

Quantifying the Road Safety Benefits of Increased Bicycle Use in North America

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Words: 6248

Figures: 1

Tables: 4

Total: $6248+250*5=7498$

Key Words:

Bicycle use	Road Safety	Collision Prediction Models
Sustainable transportation	Vulnerable Road Users	Economics

Final Draft
May 10, 2010

Abstract

High automobile dependence in North America has placed significant social and economic burdens on our communities due to its associated high frequency and severity of road collisions. Alternatively, Europeans make greater use of sustainable transportation modes, and experience generally lower traffic fatalities per capita, with comparable socio-economic status. In this research, a comprehensive literature review reveals that increased sustainable transportation mode splits --- bicycling, walking and public transit - can lead to reduced traffic fatalities among bicyclists, pedestrians, and auto drivers/passengers. Moreover, a business case is proposed suggesting significant direct and indirect economic benefits of community bicycling programs. Last, community-based, macro-level Collision Prediction Models (CPMs) are discussed as a reliable empirical tool to quantify the road safety benefits of sustainable transportation systems. Existing and new CPMs are proposed to predict the overall collision reductions resulted from increased bicycle use, taking into account new variables related to bike-auto traffic mix, terrain, and bicycle infrastructure extracted from recent advances in GIS databanks. It is hoped that the success of these new models will facilitate economic justification for the necessary bicycle infrastructure investment programs towards accelerated community road safety improvements.

Résumé

La lourde dépendance des Nord-Américains à l'égard de l'automobile impose de lourds fardeaux sociaux et économiques à nos collectivités en raison de la fréquence élevée et de la gravité des collisions de la route. En revanche, les Européens font un plus grand usage des moyens de transport durables et enregistrent un moins grand nombre de victimes de la circulation par tête, moyennant une situation socioéconomique comparable. Dans le cadre de ce projet de recherche, une analyse détaillée de la documentation révèle que l'utilisation accrue des modes de transport durables (bicyclette, marche et transports en commun) peut se solder par une baisse du nombre de victimes de la route chez les cyclistes, les piétons et les automobilistes/passagers. De plus, une analyse de rentabilisation est proposée qui incite à croire que les programmes de cyclisme communautaire ont des retombées économiques directes et indirectes importantes. Enfin, les modèles de prévision des collisions (MPC) au niveau macro dans les collectivités sont analysés comme outils empiriques fiables permettant de quantifier les avantages pour la sécurité routière des réseaux de transport durables. Des MPC existants et nouveaux sont proposés pour prédire le taux global de diminution des collisions résultant d'une utilisation accrue de la bicyclette, en tenant compte de nouvelles variables se rapportant à l'amalgame des bicyclettes et des automobiles dans la circulation, de la topographie et des infrastructures cyclables extraites des progrès récents des banques de données SIG. On espère que le succès de ces nouveaux modèles contribuera à justifier sur le plan économique les programmes d'investissement nécessaires dans les infrastructures cyclables afin d'accélérer l'amélioration de la sécurité routière dans les collectivités.

1. INTRODUCTION

Road collisions are both a social and economic burden on societies worldwide. According to the 2004 World Health Organization report on road safety, injuries due to road crashes are the 11th leading cause of death in the world [1]. Projections indicate that road crashes will be the 3rd leading cause of death by 2020 unless there is new commitment to prevention [2]. In North America, more productive years of life are lost due to road collisions than any other cause [3].

High automobile dependence is of increasing concern today, as it not only increases fuel consumption, vehicle emissions, and congestion, but also brings significant risk to road users. It is generally accepted that a country's automobile dependence is proportional to its economic status. However, European countries despite being among the most affluent countries in the world,

proudly promote and use sustainable transportation - bicycling, walking and transit. Despite similar socio-economics, terrain, and climate to Europe, North America has experienced significantly less use of sustainable transportation modes. The fact that road safety records in Europe are much better than those across North America with its automobile dependence then comes as no surprise.

Considering travel time, utility, speed and energy use perspectives, bicycling is generally one of the most efficient modes of transport for trips less than 3 kilometres [4]. Across North America, approximately 30-40% of all trips are less than 3 kilometres in distance [5]. With the right conditions therefore, it may be possible significantly raise bicycle use in North America, at the 'cost' of reduced auto use. Reduced auto use has been tied directly to improved road safety. However, in order to support policies and other programs aimed at increasing bicycle use and more sustainable communities, quantifying the road safety benefits of increased bicycling is critical. Moreover, reliable empirical tools are needed that can proactively predict road safety economic benefits during community planning stages.

