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Joint consideration of energy expenditure, air quality, and safety by cyclists

Alexander Y. Bigazzi [a,*], Steven R. Gehrke [b]

[a] Department of Civil Engineering and School of Community and Regional Planning, University of British Columbia, 2029 – 6250 Applied Science Lane, Vancouver, BC V6T 1Z4, Canada

[b] Department of Civil and Environmental Engineering, Portland State University, P.O. Box 751, Portland, OR 97207-0751, USA

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A B S T R A C T

Public health benefits are an important motivator and justification for urban cycling promotion. The health impacts of cycling are typically evaluated using three main effect pathways: physical activity (exercise), air pollution exposure, and safety (crashes). Effects of safety on cycling behaviour have been investigated, but little is known about how energy expenditure and air quality concerns influence cycling decisions. Understanding cyclist perceptions and preferences is important for planning and designing sustainable and healthy transportation networks. As such, research providing insights into the heterogeneity of these concerns is needed to inform models of behavioural change with evolving vehicles, technology, and infrastructure. The objective of this paper is to investigate the joint consideration of energy expenditure, air quality, and safety concerns by cyclists, and their relationships with cycling frequency. A structural equation model is developed based on data from a survey of 625 intercepted real-world cyclists. Air quality and energy expenditure were considered in routing decisions by 51% and 73% of the cyclists, respectively. Model results show that traffic safety and air pollution risks are perceived differently by cyclists, which has implications for modeling urban cycling behaviour in the context of evolving motor vehicle fleets. Safety concerns were associated with less frequent cycling, but not air quality concerns. Consideration of energy expenditure varies significantly among individuals and trip types, which will emerge with different preferences related to hills, stops, speeds, and electric-assistance. Energy and air quality concerns were significantly associated, suggesting health-conscious cyclists who tended to be older, have higher educational attainment, be more physically active, and cycle more recreationally. Utilitarian and recreational cycling trips had different relationships with health-related considerations and with weekly physical activity.

1. Introduction

Urban cycling has been increasing in many cities, promoted by targeted policies and programs (Pucher, Buehler, & Seinen, 2011). Still, cycling has only a small mode share in North America, and the question of how to further motivate urban cycling is relevant and important for many cities. Provision of attractive cycling routes is a key mechanism through which cities can

* Corresponding author.
E-mail addresses: alex.bigazzi@ubc.ca (A.Y. Bigazzi), sgehrke@pdx.edu (S.R. Gehrke).

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impact cycling rates (Pucher et al., 2011), and traffic calming and separated bicycle facilities are two prominent cycling promotion policies (Pucher & Buehler, 2008).

Cyclist preferences have been investigated in stated and revealed preference studies, demonstrating that cyclists perceive and value myriad factors about their trips, including distance and duration, proximity to motor vehicles of varying speeds and types, presence of hills, weather, and more (Broach, Dill, & Gliebe, 2012; Chataway, Kaplan, Nielsen, & Prato, 2014; Fraser & Lock, 2011; Motoaki & Daziano, 2015; Sener, Eluru, & Bhat, 2009; Stinson & Bhat, 2003; Tilahun, Levinson, & Krizek, 2007; Vedel, Jacobsen, & Skov-Petersen, 2017; Winters & Teschke, 2010). Cyclist preferences are typically assessed in regard to observable trip attributes, and so the current evidence base is largely oriented around proxy variables such as facility class and road grade, rather than more intangible but fundamental motivating factors such as risk and effort. Better knowledge of these fundamental influences can improve understanding of heterogeneity in cycling preferences and behaviour, and inform models of how behaviour may change with evolving vehicle fleets, technology, and infrastructure.

An important motivator and justification for cycling promotion is the potential public health benefits. A growing body of literature examines the health effects of cycling with three main effect pathways: physical activity, air pollution, and crashes (Buekers, Dons, Elen, & Int Panis, 2015; de Hartog, Boogaard, Nijland, & Hoek, 2010; de Nazelle & Nieuwenhuijsen, 2009; Deenihan & Caulfield, 2014; Fraser & Lock, 2011; Götschi, Garrard, & Giles-Corti, 2016; Int Panis, 2011; Macmillan et al., 2014; Oja et al., 2011; Tainio et al., 2016; Teschke et al., 2012; Winters, Brauer, Setton, & Teschke, 2010). This literature focuses on objective health impacts, and less is known about how energy expenditure, air quality, and safety affect decisions about whether, where, and how to cycle. The objective of this paper is to investigate urban cyclists' joint consideration of these three factors, and how they relate to cycling frequency.

1.1. Literature review

Safety perceptions and concerns of cyclists have been studied much more extensively than energy expenditure or air quality concerns. Perceived and objective cyclist safety often align, but it is perceived safety that is more relevant for modeling cyclist decision-making (Chataway et al., 2014; Heinen, van Wee, & Maat, 2010; McNeil, Monsere, & Dill, 2015; Sanders, 2015). Safety is a dominant concern of many cyclists, evinced in direct questioning and by avoidance of facilities perceived as more dangerous because of exposure to motor vehicle traffic (Chataway et al., 2014; Heinen, Maat, & van Wee, 2011, 2010; Willis, Manaugh, & El-Geneidy, 2015; Winters, Davidson, Kao, & Teschke, 2011). Perceived safety is often a major factor in decisions about whether to cycle and which routes to use, but not always the primary factor, and perceptions of safety are highly heterogeneous (Hatfield & Prabhakharan, 2016; Piatkowski & Marshall, 2015; Sanders, 2015; Winters & Teschke, 2010).

