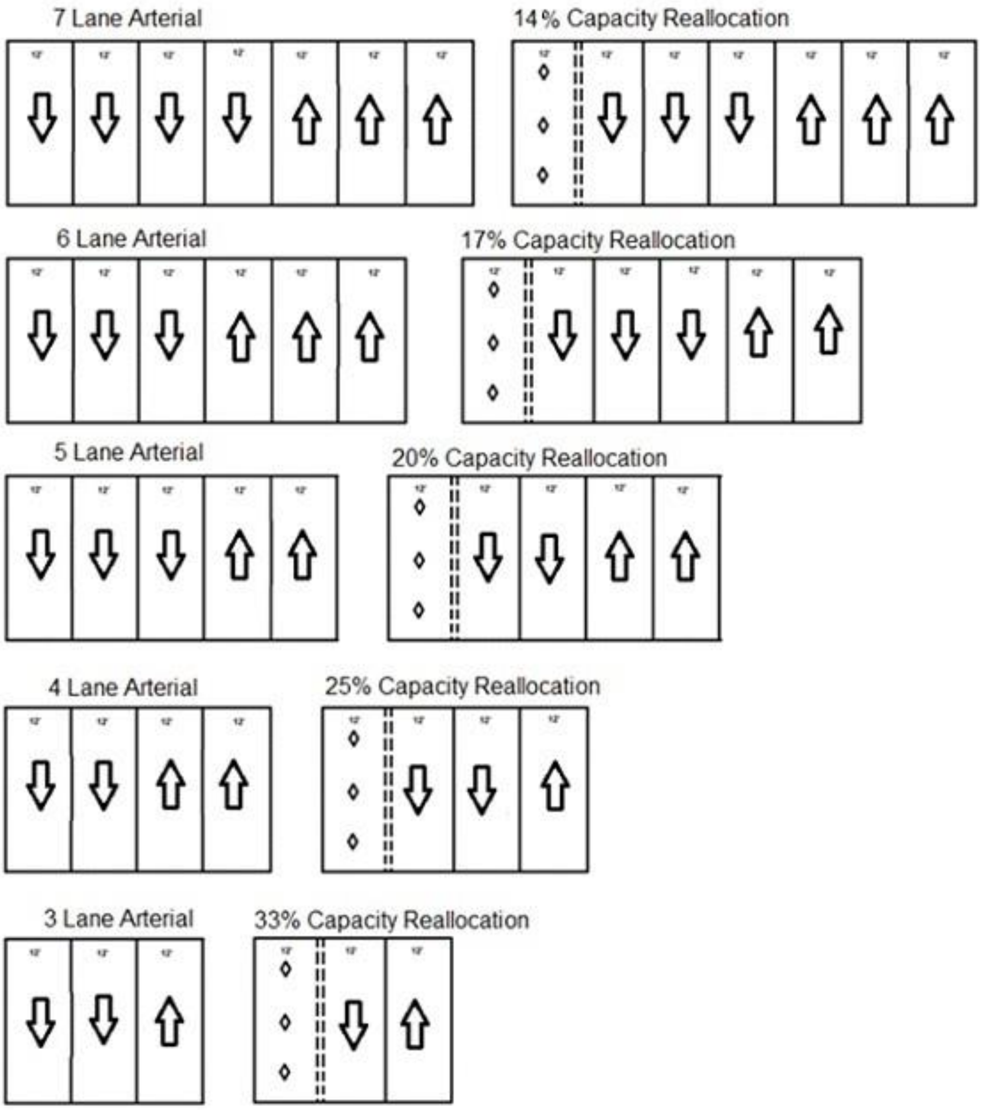

Figure 4.4. Arterial Road Conversions.

4.5 Results and Discussion

4.5.1 Full Network Scan of Separated Bike Lane Costs

The NRI Calculator is used to conduct a full network scan of the Toronto network. As aforementioned, Toronto's arterial network is made up of roads that range between 2 and 7 lanes. Two-lane roads are eliminated from the analysis. To measure the potential cost of removing one lane from each arterial type, several scans of the NRI Calculator at different levels of capacity loss (14%, 17%, 20%, 25% and 33%) were performed. The results of those scans are matched to arterials based on their number of lanes, creating an index of the estimated cost of adding a separated bike lane to each arterial in the Toronto road network.