The threefold purpose of this paper is to

- Examine the relationship between bicycle use and road safety based on a comprehensive literature review;
- Present a business case of economic benefits in support of increased investment in bicycling infrastructure in our communities; and
- Present emerging research on how to empirically predict the road safety economic benefits of increased bicycle use in North American communities.

2. LITERATURE REVIEW

2.1 More Bicycle Use, Less Fatalities

It is intuitive that decreasing motor vehicles will reduce traffic collisions and fatalities, as the reverse has been proven true for decades. However there has been little direct research into this relationship. A sourcebook by Kenworthy and Laube [6] explores transportation data from 46 international cities. The data reveals that different transportation development philosophies (i.e. the degree of automobile dependence, transportation regulation and policies) significantly influence road safety levels. For example, journey to work data shows that US, Canadian, Australian, and developing Asian cities all have suffered decreasing use in public transportation between 1980-1990; whereas European and wealthy Asian cities have improved their already strong public transport mode split instead. Related traffic fatality data in this period reveals that those European and wealthy Asian cities with least automobile dependence boasted the lowest traffic fatality rates: 8.8/100,000 population (POP) for European cities and 6.6/100,000 POP for wealthy Asian cities in year 1990; conversely, although North American cities have highly developed road systems and strict regulations, they also have the highest fatality rates (14.6/100,000 POP in year 1990) in the world. This suggests that low automobile dependence correlated with high sustainable mode split, is at least statistically (if not causally) linked to improved road safety records.

Subsequently, Newman and Kenworthy [7] reported that the Metro Toronto region with 24% transit mode split experienced 6.5 traffic fatalities / 100,000 POP; less than half that of US cities. Cities such as Amsterdam with 5.8/100,000 POP traffic deaths and Copenhagen at 7.5/100,000 POP also have the highest rates of bicycle usage. Moreover, they sought to quantify the relationship between car ownership and traffic fatalities, as shown in Table 1. Although comparable in socio-economic status to some of the wealthiest communities in the world, most US cities have fared poorly in their ability to improve road safety. More importantly, these same wealthy US cities have also chosen to invest significantly less in their transit and bicycle systems.

Regions	% Difference in deaths compared to US cities	% Difference in car ownership compared to US cities
Australia	- 18%	- 40%
European Countries	- 40%	- 59%
Wealthy Asian Countries	- 55%	- 86%

Table 1- International Road Safety Patterns versus Car Ownership [7]

One study by Osberg and Stiles [8] discusses bicycle use and road safety in three cities: Boston, Paris and Amsterdam. Although these three cities were chosen for comparison because of their socio-economic similarities, they have significantly different levels of bicycle use due to historic differences in policies and culture related to bicycling. Boston, with the dubious reputation of being one of the worst cities for cyclists, rewrote its transportation planning rules to encourage the promotion of bicycling and walking. However, it was unsuccessful in shifting bicycle use to a higher mode share due to lack of sustained policy and infrastructure investment. Paris, boasting a good public transit system but still depending heavily on automobiles, did invest more than Boston in promoting bicycle use, and has had more success. Amsterdam has long been admired for its investment in well-integrated local and national supporting policies, budgets, and infrastructure programs on sustainable transportation modes. Not surprisingly, 27% to 50% of all trips are made by bicycle in Amsterdam, despite income levels rivalling those of Boston and Paris. On a national level, road safety records show a similar trend, with the Netherlands leading the way. Despite holding the highest bicycle fatality rate of the three with 1.8/100,000 population (0.6/100,000 for France, and 0.3/100,000 for the US), the Netherlands has the lowest total road fatality rate, at 5.8 deaths per 100,000 population (10.0/100,000 for France, and 8.8/100,000 for the US). Moreover, the Netherlands has a net rate of 4.0 vehicular fatalities per 100,000 population versus 9.4 and 8.5 for France and the US, respectively, adding to the mounting evidence that a shift towards bicycle use results in overall transportation safety improvement. While fatalities due to increased bicycle collisions would no doubt occur, the above data suggests that for every 1 additional bicycle-related deaths per 100,000 population due to increased bicycling, there would be 3 to 4.5 fewer vehicular-related deaths per 100,000 population due to reduced auto use. This would suggest that a reasonable risk trade-off between increased bicycle use and road safety improvement is possible.