Physical effort and energy expenditure appear in various indirect forms in cycling behaviour research, but have rarely been directly assessed. Energy expenditure was explicitly included in a cycling speed choice model and found to have a marginal disutility at typical riding speeds (Bigazzi & Lindsey, 2018). Perspiration or sweat, a physiological response to cycling effort mediated by environmental conditions and clothing, is a concern for many utilitarian cyclists and has a negative influence on cycling activity (Dill & Rose, 2012; Piatkowski & Marshall, 2015). Cyclists generally avoid large hills (Broach et al., 2012; Fraser & Lock, 2011; Heinen et al., 2010; Winters et al., 2011, 2010), although at least two stated-preference studies found a preference (stronger in males) for moderate hills compared to flat terrain (Sener et al., 2009; Stinson & Bhat, 2003). Avoidance of hills is generally assumed to be due to a preference for less effort, but the effect could be conflated with slower cycling speed on hills (Heinen et al., 2010; Parkin & Rotheram, 2010). Similarly, the observed negative effects of distance and stops on cycling could be a conflation of travel time and effort because of the mediating effects of speed (Heinen et al., 2010). Overall, the role of physical effort and energy expenditure in motivating cycling decisions is still unclear. Some physical activity is likely desired by cyclists, motivated by the enjoyment of movement and exercise or by expected health benefits from physical activity (Götschi et al., 2016; Mokhtarian, Salomon, & Singer, 2015). However, at the margin, cyclists seem to avoid excess physical effort.

The influence of air pollution on cycling decisions remains unclear. Air pollution exposure for cyclists has been studied primarily through the lens of objective risk (Bigazzi & Figliozzi, 2014). Cyclists have high breathing rates that elevate pollutant inhalation, but exposure concentrations and inhalation doses can be reduced by traveling on low-traffic routes (Bigazzi, Figliozzi, Luo, & Pankow, 2016; Bigazzi & Figliozzi, 2014; Broach & Bigazzi, 2017; MacNaughton, Melly, Vallarino, Adamkiewicz, & Spengler, 2014). Travellers' consideration of air pollution is less clear than their actual exposure risk. The public has a general awareness that outdoor urban air pollution affects human health (Bianco, Nobile, Gnisci, & Pavia, 2008; Day, 2006), and some people perceive negative health effects from exposure during travel specifically (Badland & Duncan, 2009; Cole-Hunter, Morawska, & Solomon, 2015). Numerous studies in environmental economics have evaluated the public's positive valuation of urban air quality, typically in the context of willingness to make trade-offs in residential property attributes (Bayer, Keohane, & Timmins, 2009; Levinson, 2012; MacKerron & Mourato, 2009). Several empirical studies have looked at cyclist routing behaviour and pollution exposure, finding that cyclists generally choose low-exposure routes when available (Bigazzi, Broach, & Dill, 2016; Broach & Bigazzi, 2017), although cycling volumes can be positively related to pollution levels (Hankey, Lindsey, & Marshall, 2017; Strauss et al., 2012). These studies do not identify air pollution as a specific motivator for the observed cycling behaviour.

A few studies have included air quality as a factor influencing cycling decisions (Anowar, Eluru, & Hatzopoulou, 2017; Badland & Duncan, 2009; Cole-Hunter et al., 2015; Winters et al., 2011). In stated preference research in Vancouver, Canada, the availability of routes "away from traffic noise & air pollution" motivated cycling (Winters et al., 2011), but this route attribute was not clearly distinct from more general avoidance of traffic. In a multimodal Australian survey, 45% of respondents recognized the negative health effects of pollution exposure during commuting (Badland & Duncan, 2009). Still, only 13% identified air pollution as a "major barrier to walking or cycling to/from work" and only 14% reported taking a different walk or cycle route "to avoid air pollution". The authors hypothesize that this potentially counterintuitive finding may be attributable to generally low air pollution levels in the surveyed area and to most respondents already using low-pollution walk and cycle routes. In addition, only 64 of the 745 respondents (9%) actually used active travel modes to commute, but all were asked about their walk and cycle route preferences, so the decision context may have been unfamiliar to many of them. In a more recent survey of 153 cyclists in the same region, 80% perceived air pollution exposure during their cycle commutes, and 68% indicated willingness to change commute route to avoid air pollution "if proven to be appropriate and effective" – significantly more for women (80%) than men (63%) (Cole-Hunter et al., 2015). Pollution avoidance still ranked behind time and safety in route attribute priorities for respondents. A recent online stated choice experiment examined the influence of information about air quality on bicycle route decisions, quantifying trade-offs with duration, infrastructure, traffic, and grade (Anowar et al., 2017). Respondents were given explicit concentration values for each route (e.g., 15 ppb mean NO_2 exposure level), resulting in a (highly heterogeneous) negative effect of air pollution level on route attractiveness. The extent to which cyclists considered or ascertained air quality in their real-world cycling decisions (without concentration value prompting) was not examined.

1.2. Objective

To summarize, energy expenditure and air quality concerns of cyclists have rarely been directly assessed, and more work is needed to understand how they vary among travellers and relate to safety concerns and other factors. In response, this study investigates two main research questions. First, to what extent do cyclists consider energy expenditure and air quality? Second, how do those considerations relate to safety concerns, socio-demographics, and cycling frequency? We aim to answer these questions using data from a survey of intercepted real-world cyclists, to elicit cyclist preferences and perceptions in a real travel context. The first question is addressed through direct elicitation of energy and air quality concerns, and the second question through confirmatory factor analysis and a structural equation model built on the intercept survey data.

2. Method

2.1. Conceptual framework

Fig. 1 illustrates the conceptual framework motivating the study design. The key research questions relate to the three hypothesized latent considerations shown in circles in Fig. 1 (safety, energy, and air quality). We seek to establish the existence of these concerns with questions about cycling comfort on different types of facilities, perceptions of physical activity and exercise, and explicit considerations of energy expenditure and air quality.