The links where a separated bike lane has no travel time impact, or even improves network travel time – a Braess Paradox – are mapped in Figure 4.5. These are the ideal locations for a planner to uncover as they may be considered by both cyclists and drivers as 'sensible locations' for a separated bike lane. Figure 4.6 maps the road links where a one-lane loss of capacity does impact travel time. Some of these areas too, may be considered 'sensible' by drivers and cyclists, but at this time, the cost Toronto drivers are willing to accept is not known to us. Most of these costs are small and may very well be acceptable. By separating the Toronto road network into a cost/no-cost dichotomy, the maps show the potential to create a cycling network that in many places offers little connectivity. Indeed, many no-cost links are adjacent to increased-cost links. If a particular cost threshold was known to a planner, however, much greater connectivity would likely be generated. For the purpose of this demonstration, a strict separation of no cost and very costly links serves to highlight the information produced by the full scan.

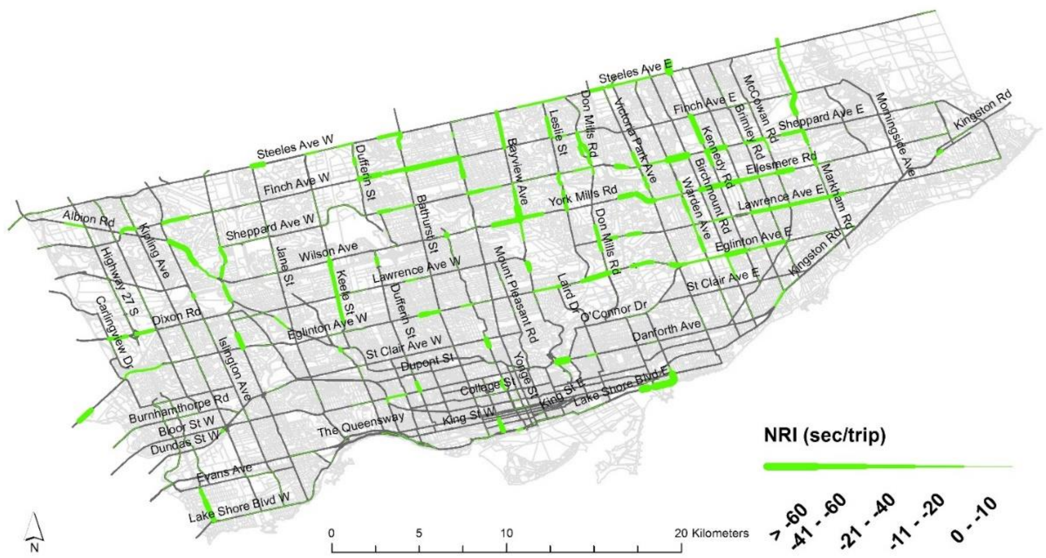

Figure 4.5 No Cost Links.

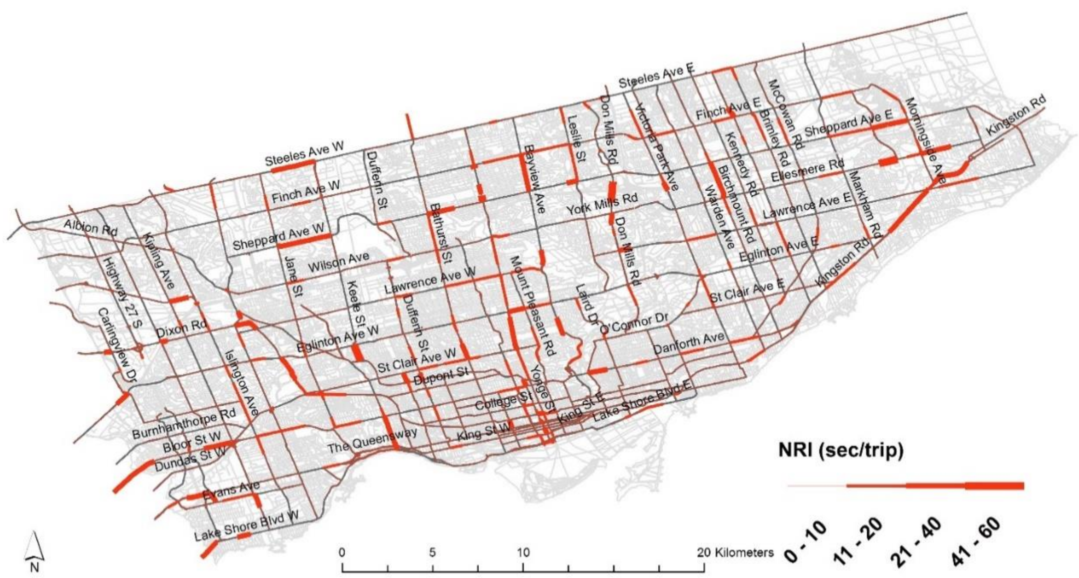

Figure 4.6 Cost Links.