How could Amsterdam have such high bicycle use and what was its effect on road safety? The literature suggests that Dutch authorities have had struggles with auto-overdependence, but chose to deal with them in a more proactive, sustained manner than many other governments. In response to an alarming rise in traffic fatalities between 1982 and 1987, the Dutch government launched a pilot project in Delft to reduce auto use and increase bicycle use. Integrated policies, measures, and funding were taken to provide the city with a complete network of bicycle routes and facilities. Road safety benefits became quickly apparent and have been 'sustained' at ever improving levels, prompting Dutch road authorities to coin the phrase 'Sustainable Road Safety'. This success prompted the Dutch government to push forward with what would soon be known as the Dutch Bicycle Master Plan (BMP). Its main objective was to reduce the number of road fatalities by 50% and injuries by 40% by the year 2010, as a means of contributing to solving traffic congestion problems and restricting the growth of cars [9]. Recent reports from the Dutch Road Safety Research Institute (SWOV) claim that the fatalities since year 2000 have decreased from 1166 to 750, a reduction of 36% [10]. The Dutch BMP, supported by their Sustainable Road Safety Program, appears to have played a significant role in their increased bicycle use and improved road safety. But is it empirically predictable in a reliable way?

2.2 Increased Bicycle Use, Increased Bicycle Safety

The above evidence suggests that increased use of sustainable transport modes is associated with reduced road fatalities overall. At the same time a small increase in Vulnerable Road User

(VRU) injuries and fatalities is expected to occur as more people bicycle. Is this increase acceptable?

Smeed [11] first proposed the concept of “Safety In Numbers” in relation to the transportation field when he claimed that fatalities per capita are lower with more traffic volume. His claim became known as Smeed’s Law after research from 20 countries revealed the following negative exponential equation:

$$\frac{F}{N} = 0.0003 \left(\frac{N}{P} \right)^{-\frac{2}{3}} \quad (1)$$

where F = road fatalities; N = registered motor vehicles; and P = population.

In today’s society where sustainable transport modes are largely encouraged, some researchers are suggesting that this Law is also appropriate for bicyclists and pedestrians. In other words, while initial increases in bicycling and walking may incur increases in injuries, beyond some ‘critical’ number the fatality or injury risk per cyclist or pedestrian is lower with an increase of bicyclists or pedestrians. Several appear to confirm that increasing sustainable transport use may in fact benefit VRU safety [12, 13, 14, 15, 16, 17]. Ekman [12] analyzed bicyclist volumes and serious cycling collisions at 95 intersections in Malmö, Sweden. He found there was an inverse relationship between bicycle-motor collision rates and bicyclist volumes.

Leden et al. [13] evaluated the before-after safety effect of improved bicycle crossing facilities at 45 non-signalized intersections in Gothenburg, Sweden. Adjusting for changes in bicycle volume, they found that bicyclist road collisions decreased by 20%. They suggested that the improved crossing facilities increased bicycle flows, but also lead to reduced bicycle-auto collisions. Leden [14] also examined data on pedestrian collisions, intersection geometry, pedestrian volume and vehicle volume at 300 signalized intersections in Hamilton, Canada. This study revealed similar findings to their bicycle study: decreased pedestrian injury rates are associated with increased pedestrian flows; however, increased pedestrian injury rates are associated with increased vehicle flows.

Jacobsen [15] compared bicycling and walking volumes and bicyclist-auto and pedestrian-auto injuries based on five datasets (three population level data and two time series data) from 68 Californian cities, 47 Danish towns and 14 European countries. He developed a Generalized Linear Regression Model (GLM) as follows, which describes an empirical rule between injuries and bicycle/pedestrian measures:

$$I = aE^b \quad (2)$$

where, *I* is the injury measure, *E* is the measure of bicycling or walking, and, *a* and *b* are the parameters. The injury risk per capita can be measured by dividing both sides of equation (2) by *E*, resulting in the equation (3):

$$Injury Risk = I / E = aE^{(b-1)} \quad (3)$$

In other words, this model predicts that a bicyclist’s injury risk would decrease to 66% of the old injury risk if cycling in a community doubled.

Robinson [16] reviewed three datasets in Australia, and was able to verify that Australian data also produced results similar to Jacobsen’s model. He found that a doubling of the mean cycling distance per capita was associated with a 35% decrease in the risk of fatality per kilometre bicycled. Moreover, he found that a doubling of the volume of regular cyclists was associated with a 34% decrease in bicyclist injuries.