There are various ways to measure traffic safety concern, which is often conflated with cyclist comfort in the literature (Krizek & Roland, 2005). The level of safety concern varies among cyclists (Piatkowski & Marshall, 2015; Sanders, 2015), and significant relationships have been found among cyclists' fear of traffic, perceived safety of infrastructure, and avoidance of cycling in mixed traffic (Chataway et al., 2014). In past research, comfort on different types of bicycle facilities has been interpreted as indicative of perceived collision risk (Li, Wang, Liu, & Ragland, 2012) and "[concern] about potential vehicle–cycle conflicts" (Hunt & Abraham, 2007). Stated comfort level on different types of facilities is also used in a well-known cyclist typology (the "4 types of cyclists" developed in Portland, Oregon by Geller (2009)), an investigation of which concluded that "traffic and safety concerns" was the key differentiation among cyclist types (Dill & McNeil, 2013). In this study, we use similar questions about comfort levels cycling on facilities with varying exposure to motor vehicle traffic as indicators of respondents' safety concerns. Limitations of this approach are discussed below.

Explicit stated consideration of energy expenditure and air quality in route decisions are used as the main indicators of energy expenditure and air quality concerns. Past research also used route perceptions and preferences to characterize general cycling characteristics (Damant-Sirois, Grimsrud, & El-Geneidy, 2014). Because energy expenditure can be associated with both positive and negative influences on cycling (see discussion above), questions about consideration of bicycling as a form of exercise and enjoyment of physical activity are included as additional indicators of energy consciousness.

The framework in Fig. 1 includes two-way interactions among all three latent constructs. These constructs could be positively associated in cyclists more aware and conscious of the health-related impacts of cycling. Safety and air quality concerns could also be positively related in more risk-averse travellers, and potentially both higher for women (Garrard, Rose, & Lo, 2008). Energy and air quality concerns could be positively related in cyclists more aware of the indirect health impacts of cycling that manifest over long time scales (Götschi et al., 2016).

We also explore the relationships of these concerns with cycling frequency for different trip purposes. The conceptual framework allows for two-way effects in which the three concerns influence cycling frequency and are also influenced by cycling frequency. Greater concern about air pollution risk could decrease cycling activity, as has been found for safety concerns (Badland & Duncan, 2009; Cole-Hunter et al., 2015; Winters et al., 2011). Also, more frequent cycling could reduce

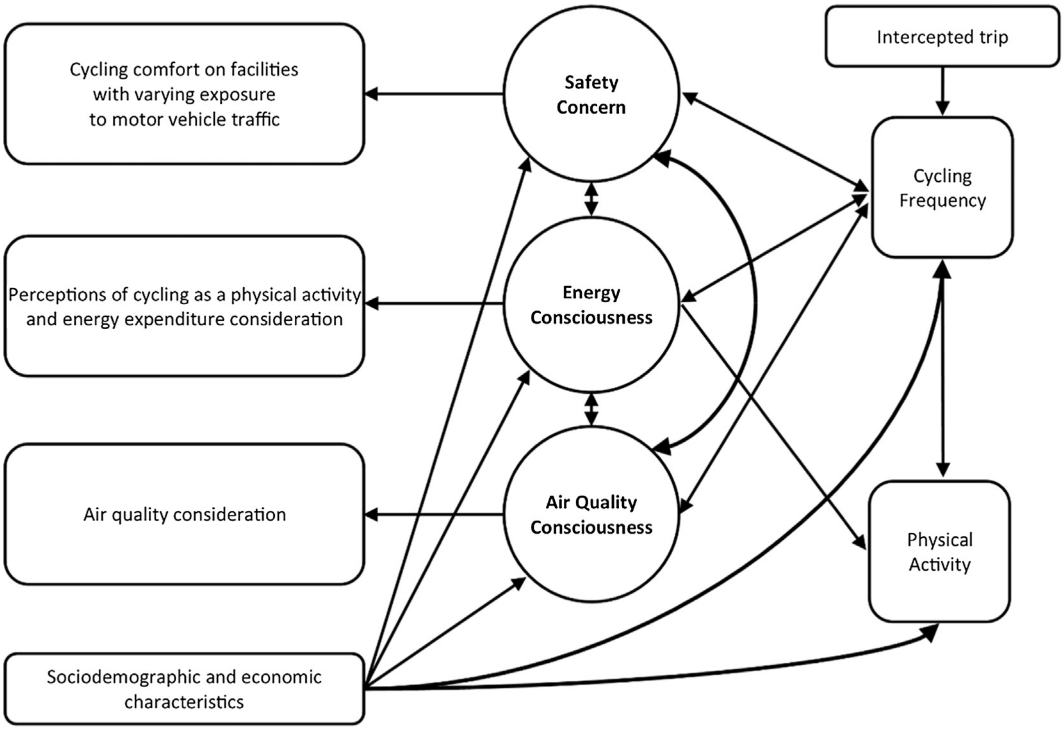

Fig. 1. Conceptual framework for cyclist consideration of safety, energy, and air quality.

perceived risks (Chataway et al., 2014). The relationship between energy consciousness and cycling frequency is unknown, and could be positive or negative. Another outcome included in the framework is general physical activity, defined as self-reported minutes per week of moderate and vigorous physical activity. This outcome is assumed to be influenced by energy consideration, and have a two-way positive relationship with cycling frequency.

Sociodemographic and economic characteristics of the travellers are included in the framework as potential influencing factors of all three latent constructs, consistent with past research on perceived safety (Chataway et al., 2014; McNeil et al., 2015) and air quality consideration (Anowar et al., 2017; Cole-Hunter et al., 2015). These characteristics are also controls for cycling frequency and physical activity outcomes (Garrard et al., 2008; Willis et al., 2015; Winters et al., 2011). Intercepted trip purpose is included as a control for cycling frequency outcomes.

The conceptual framework in Fig. 1 was developed to investigate the hypothesized latent considerations, and not intended as a comprehensive model of all relevant factors influencing cycling behaviour. Some factors not in this framework that are known to influence cycling behaviour include travel time and distance, riding surface, and weather (Broach et al., 2012; Fraser & Lock, 2011; Motoaki & Daziano, 2015; Rietveld & Daniel, 2004; Stinson & Bhat, 2003; Winters et al., 2011). The framework also excludes potential mediating effects of long-term cycling experience (although recent cycling frequency is included), social norms, and identity (Aldred & Jungnickel, 2014; Aldred, 2013; Heinen et al., 2011; Piatkowski & Marshall, 2015; Sanders, 2015; Willis et al., 2015).