In addition to the mapped results, Table 4.1 presents the top 10 locations where separated bike lane costs are found to be the lowest. In Table 4.2, we present the top 10 locations where costs are measured to be highest. In all, a total of 1504 arterial road links were evaluated by the NRI Calculator scans.

Table 4.1 Top 10 Most Cost Links.

Location (street - cross street)	Cars Impacted	NRI (sec/trip)
Lakeshore Blvd E - Woodbine Ave	1568	-108
Sheppard Ave E - Warden Ave	1980	-108
Danforth Ave - Broadview Ave	2958	-76
Bayview Ave - York Mills Rd	2314	-90
Ellesmere Rd - Birchmount Rd	2252	-78
Steeles Ave W - Jane St	1303	-76
Kennedy Rd - Finch Ave E	1571	-76
York Mills Rd - Bayview Ave	2449	-76
Albion Rd - Islington Ave	2422	-73
Finch Ave W - Yonge St	3323	-71

Table 4.2 Top 10 Least Cost Links.

Location (street - cross street)	Cars Impacted	NRI (sec/trip)
Bayview Ave - Lawrence Ave W	797	67
Ellesmere Rd - Neilson Rd	729	57
Sheppard Ave W - Yonge St	4364	53
Don Mills Rd - York Mills Rd	1741	50
Keele St - Eglinton Ave W	1079	47
Eglinton Ave W - Mount Pleasant Rd	3309	39
The East Mall - Evans Ave	961	37
Kingston Rd - Eglinton Ave E	3524	36
Dixon Rd - Martin Grove Rd	1711	35
Kingston Rd - Lawrence Ave E	3543	34

4.5.2 NRI Evaluation of Bloor Danforth

In addition to the full network scan, the NRI approach is also used to measure the cost of adding a separated bike lane along the span of the entire Bloor-Danforth corridor (shown in Figure 4.2). For this evaluation, the Calculator is not used as the results of the scan are estimates of individual link costs, and therefore, do not possess additive properties.

Most of the Bloor-Danforth corridor consists of 4 lanes of traffic, 2 lanes in each direction. To measure the potential travel time cost of adding a separated bike lane to the entire corridor we reduce capacity across the Bloor-Danforth on each 4 lane stretch by 25% of the total road capacity. The estimated cost of that reallocation is presented in Table 4.3.

Table 4.3 Cost Estimate of the Bloor-Danforth.

Bloor-Danforth Cost Evaluation	**Total**	**Unit**
Total Toronto Network Peak Travel Time	119,240	hours
Bloor-Danforth NRI Estimated Cost	56	hours
Normalized NRI	3-5	sec/trip
Bloor-Danforth Peak Volume	114,560	vehicles

The total estimated cost of installing a separated bike lane is small, just 3-

5 seconds per trip. The range in travel time impact depends on which direction of traffic flow the separated bike lane is added to along the corridor. However, depending on direction, the cost of the installation impacts between 38 and 76 thousand Toronto drivers during the peak period. As a result, the non-normalized NRI value is quite substantial – 56 hours. This information can be used to begin a dialog with those drivers, conveying to them a data-driven estimate of the potential impact on their commutes. Should that cost be acceptable, the consultation may disarm concerns that later could lead to the installation's removal.

4.6 Conclusion

Building separated bike lanes in Toronto has been a challenge for decades, one shared by many municipalities across North America. To overcome these challenges, driver concerns must be addressed with a communicable data-driven cost metric. A means to achieve this is to use the NRI approach either as a full scan or as a targeted corridor cost evaluation.

The above study demonstrates each approach to integrating the NRI into cycling planning, illustrating the valuable information the results may potentially provide. A planner can use the NRI to identify every potential location for a separated bike lane and address potential concerns of travel time increases on a targeted corridor. In many cases, the travel time impacts following an installation may be relatively small. Once known, these cost estimates can be used to address and eliminate concern.