Grey et al. [17] also used GLM techniques, together with a dataset of 247 intersections in Oakland, California, to explore the effect of pedestrian volume on safety for pedestrians. Different from Jacobsen, Grey’s resulting model form was:

$$C_i = \alpha P^{\beta_1} V^{\beta_2} e^{\beta Z} \quad (4)$$

where, C is pedestrian collision frequency at location i ; P is the pedestrian volume in location i ; V is the vehicle volume in location i ; Z is a set of intersection characteristics; β_1 , β_2 , β are corresponding parameters; and, α is an intercept term. Similarly, the responding collision risk was modelled as:

$$\text{Collision Risk} = \frac{C_i}{P} = \alpha P^{(\beta_1 - 1)} V^{\beta_2} e^{(\beta Z)} \quad (5)$$

Although this model was for estimating pedestrian collisions, a model for bicycle collisions could be formed similarly. Grey et al.'s analysis result was also consistent with studies by Leden [14], Jacobsen [15], and Robinson [16], showing that a doubling of pedestrians was associated with a 24% decrease in collision rate.

2.3 More Bicycle Use, Healthier Economies

While there was a lack of literature found on bicycling social cost benefit analyses (SCBA) in North America, several European studies suggest that the benefits of a sustained bicycle infrastructure program significantly outweigh the costs. Several local walking and cycling routes was assessed by the English government [18] in the cities of Bootle, Hartlepool, and Newhaven, located in the west, east and south of England respectively. The results revealed that walking and cycling schemes have a very high Benefits/Costs (B/C) ratio of 20:1, which compared very favourably with the typical 3:1 B/C ratio for rail/road-related transport projects.

Sælensminde [19] undertook SCBA's of walking and bicycling networks in three Norwegian cities. His analyses considered health, road safety, environmental, and parking impacts due to mode splits shifting from driving to walking/bicycling, and found a B/C ratio at 4 or 5 to 1. Krag [20] noted that Denmark has also been pursuing a comprehensive bicycle program, including network expansion, auto speed management, secure bicycle parking, improved network maintenance, and bicycle road signing and information. Based on reported program infrastructure funding of 20.3 million Euros over a 12 year period and a 50 year sustained program life, he calculated a net present value of 3.1 billion Euros, a B/C ratio of 1.35, and an Internal Rate of Return of 66%.

3. BICYCLING TRANSITION IN NORTH AMERICA

The most comprehensive economic analysis of the benefits of increased non-auto mode use (i.e. transit, cycling, walking) was performed by Newman & Kenworthy in 1999 [7], focusing on 46 cities worldwide in both developed and developing countries. Overall, they found that cities with higher than average investments in non-auto infrastructure systems had higher disposable incomes per capita, and above average GDP performance. In discussing this finding, however, some special economic factors need to be recognized that may have historically facilitated mainly non-auto land use and transportation patterns, as follows:

- Many Southeast Asian cities are in developing countries, with less than half of their population motorized. Their land use supports dominant low-cost, bicycle-oriented mode shares.
- Many European cities although in developed countries, have been rebuilt following the world wars, during depressed economic periods where mass transit and bicycling were the only modes affordable. Perhaps economic factors also facilitate (if not drive) development patterns.

European cities with high historic transit and bicycling use have continued and/or returned to those transport patterns in present day despite increasing personal income, which casts doubt on the usual assumption that mode split is predicted mainly by personal income. It would appear that land use and transportation development patterns are also a major key in driving the transition to

more sustainable travel modes, but at what cost? Pucher et al [21] have done much research in this regard concerning Germany's transition from auto-dependent patterns of the 1970's over a twenty-year period, to cities now past 40% bicycle mode split and high transit use, with high inter-urban rail use – and with personal incomes exceeding those in North America. Interestingly, Germany's transition period straddled their re-unification period, which included an economic recession, again suggesting an economic facilitation link as part of any transition process.

Historic North American development patterns appear to provide additional evidence that economics significantly influence development patterns. In the post-war period when our economy has boomed, many of our public transit/tram systems were removed in favour of auto-dominated land use and transportation (i.e. sprawl patterns). Now, with dire global warming and peak oil economic realities looming, governments have been more willing to consider more compact, sustainable (i.e. walk-, bicycle-, transit-oriented) development patterns, but most communities are already developed. The problem then is one of implementing a land use transition of these existing communities, not one of building on bare ground. How can a transition be facilitated from sprawling, auto-dependent communities and cultures built over the past 100 years, to more sustainable communities, including more bicycle-friendly infrastructure, without major economic collapse? While European experience suggests the benefits significantly outweigh the costs, governments (and businesses and residents) in North American cities have been slow to pursue transition.