2.2. Data

Data for this study were collected during a cyclist intercept survey, in order to elicit cycling preferences within a specific cycling context. A three-page paper questionnaire[1] was developed with questions about attributes of the current trip, general travel habits, comfort in various cycling environments, concerns about air pollution and energy expenditure, and socio-demographics. Comfort level from "very uncomfortable" to "very comfortable" was asked for cycling on bicycle paths, low-traffic streets, major streets with physically separated bike lanes, major streets with painted bike lanes, and major streets without bike lanes. Cycling frequency was assessed as the number of the past 30 days in which the respondent cycled for each of three purposes: commuting, shopping/errands/dining, and recreation/exercise. The 30-day window was selected to capture a representative period of behaviour which could easily be recalled; consistent with past travel and health research (Bolen, Kresnow, & Sacks, 1998; Centers for Disease Control and Prevention (CDC), 2018; Dellinger & Kresnow, 2010; Mendoza et al., 2011; National Highway Traffic Safety Administration (NHTSA), 2003).

[1] Available at http://reactlab.civil.ubc.ca/2016-ubc-cyclist-intercept-study-questionnaire/.

Cyclists were initially contacted with signs one block in advance of the intercept locations. Time to complete the questionnaire was 5–10 min. The length of the questionnaire was limited to minimize respondent burden and achieve a more representative sample of cyclists. The survey method was approved by the research ethics board at the University of British Columbia. Data were collected July-August 2016 on 16 days at 8 locations along bicycle facilities in Vancouver, Canada. Recruitment locations were selected to capture riders in a variety of contexts: medium- and high-volume commuting routes near downtown (York Avenue, Union Street and Expo Boulevard cycle tracks), recreational paths popular with leisure cyclists (the "Seawall" off-street waterfront path at Sunset Beach, Ontario Street and Science World) and residential areas away from the urban core (a cycle track and an off-street path both around 9 km south of downtown). Sampling times were between 12:00 and 19:00 on weekdays without precipitation – see Tengattini and Bigazzi (2018) for additional recruitment details. In total, 625 complete questionnaires were received. Stated trip purposes were 41% commuting, 19% shopping/errands/dining and 41% recreation/exercise.

2.3. Modeling

A two-step analytic approach consisted of the development of an initial measurement model followed by a structural model (Anderson & Gerbing, 1988). For the first step, confirmatory factor analysis (CFA) was used to measure relationships among observed indicators theorized to represent one or more underlying latent constructs (Brown, 2014). In the conceptual framework above, three latent constructs reflecting on-street safety concerns, energy consciousness, and air quality consciousness on behalf of the surveyed cyclists are hypothesized to exist. The proposed indicators of these constructs included in the questionnaire were categorical; therefore, the measurement model was estimated with a robust weighted least squares mean- and variance-adjusted estimator, probit link function, and theta parameterization.

In the second step, an SEM was estimated to explore the relationships between the identified latent factors and observed variables outlined in the conceptual framework. SEM is a well-established analytic tool for measuring latent factors reflected by multiple indicators simultaneously with multidirectional indirect and direct relationships among unobserved and observed variables (Golob, 2003). Following the conceptual framework, the final SEM included latent variables that were predicted by exogenous variables in the questionnaire, and also covaried with or predictive of three observed travel behaviours (number of the past 30 days engaged in cycling for each of three purposes: commuting, shopping/errands, and recreation) and two physical activity outcomes (typical hours per week engaged in moderate- and vigorous-intensity physical activity). Concurrently, these five exogenous outcomes were also predicted by the socio-demographic and economic characteristics of the individual cyclists. The CFA and SEM analyses were each performed using the statistical software R with the 'lavaan' package (Rosseel, 2012).

3. Results

The study sample compares well to cyclists from a 2011 Vancouver regional travel survey (TransLink, 2013) and to the regional population in Metropolitan Vancouver (Statistics Canada, 2012) in regard to age, income, and sex. Respondents were 63% male, more than the regional average (49%) but less than cyclists in the regional travel survey (71%). Median household income of all three samples is in the $75,000–$100,000 bracket. The study sample includes fewer youth under 18 years, but was similar (within 5%) to the age distribution of cyclists in the regional travel survey for all other brackets; both cyclist samples have substantially larger portions in the 25–44 age bracket and fewer 65+ than the regional average.

Table 1 gives the joint distribution of responses to direct questions about cyclist consideration of energy and air quality in routing decisions. Most cyclists agree (strongly or otherwise) that they consider energy (73%) and just over half state that they consider air quality (51%), while 41% jointly consider energy and air quality. Only 6% disagree (strongly or otherwise) with both questions, while 12% and 26% disagree for energy and air quality individually. Percentages are high along the table's diagonal, indicating a positive relationship in agreement between the two questions (i.e., cyclists tend to consider both or neither). Regarding other questions about energy expenditure, 18% "agree" and 77% "strongly agree" that they "enjoy physical activity", while 21% "agree" and 69% "strongly agree" that "bicycling is a form of exercise for [them]". Table 2 summarizes responses to questions about comfort cycling on different types of facilities. Most of the respondents were comfortable cycling on all facilities except major roads without bicycle lanes, and cyclist comfort increased with separation from motor vehicle traffic, as expected.