The NRI approach to estimating the cost of a separated bike lane still needs to be validated. If proven reasonable, these simulated estimates may supersede the need for a pilot project. In many ways, the approach fulfils a similar purpose of a trial lane, to evaluate impacts, except in this case through modelling rather than construction. This virtual approach provides several advantages over a real-world pilot, chief among them avoiding the initial cost of constructing a potentially temporary facility and the possible conflict and expense incurred should the pilot project be removed at a later time. These factors considered, ex-post observation will provide the most accurate evaluation of a facility, and while the NRI approach should provide a reasonable impact assessment, it still requires validation. This validation is one suggestion for future research.

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Chapter 5 Conclusions and Future Research

This thesis set out to build new cycling planning frameworks using the NRI approach to road capacity evaluation. The goal of this application is to help address driver concerns by evaluating the potential travel time cost that a bicycle facility may generate. These concerns have led to political challenges across North American municipalities, limiting the development of cycling networks in urban areas. This final chapter summarizes the main contributions to the literature.

5.1 Contributions

The research yields several contributions to planning practice. They are listed as follows:

1) The value of the NRI as a cycling planning tool compared to current practice

Throughout the dissertation, the system approach the NRI takes in evaluation has been shown to be superior in this context to other commonly used tools of transportation and cycling planning. The V/C ratio is the most common metric to identify traffic congestion (Dheenadayalu et al., 2004). In Chapter 2, the NRI is compared against the V/C ratio as a means of choosing which link to install a separated bike lane. The V/C ratio views a road link's level of service in isolation with no possibility to examine the coping capacity of the road network as a system. The NRI on the other hand accounts for network robustness in its evaluation of capacity loss, identifying which losses can be absorbed by the system and which cannot. As a result, when directly compared using the hypothetical network, the NRI identifies 50% more road links that can accept a one lane reallocation from vehicles to bikes with minimal disruption.

In Chapter 3, the NRI is again directly compared against a tool in current cycling planning practice: the nomograph. The nomograph is a commonly used chart that guides planners' choice of bicycle facility design based on traffic speeds and volumes (MTO, 2014). This may directly contradict congestion metrics like the V/C ratio as sufficient capacity is necessary to move high volumes of traffic. However, as Chapter 2 highlighted, the V/C ratio is not the best approach to identifying the least disruptive location for a bicycle facility. To overcome the limitations of both tools, the NRI approach can be used in a sensitivity analysis framework to measure the potential impact of different bicycle facility types. The results of that framework's analysis can then be used to create a cycling network that is robust, but less disruptive than the one that following the nomograph suggests. The NRI approach to building a cycling network this way was shown in application to the hypothetical network in

Chapter 3 to reduce the potential travel time costs of building a complete urban cycling network on drivers by one full minute per trip.

Moreover, in each Chapter the NRI approach uncovers road capacity that may result in a Braess Paradox after a bicycle facility is installed. A Braess Paradox occurs when a network capacity loss results in a net improvement in network function, in this case improved travel time. These phenomena cannot be uncovered by viewing links in isolation via the calculation of a link's V/C ratio and the nomograph offers no insight. However, these links are likely extremely important to cycling planning as the identify location where the addition of a bicycle facility aids both drivers and cyclists alike – the easiest path to implementation.

2) The value of conducting a full network scan of bicycle facility costs with the NRI

A full network scan of travel time costs can be conducted using the NRI Calculator to automate calculating the cost of reduced capacity through the NRI approach. This full scan of travel time impacts can be set at any level of capacity reduction. In Chapters 2 and 4, it was used to identify all the least disruptive locations for a separated bike lane – a facility that requires a one-lane reallocation to bikes. In Chapter 4, the full network scan uncovered every link in the Toronto road network that generated no increase in travel time for drivers.

These locations are likely the easiest for a planner to implement in the

sometimes hostile Toronto cycling environment, as they can be more easily sold to concerned drivers.

In Chapter 3, the NRI Calculator was used in a sensitivity analysis to identify the types of bicycle facilities that created the least travel time impact. In theory, since bicycle travel is only prohibited on highways, every road in the network could possibly act as the location of a cycling facility.

The full scan presents one of many ways to narrow the entire network to fewer possibilities either for facility location or type, especially if driver concerns have limited development in the past. After the full scan, further analysis of the remaining locations can take into account many other criteria in order to prioritize projects for installation. However, implementing the full scan as a complete blueprint did exhibit improvement over other planning methods as discussed in the subsection above.