Any government considering whether and how to risk the economic, social, and environmental well-being of their community in pursuing a transition from historic sprawl to sustainable community patterns requires two assurances. First, they need to see and hear that the transition is possible, and that other communities similar to theirs have done so in recent years. Second, they need to see that the forecast benefits do in reality outweigh the forecast costs, within reasonable limits of risk and uncertainty.

In North America, Boulder Colorado (population 95,000) implemented a transition to sustainable transportation in the 1990's, and now boasts a higher bicycling and transit infrastructure budget per capita per year than any other North American city of similar size, with over 20% bicycling and transit more than doubling [22]. There are other cities – large and small – that are worth mentioning that have made this transition away from auto-dependence – Davis with over 20% bike mode split in California; Vancouver's West End in BC; and, Portland in Oregon [6, 7]. The local and international evidence suggests that it is possible and reasonable to do in North America. But governments contemplating a transition to non-auto dependent land use and transportation patterns need to be strong enough not only to pursue the transition, but also to see it through to completion. To sustain the transition, community leaders need to be supported by a well-qualified team that will bring them a robust business case for that transition.

Based on a review of the literature [6, 7], the key is to design and implement the transition as quickly as possible. While this can be costly (Germany was almost bankrupted), the transition was achieved within a relatively short 20 years [21]. Researchers have suggested that drivers will 'acclimatize' to sharing the road with bicyclists once a mode split in the range of 15% to 25% is achieved [23, 24, 27]. Perhaps the most successful bicycling programs have involved separated bicycle facilities (e.g. Netherlands, Ottawa, Vancouver), wherein the '3rd wave' of bicyclists are coaxed out of their cars. The term '3rd wave' was coined by Jack Becker of the BC Cycling Coalition in recognition of the observation that most people would like to do something 'right for the environment' but are intimidated by the thought of bicycling on a road [28]. The 1st wave of cyclists were those hard core cyclists that 'just did it'. The 2nd wave of cyclists were those that now ride in our bike lanes beside major roads. Becker contends that it is necessary to require separated infrastructure to pull the 3rd wave onto bicycles. The research agrees with Becker, suggesting that more and longer bicycle trips are observed when a well-established network of separated bicycle

routes exists (including integrated end-of-trip facilities), as compared to just on-road facilities [8, 21, 23].

An economic SCBA of the transition from more auto-dependence to more bicycle-friendly communities is beyond the scope of this paper, and dependent on community-specific data. The BCCC did a detailed account on a provincial scale using pre-2007 data [28]. A possible community-based SCBA may be available once data becomes available after the Vancouver 2010 Winter Olympics, in which much of the city's auto-dominated transport was curtailed in favour of transit, bicycle, and walking modes. Early feedback is positive, so much so that Vancouver is now moving to make some of the separated bicycling routes permanent in road space formerly occupied by auto traffic lanes (e.g. Burrard Street Bridge). While each SCBA will be community dependent, Table 2 below provides at least a cursory review of the major cost benefit considerations.

Table 2 - Auto-dependent versus Bicycle-oriented Development Patterns*

Economic impacts	Auto Dependent	Bicycle Friendly	Net Result of More Bicycling Infrastructure
Infrastructure Costs [6,7, 28]	\$ Billions now & later: Much more costly to increase supply and maintain; rising	\$ Millions now, less later: The BCCC estimates only \$200 million per year in BC	Lower initial infrastructure investments. More disposable income for government for health and education
Economic Health [6,7]	Rising auto infrastructure costs will divert funds from supporting local businesses & programs.	With more disposable income in the community, local businesses & residents will prosper	Local bicycle businesses will thrive. More disposable income for government / industry to transition to less auto dominated economy.
Resident Health [28]	Rising health care costs, obesity is the new tobacco	Healthier population, less obesity, lowering health care costs	More disposable income for government to spend on education.
Road Safety [6, 7, 8, 23]	High frequency & severity of injuries continues, leading cause of death in NA	As more people bicycle, less overall road collisions & injuries.	Reduced collisions, injuries, fatalities & health care costs.
Capacity	Finite unless more is built. Increasing congestion slows people & freight; goods & services cost more. GHG emissions increase.	Diverting people from cars to bikes leaves more capacity for freight & public transit, less need to expand infrastructure capacity	More disposable income for government
Energy [23, 26, 28]	Costs to deal with Peak Oil & Climate Change will make driving less affordable	Human powered, renewable energy (or electric assist) will help meet Canada's GHG reduction targets and cushion the price impacts of Peak Oil	Bicycling will be a key transition strategy towards sustainability.
Space [23, 28]	More parking lots, more roads means less developable land at higher costs	Twenty bikes can be parked in one car space; bicycle paths to hold equivalent people/hour would be less than ½ that of vehicle lanes	More useable land space in the longer term as car lanes are converted to bicycle lanes

* References denote related research reports.