3.1. Confirmatory factor analysis

Fig. 2 illustrates the results of the CFA. Overall, the CFA model fit indices depict a strong fit to the sample data (CFI = 0.98, TLI = 0.97, RMSEA = 0.06). The measurement model produced three constructs of the safety concern, energy consciousness, and air quality consciousness of surveyed cyclists. Safety concern (Cronbach's alpha(α) = 0.78) was reflected by indicators of cyclist comfort level riding on four different types of on-street facilities ("How comfortable would you feel cycling on your own in each of the following situations?", with four response levels ranging from "very uncomfortable" to "very comfortable"). The safety indicators were reverse-coded so that the latent construct represents concern about safety (i.e. discomfort cycling). The safety construct indicator with the highest standardized loading (i.e. the strongest distinguisher among

Table 1
Joint distribution of responses to direct questions about energy and air quality consideration.

		"I consider energy expenditure (physical effort) when choosing a bicycle route."					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree	Total
"I consider air pollution (air quality) when choosing a bicycle route."	Strongly disagree	2.5%	1.6%	0.8%	2.5%	3.9%	11%
	Disagree	0.3%	2.0%	2.1%	5.1%	5.2%	15%
	Neutral	0.8%	1.1%	5.1%	8.5%	7.4%	23%
	Agree	0.8%	1.6%	4.6%	14.1%	7.7%	29%
	Strongly agree	0.5%	1.0%	1.8%	6.1%	12.8%	22%
	Total	5%	7%	14%	36%	37%	100%

Table 2
Responses to "How comfortable would you feel cycling on your own in each of the following situations?".

	Very uncomfortable	Uncomfortable	Comfortable	Very comfortable
On bicycle paths far away from motor vehicles	0.5%	0.7%	10.1%	88.7%
On local neighbourhood streets with little traffic and low speeds	0.5%	0.8%	26.6%	72.1%
On major streets, provided they have bicycle lanes separated from traffic with a physical barrier	2.3%	4.4%	38.7%	54.6%
On major streets, provided they have painted bicycle lanes	2.6%	17.6%	47.7%	32.0%
On major streets without bicycle lanes	28.9%	35.7%	24.5%	10.9%

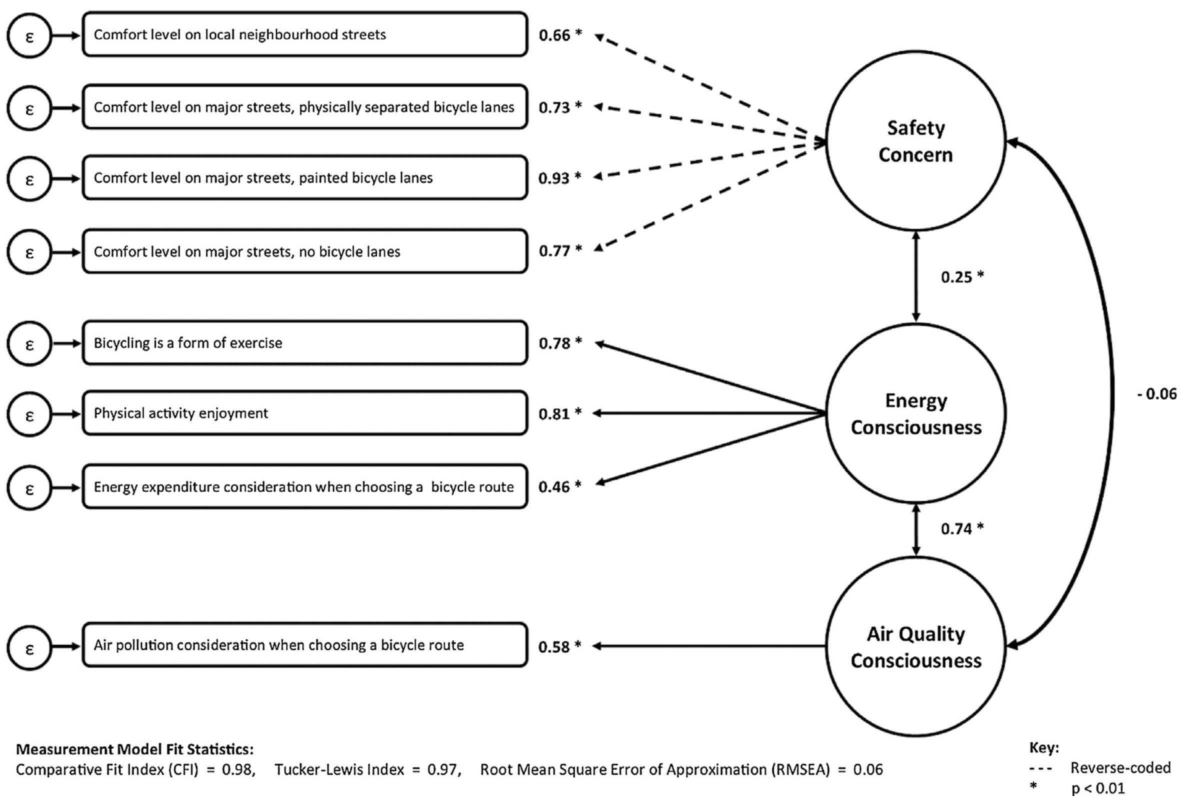

Fig. 2. Measurement model for latent constructs with standardized (β) coefficients.

respondents) was the stated comfort level on major streets with painted bicycle lanes ($\beta = 0.93$, $p < 0.01$); the lowest-loading indicator was the stated comfort level on local neighborhood streets ($\beta = 0.66$, $p < 0.01$).

A second latent construct, energy consciousness ($\alpha = 0.67$), was reflected by two indicators of perceptions of cycling and physical activity (“Bicycling is a form of exercise for me” and “I enjoy physical activity”), and a third indicator of consideration of energy expenditure in routing decisions (“I consider energy expenditure (physical effort) when choosing a bicycle route”). The former two indicators produced strong standardized loadings, while the latter produced the lowest loading ($\beta = 0.46$, $p < 0.01$) for this construct. A question about air pollution consideration (“I consider air pollution (air quality) when choosing a bicycle route”) was the sole observed indicator of the air quality consciousness construct ($\beta = 0.58$, $p < 0.01$).