3) The value of the NRI as a cost measurement tool in cycling planning

In addition to using the NRI to identify the least disruptive locations and facility type, the NRI can be integrated into cycling planning as a tool to measure the costs of a targeted corridor. If other parallel routes are presented as possible options, these measurements can be used to compare bicycle facility routes. This route comparison was undertaken in Chapter 2, where the NRI approach was used to evaluate several possible paths for a separated bike lane across a hypothetical road network. Using the full scan as a blueprint to avoid the critical links that greatly increased travel time, the results of the Chapter 2 analysis showed that the most direct path for a separated bike lane is not necessarily the least disruptive for drivers. That connections for cyclists throughout the network can be made without compromising driver travel times if slight detours are incorporated into the route.

In Chapter 4, the NRI approach was used to measure the cost of installing a separated bike lane on Toronto's Bloor-Danforth corridor. This arterial had been discussed as a potential site for a separated bike lane for 40 years in Council (Davis, 2016). The results show that the travel time impact of the installation would be minimal, although many drivers would be affected by the loss. Using the NRI as a measurement tool may alleviate some of the political challenge to the route.

4) The value of the NRI as a communicable metric

The original NRI study conducted by Scott et al. (2006) used the output of the NRI Calculator to index results in total network vehicle hours traveled (VHT). Chapters 2 and 3 normalized the value of the NRI to a change in system-wide travel time per trip. In Chapter 4, the values were normalized to the change in system-wide travel time per trip along the affected road link. Additionally, in each case, the NRI value is recalculated in minutes or seconds, not hours. This change from aggregate network VHT to a minutes or seconds per trip metric may allow a planner to more easily communicate the evaluated results to the general public as a driver may more intuitively grasp the potential impact of x number of seconds per trip rather than x network hours.

In Chapter 2, the range of impacts depending on the route chosen for a separated bike path costs drivers a per trip travel time between 34 and 57 seconds. In Chapter 3, the network suggested by the NRI full scan approach costs travelers one full minute less than the nomograph approach. In Chapter 4, the addition of a separated bike lane to the Bloor-Danforth Corridor costs drivers on that link between 2 and 5 seconds. These impacts (which range between 2 seconds and 1 minute in each chapter) are intuitive to drivers, more easily grasped than total network VHT (which range between 54 and 32,969 network hours). This highlights the value of normalizing the NRI as trip-based metric, and its presentation in smaller units of time.

5.2 Future Considerations

It is important to recognize that the results of the NRI approach to cycling is based on simulation. Furthermore, the framework is driven by driver concerns over increased travel time. These concerns are just one of many criteria that must be accounted for in cycling planning, of which the concerns of the cyclists themselves should carry great weight. Future considerations, therefore, center on validation and integration of the model in and into planning practice.

1) Validation of the estimated cost of a bicycle facility by the NRI through observation

The NRI approach to estimating the cost of a separated bike lane still needs to be validated. If proven reasonable, these simulated estimates may supersede the need for a pilot project. In many ways, the approach fulfils a similar purpose of a trial lane, to evaluate impacts, except in this case through modelling rather than construction. This virtual approach provides several advantages over a real-world pilot, chief among them avoiding the initial cost of constructing a potentially temporary facility and the possible conflict and expense incurred should the pilot project be removed at a later time. These factors considered, ex-post observation will provide the most accurate evaluation of a facility, and while the NRI approach should provide a reasonable impact assessment, it still requires validation. This validation is one suggestion for future research.

2) Validation of the NRI's ability to address concern through public consultation

Can the application of Network Robustness Index results generate a behavioral shift in the "drivers versus cyclists' myth" and alleviate driver concern? The NRI results from real-world case studies (like that in Chapter 4) can be applied in a public setting to evaluate their ability to generate the acceptance of bicycle lane additions in congested urban centers. Survey data on driver attitudes can be collected towards a bicycle lane on a targeted route or an entire network can be collected before and after the NRI results are presented. Additionally, interviews can be conducted with transportation and planning experts to appraise the value of the tool in developing cycling networks in Canada's urban centers. This appraisal of the value of the NRI as a tool to overcome the political challenges driver concerns may create is a future consideration that may help usher its adoption into planning practice.

3) Integration of the NRI into a larger multi-criteria cycling planning framework

Again to reiterate what has been earlier stated, 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. The new frameworks best serve 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. Ways to integrate the NRI results into a larger multi-criteria planning process and the weight it should hold is another suggestion for future consideration.

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This reference list only refers to the sources cited in Chapter 1 (Introduction) and Chapter 5 (Conclusion). Other references are self-contained at the end of each chapter.

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