Researchers [7, 8, 21, 23, 28] suggest that with strong leadership and careful planning the net result of the transition will be a healthier local economy, more disposable income for both governments and their citizens, and safer and healthier citizens, thus reducing health care costs. With high upfront costs that such a transition would necessarily entail, the likely shape of the general cash flows for the transition would likely look much those in Figure 1 below.

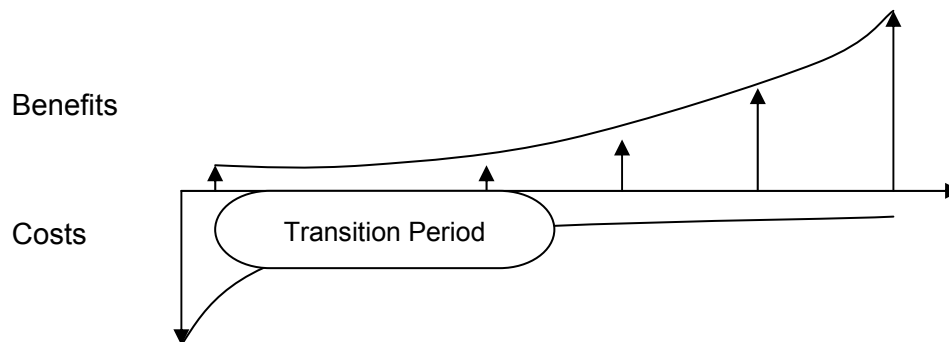


Figure 1 - Cash Flow Analysis of Bicycle Improvement Program

4. QUANTIFYING ROAD SAFETY BENEFITS

4.1 Methods of Evaluating Road Safety Benefits

Two methods are used to evaluate the safety effect of any project that will result in the change of bicycle use. The first is a simple before-and-after observational statistics method, generally measuring the change of collision or fatality rates at city, regional, or national scales. The second method looks closer, at a neighbourhood-level, using community-based statistics to develop predictive models for a more proactive safety evaluation. These predictive models have been previously developed as community-based, macro-level collision prediction models (CPMs) for the cities of Vancouver, Victoria, Kelowna, and Ottawa [23].

The studies of Ekman [12], Osberg and Stiles [8], and Leden [13, 14] generally follow the first method. However, it has three obvious limitations: 1) its scope requires extensive data collection efforts; 2) it is a reactive method with little reliable predictive capacity; and 3) it does not consider possible causal factors influencing collisions.

The second method develops CPMs with Generalized Linear Regression techniques [23], and has three advantages over the first method: 1) it can be used in proactively to evaluate road safety benefits in advance of bicycle infrastructure/facility construction; 2) it requires less extensive data, and it picks up more of the confounding factors in that data; and 3) it can take into account more possible causal variables influencing collision changes.

Both Grey et al [17] and Jacobsen [15] used this GLM method. However, Grey et al.'s study only predicted VRU collisions at an intersection level, not on an area-wide, community-planning level. In Jacobsen's research, the bicycle collision model was at the community level, but included only one explanatory variable: the measure of bicycling or walking (i.e. bicycle trips, or bicycling kilometres travelled). Moreover, it predicts only bicycle collisions, not total (i.e. auto, bike, and walk) collisions.

Lovegrove's [23] research on CPMs used collision frequency as the dependent variable and developed 16 different types of models as presented in Table 3 below, based on the following stratifications for explanatory variables:

- Four main neighbourhood traits: Exposure, Socio-Demographic, Transportation Demand Management (TDM), and Road Networks.
- Land Use - rural or urban

- Exposure Data derivations - modelled or measured (modelled traffic volume or exposure data was derived from transportation planning model VKT outputs)

Themes	Land Use	Derivation	Group #
Exposure	Urban	Modelled	1
		Measured	2
	Rural	Modelled	3
		Measured	4
Socio-Demographic	Urban	Modelled	5
		Measured	6
	Rural	Modelled	7
		Measured	8
Transportation Demand Management	Urban	Modelled	9
		Measured	10
	Rural	Modelled	11
		Measured	12
Network	Urban	Modelled	13
		Measured	14
	Rural	Modelled	15
		Measured	16