The three constructs were associated with one another in the measurement model. Individuals who were conscientious of air quality also tended to exhibit higher levels of energy consciousness ($\beta = 0.74$, $p < 0.01$). In turn, individuals who were energy conscious were also more likely to express on-road cycling safety concerns ($\beta = 0.25$, $p < 0.01$). However, no significant relationship was found between the constructs of safety concern and air quality consciousness.

3.2. Structural equation model

The three-factor measurement model from the CFA was inserted into an SEM specification of the pathways outlined in the conceptual framework in Fig. 1. Table 3 details the estimation results for the final model, including the predictors of the three

Table 3
Estimated structural equation model with unstandardized (B) and standardized (β) coefficients.

Parameter estimates:	B	SE (B)	β	p-value
Regressions				
Safety concern ∼				
Individual education: some high school or less	1.54	0.45	0.20	0.00
Individual education: completed high school	0.06	0.23	0.01	0.80
Household vehicles per licensed drivers: <1	−0.61	0.19	−0.18	0.00
Energy consciousness ∼				
Individual education: some high school or less	−1.01	0.49	−0.15	0.04
Individual education: completed high school	−0.30	0.26	−0.06	0.25
Air quality consciousness ∼				
Individual education: some high school or less	−0.73	0.22	−0.21	0.00
Individual education: completed high school	0.11	0.17	0.05	0.52
Individual age: 40–49 years old	0.34	0.15	0.16	0.03
Individual age: 50 or more years old	0.21	0.14	0.13	0.13
Bicycling for commute purposes ∼				
Intercept trip purpose: commute	1.28	0.13	0.49	0.00
Individual age: 40–49 years old	−0.35	0.15	−0.10	0.02
Individual age: 50 or more years old	−0.58	0.12	−0.21	0.00
Household vehicles per licensed drivers: <1	0.27	0.10	0.11	0.01
Bicycling for shopping purposes ∼				
Intercept trip purpose: commute	−0.11	0.10	−0.05	0.29
Individual education: some high school or less	−0.78	0.21	−0.16	0.00
Individual education: completed high school	−0.19	0.13	−0.06	0.14
Household vehicles per licensed drivers: <1	0.35	0.10	0.17	0.00
Bicycling for recreational purposes ∼				
Intercept trip purpose: commute	−0.46	0.10	−0.21	0.00
Individual sex: female	−0.49	0.09	−0.22	0.00
Moderate-intensity physical activity ∼				
Energy consciousness	0.26	0.07	0.36	0.00
Vigorous-intensity physical activity ∼				
Energy consciousness	0.22	0.07	0.31	0.00
Individual age: 40–49 years old	−0.24	0.14	−0.08	0.10
Individual age: 50 or more years old	−0.27	0.11	−0.11	0.02
Individual sex: female	−0.24	0.10	−0.11	0.02
Covariances				
Safety concern ∼∼				
Energy consciousness	−0.73	0.32	−0.32	0.02
Air quality consciousness	0.13	0.11	0.11	0.27
Bicycling for commute purposes	−0.30	0.11	−0.19	0.01
Bicycling for shopping purposes	−0.34	0.09	−0.21	0.00
Bicycling for recreational purposes	−0.24	0.12	−0.15	0.04

Table 3 (*continued*)

Parameter estimates:	B	SE (B)	β	p-value
Energy consciousness ~~				
Air quality consciousness	0.66	0.19	0.64	0.00
Bicycling for commute purposes	0.11	0.14	0.07	0.43
Bicycling for shopping purposes	0.21	0.13	0.15	0.09
Bicycling for recreational purposes	0.45	0.19	0.31	0.02
Air quality consciousness ~~				
Bicycling for commute purposes	0.13	0.07	0.18	0.09
Bicycling for shopping purposes	0.18	0.06	0.26	0.00
Bicycling for recreational purposes	0.19	0.06	0.27	0.00
Bicycling for commute purposes ~~				
Bicycling for shopping purposes	0.51	0.05	0.51	0.00
Bicycling for recreational purposes	0.12	0.08	0.12	0.14
Moderate-intensity physical activity	0.10	0.11	0.10	0.35
Vigorous-intensity physical activity	0.07	0.06	0.07	0.22
Bicycling for shopping purposes ~~				
Bicycling for recreational purposes	0.38	0.08	0.38	0.00
Moderate-intensity physical activity	0.23	0.06	0.23	0.00
Vigorous-intensity physical activity	0.15	0.07	0.15	0.03
Bicycling for recreational purposes ~~				
Moderate-intensity physical activity	0.22	0.07	0.22	0.00
Vigorous-intensity physical activity	0.29	0.06	0.29	0.00
Moderate-intensity physical activity ~~				
Vigorous-intensity physical activity	0.52	0.05	0.52	0.00

Notes: Sample size (n) = 625. χ^2 (116) = 145.31, p = 0.03. Goodness-of-fit measures: Comparative Fit Index (CFI) = 0.97, Tucker-Lewis index (TLI) = 0.96, Root Mean Squared Error of Approximation (RMSEA) = 0.02, and Standardized Root Mean Squared Residual (SRMR) = 0.05.

latent constructs, predictors of the cycling outcomes, and relationships among the five exogenous outcomes. In the table, "Bicycling for ___ purposes" are the three cycling outcomes: variables representing how many of the past 30 days respondents reported riding a bicycle for "commuting to/from work or school," "shopping, errands, restaurant/dining, etc.", and "recreation or exercise". "Moderate-" and "vigorous-intensity physical activity" are the two physical activity outcomes: variables representing the self-reported typical number of hours per week engaged in each level of physical activity. As with the measurement model, the estimation of the final pathway model indicates a strong fit to the sample data (CFI = 0.97, TLI = 0.96, RMSEA = 0.02).

In the final SEM, a set of sociodemographic and economic characteristics were found to be predictive of the cyclist's safety concern, energy consciousness, and air quality consciousness. Surveyed cyclists who had completed only some high school or less (mostly under 18 years of age) were more likely to express safety concern for on-street cycling ($\beta = 0.20$, $p < 0.01$), but were less conscious of both energy ($\beta = -0.15$, $p = 0.04$) and air quality ($\beta = -0.21$, $p < 0.01$) compared to individuals with at least some college education. Cyclists with limited vehicle access were significantly less concerned about safety than those with at least one household vehicle per licensed driver ($\beta = -0.18$, $p < 0.01$). Cyclists over 40 years of age tended to be more air quality conscious than younger cyclists ($\beta = 0.16$, $p = 0.03$ for ages 40–49 and $\beta = 0.13$, $p = 0.13$ for ages 50+).

The direction and significance of SEM coefficients in Table 3 for the pathways between the latent constructs and the five cycling and physical activity outcomes are visualized in Fig. 3. Among the latent variables, energy and air quality consciousness were significantly positively related ($\beta = 0.64$, $p < 0.01$), while safety and energy consciousness were significantly negatively related ($\beta = -0.32$, $p = 0.02$) and the safety-air quality relationship was positive but not significant ($\beta = 0.11$, $p = 0.27$). Greater safety concern was significantly associated with less cycling frequency for all three trip purposes ($p \leq 0.04$). Energy consciousness was significantly positively associated with more recreational and exercise cycling ($\beta = 0.31$, $p = 0.02$). Interestingly, air quality consciousness was significantly associated with more shopping ($\beta = 0.26$, $p < 0.01$) and recreational ($\beta = 0.27$, $p < 0.01$) cycling. Note that all of these associations are included as two-way effects in the SEM (covariance). Energy consciousness of the cyclist had a significant positive effect on each level of physical activity ($p < 0.01$). The physical activity outcomes covaried significantly with each other ($\beta = 0.52$, $p < 0.01$) and with non-commute cycling frequency ($p \leq 0.03$), and cycling frequency significantly covaried among the three purposes with the exception of commute and recreational cycling. Note that significant relationships with physical activity could reduce the modeled direct effect of energy consciousness on cycling frequency.

A number of socio-demographic and economic characteristics also predicted the five exogenous outcomes. Surveyed cyclists who were at least 40 years old tended to engage in less commute cycling ($\beta = -0.10$, $p = 0.02$ for ages 40–49 and $\beta = -0.21$, $p < 0.01$ for ages 50+) and less vigorous physical activity ($\beta = -0.08$, $p = 0.10$ for ages 40–49 and $\beta = -0.11$, $p = 0.02$ for ages 50+) than their younger counterparts. Respondents with less access to private vehicles made more commute ($\beta = 0.11$, $p = 0.01$) and shopping-related ($\beta = 0.17$, $p < 0.01$) cycling trips. Female respondents tended to cycle less for recreational purposes ($\beta = -0.22$, $p < 0.01$) and engage in less vigorous physical activity ($\beta = -0.11$, $p = 0.02$) than male

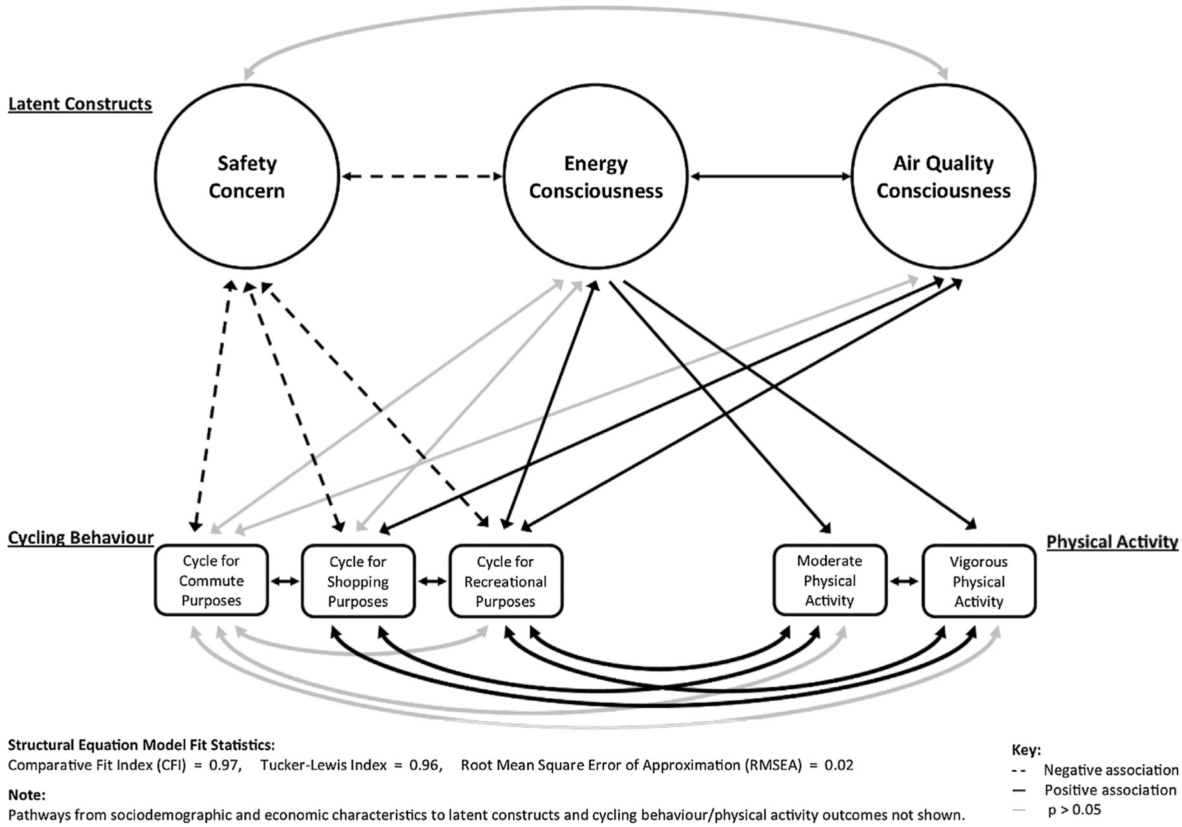

Fig. 3. Estimated pathways between latent constructs and outcome variables in SEM.

respondents. The purpose of the intercepted cycle trip was also tested in the model as a determinant of cycling frequency; cyclists who were intercepted on commute trips cycle-commuted more frequently ($\beta = 0.49$, $p < 0.01$), as expected, but also cycled less for the other two purposes.