Table 3 - Model Groups [23]

CPMs were developed using generalized linear regression modelling software, with three user-specified functions. First, a logarithmic link function was used for the linear transformation. Second, the maximum likelihood method (MLE) was chosen to provide parameter estimates for each model developed in each group. Third, the error structure of the models was assumed to follow the negative binomial distribution. The form of macro-level CPMs was formulated as:

$$E(\Lambda) = a_0 Z^{a_1} e^{\sum b_j X_j} \quad (6)$$

where $E(\Lambda)$ = the predicted collision frequency (3-year); a_0 , a_1 , b_j = model parameters; Z = leading exposure variables (e.g. VKT, TLKT); and, X_j = explanatory variables. The procedure for selecting the appropriate variables was a forward stepwise procedure by which the explanatory variables were added to a model one by one, depending on three tests: (1) a significant parameter t-statistics; (2) a significant refinement in model fit; and (3) little or no correlation with other variables. Standard goodness of fit tests verified that the final CPMs developed were reliable, including Pearson χ^2 and Scaled Deviance tests at a 95% statistical confidence level [23]. Although an extensive number of CPMs were developed, Lovegrove has only been able to develop one CPM for bicycles to date.

4.2 Future Research to Fill Knowledge Gaps

Although community-based, macro-level CPMs were successful and case studies have demonstrated them as important tools to predict the road safety benefits of increasing bicycle use, knowledge gaps still exist. For example, by reviewing Jacobsen's methodology and resultant conclusions [15], Forester [24] proposed three issues on Jacobsen's research: 1) Jacobsen poorly represented his data; 2) because of focusing only on bicycle mode split, Jacobsen ignored other possible causal factors contributing to collisions; and, 3) the comparison between American and European cities was considered misleading as their transportation systems differ greatly. Forester believed that Jacobsen's study could only demonstrate a casual link between mode split and collisions. A deeper investigation was needed to establish a more reliable relationship between them.

Another gap, identified by Lovegrove, was the lack of community-based, macro-level CPMs to predict overall collisions - including auto, transit, pedestrian and bike collision types based on

bicycle and/or pedestrian mode splits. Developing reliable macro-level CPMs that take into account the variables influencing traffic mode splits and predicting overall collisions is a key point of quantifying safety benefits of increased bicycle use. Planners, engineers, and governments could then use these CPMs to make more proactive, science-based, land use and transportation community planning decisions toward sustainability.

4.3 Research to Develop Reliable Empirical Prediction Tools

UBC-O researchers are now pursuing development of community-based, macro-level CPMs that predict overall collision reductions associated with bicycling mode increases. In the process, several inherent problems related to data, variables, model form, and model testing will need to be addressed.

4.3.1 Data & Variables

Selecting proper explanatory variables representing bicycle mode split is the first step to develop new CPMs. Table 4 presents possible variables to test.

Variable	Data Source	Symbol
Number of commuters by bicycling %	Census	BIKE
Bicycle lane kilometres – on-road	GIS map	BLKM
Bicycle lane kilometres – off-road	GPS tracking in field	BLKF
Bicycle parking spaces	City hall	BPS
Population density	Census	POPD
Home density	Census	NHD
Employee density	Census	EMPD
Work-home trip distance (Kilometres)	GIS map	WHTD
Area of hills % (area of hills/ zonal area)	GIS map	HIAR
Mean precipitation	GIS map	PRPT
Mean temperature	GIS map	TEPT
Bike-auto collisions	GIS map, ICBC	BAC
Bike-only collisions	Health authorities	BOC

Table 4 - Variables Reflecting or Impacting Bicycle Use

The amount of bicycle infrastructure and facilities would be the dominant factor as a complete bicycle lane network and parking facilities can promote bicycle mode shift [25]. Urban sprawl is another factor that has been found to cause a dramatic effect on transportation mode split. A study by Ewing, Pendall, and Chen [26] found that compact regions have better sustainable transportation outcomes, including higher sustainable mode splits and fewer fatalities than sprawling ones. In addition, other factors such as terrain, weather, and land use mix are also associated with bicycle use. For example, level terrain is more appropriate for bicycle use than hills; warmer and drier places are better for bicycle use than cooler and rainier ones. Four variables have been involved in Lovegrove’s research [23], including BIKE, POPD, EMPP, NHD defined below; other new variables related to on/off-road bicycle paths, bicycle parking, terrain, climate, trip distance will also be pursued in updated macro-level CPMs. BLKM and BLKF are two leading exposure variables that reflect the status of bicycle use. Adding them into the CPM form in the lead exposure variable *B* is considered a reasonable approach, since it not only can predict overall collisions, but also considers the impact of traffic mix on collisions (i.e. *Z/B*). Enhanced bicycle collision data is also being pursued with local health authorities.

4.3.2 Model Form & Regression Process

Different from the general model, the bicycle-related macro-level CPMs will add two more independent variables in the model from: BIKE or BLK (BLKM+BLKF). The updated form of such macro-level CPMs is presented as follows:

$$E(\Lambda) = a_0 \left(\frac{Z}{B} \right)^{a_1} e^{\sum b_j X_j} \quad (7)$$

where, $E(\Lambda)$ = the predicted collision frequency (3-year); a_0, a_1, b_j = model parameters; Z = leading exposure variables (e.g. VKT, TLKT); B = leading exposure variables of bicycle use (e.g. BIKE, BLKM, BLKF); and, X_j = other explanatory variables. In this model form, leading exposure variables of bicycle use cannot be zero in mathematic logic. If some zones have zero values of bicycling exposure variables, they should be excluded when developing new CPMs. However, this exclusion will not affect the modelling results significantly because the number of these “special zones” is very small compared to the number of other zones with bicycle lanes or bicycle commuters. Once the model form has been selected, several statistical software packages (e.g. GenStat, GLIM4) can be used to do the Generalized Linear Regression (GLIM) analysis. Similarly, a Negative Binomial error structure is assumed in the regression analysis.

4.3.3 Data Extraction & Model Goodness of Fit

Sufficient data of good quality is fundamental for well-fit and reliable statistical models. Using geo-statistical methods, data for all variables can be aggregated into geographic units, usually, Traffic Analysis Zones (TAZs). TAZs are used for aggregating data because their sizes and layouts follow reasonable trip assignment, demographic analysis (e.g. population and employment densities at roughly uniform levels), and land use boundaries. Also, most TAZ boundaries closely follow those of census tracts and municipalities. As bicycle collisions are relatively rarer events than auto collisions, collision data for bicycle-related collisions can be collected over more years to ensure sufficient data points for regression analysis.

CPM goodness of fit is ascertained as described by Lovegrove [23], using two statistical performance measures, Scaled Deviance and Pearson χ^2 [23, 29, 30]. They are defined in Equation (8) and (9) as follows:

$$SD = 2 \sum_{i=1}^n \left[y_i \ln \left(\frac{y_i}{E(\Lambda_i)} \right) - (y_i + \kappa) \ln \left(\frac{y_i + \kappa}{E(\Lambda_i) + \kappa} \right) \right] \quad (8)$$

$$Pearson \chi^2 = \sum_{i=1}^n \frac{[y_i - E(\Lambda_i)]^2}{Var(y_i)} \quad (9)$$

where, y_i is the observed collision data, $Var(y_i)$ is the variance, $E(\Lambda_i)$ is the predicted collision data; and κ is the over dispersion parameter for the model (an output of the GLM regression analysis). A 95% desired level of confidence is typical.

5. CONCLUSIONS

An extensive review of literature was conducted to ascertain at least a qualitative opinion on the road safety and economic implications of increased bicycle use. The literature suggests three conclusions: 1) although increased bicycle-collisions is associated with increased bicycling, research suggests that this will disappear as bicycle mode split approaches 20% level; 2) total collisions (auto, bike, walk) will decrease as more travel is done by bike and less by private auto, as the number of bicycle-collisions increases more slowly than the number of bicycles; and, 3) much healthier economies and higher benefit/cost ratios will be result from increased and sustained bicycling infrastructure programs.

Although the factors impacting sustainable transport mode shift are multiple, European experience supports limited North American experience on the importance of proper and sustained transportation bicycle infrastructure programs. Governments in North America can learn from the experience of the Dutch government.

Preliminary research has demonstrated a systematic method of developing reliable, community-based, macro-level CPMs to quantify the road safety benefits of increasing bicycle use. However, several knowledge gaps must be overcome. Research has begun to address these gaps. Bicycle-related CPMs are critical for road safety improvement programs at a proactive level, and will provide economic justification for these much-needed major bicycle infrastructure investments across Canada.

ACKNOWLEDGEMENTS

The authors would like to thank the Natural Sciences & Engineering Research Council for their support of this research.

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