4. Discussion

Air quality and energy expenditure were both explicitly stated concerns for at least half of the intercepted cyclists. The 51% who reported considering air quality when choosing a cycling route is more than reported in Badland and Duncan (2009) and less than in Cole-Hunter et al. (2015), although neither asked exactly the same question. Energy and air quality concerns were significantly related in this sample of cyclists, and both stronger for more frequent cyclists – especially recreational cyclists – and for those with higher educational attainment. These concerns could correlate in more health-conscious individuals, who are more aware of the indirect health benefits and risks of cycling. The relationship aligns with past research showing that people who are aware of one connection between the environmental and their health are more likely to be aware of other such connections (Bianco et al., 2008).

The SEM results suggest that air pollution and traffic safety risks are perceived differently by cyclists. The two latent constructs were not significantly related, which may have indicated general risk-aversion in certain cyclists. This finding is reasonable, as risk perception is known to vary across domains, effect pathways, and levels of power and control (Finucane, Slovic, Mertz, Flynn, & Satterfield, 2000; Hammitt & Liu, 2004; Vilela da Silva & Braga, 2018; Weber Elke, Ann-Renée, & Betz, 2002). Previous research also found different perceptions of air pollution and traffic safety risks for motor vehicle passengers in Thailand (Vassanadumrongdee & Matsuoka, 2005). Air quality was more of a concern for older cyclists and those with higher educational attainment, as expected (Badland & Duncan, 2009; Bianco et al., 2008). Safety was more of a concern for cyclists with less educational attainment, which could be related to a correlation between age and education.

People with stronger safety concerns cycle less, but not those with stronger air quality concerns. Previously, traffic safety concern was found to be a significant barrier to cycling (Sanders, 2015; Winters et al., 2011), while 13% reported air pollution was a barrier (Badland & Duncan, 2009). Conversely, considering the two-way effects in the model, cycling more frequently may decrease safety concerns, consistent with Sanders (2015), but increase air quality concerns. Cycling frequency has been associated with increased perception of air pollution exposure (Cole-Hunter et al., 2015), but in another study less experienced cyclists were more deterred by pollution level on a route (Anowar et al., 2017). The difference in findings is likely due to important distinctions between measures of recent cycling frequency and duration of regular cycling experience, and between the awareness of, versus concern about, air pollution risks.

Safety concern had a significant inverse relationship with energy concern, indicating that cyclists more worried about safety are thinking less about the energy aspects of their trip. Energy-conscious riders tended to get more exercise and ride more recreationally, suggesting that their concern with energy may not be trying to conserve it but to engage in more exercise. The notion of confident and exercise-oriented recreational cyclists is consistent with previously-identified cyclist social identities (Aldred, 2013).

Differences between recreational and utilitarian cycling are evident in the results. Commute cycling frequency was least impacted by energy and air quality concerns, and least associated with weekly physical activity. Cyclists intercepted on a commute trip tended to cycle less for other purposes, particularly recreational. In other words, less-utilitarian cycle trips seem to be more impacted by health-related considerations. This finding is consistent with a cyclist typology that distinguished among motivators for cycling, identifying systematic differences between speed and convenience-focussed dedicated cyclists and health-focussed leisure cyclists (Damant-Sirois et al., 2014).

Gender differences were not significant for any of the three latent concerns. Past research identified gender differences related to cycling on hills and physical activity (Bhat & Lockwood, 2004; Sener et al., 2009), as well as willingness to avoid air pollution risks during cycling (Cole-Hunter et al., 2015), but similar differences did not emerge in this study. Income was also tested but not significant for any of the latent or outcome variables. Pucher et al. (2011) found little relationship between cycling rates and income, but did postulate that there would be differences related to utilitarian vs. recreational trips.

5. Conclusions

The findings of this study are primarily illuminating for understanding of cyclists' consideration of energy expenditure and air quality. There are implications for improving modeling of cycling behaviour as well. First, we should consider air pollution and safety risks as distinct effects of traffic proximity for cyclists. These results show that they are distinct considerations, and the distinction will likely become more important for travel behaviour as the effects of traffic proximity on safety and air pollution risks could change dramatically in the near future with a growth in electric and/or autonomous vehicles. In addition, we should endeavor to explicitly model energy considerations in cycling behaviour, rather than proxy variables such as road grade. Energy consideration varies significantly among individuals and trip types, which can be expected to emerge as different route preferences related to hills and stops, different speed choices, and different valuation and adoption of electric pedal-assistance (i.e., e-bikes).

In terms of policies, this study reaffirms support for the common recommendation to provide bicycle facilities separated from motor vehicle traffic. Safety concerns are a deterrent to all types of cycling, and cyclists are more comfortable on facilities separated from motor vehicle traffic. Differences in safety concerns among cyclists were most evident for painted bike lanes on major roads – other facilities tended to be more universally comfortable or uncomfortable. Hence, we can expect to see the most heterogeneity in cyclist preferences and behaviour for these types of facilities.

The findings also suggest that educating the public about air pollution risks for cyclists may not be a deterrent to cycling – at least in cities such as Vancouver with relatively good air quality. Air pollution consciousness was actually higher in those with higher cycling frequency. Empowering individuals with specific information about the pollution risks of their route choices may enable more informed routing decisions, without scaring people off their bikes.

A main limitation of this study is that it relies on self-reported considerations, preferences, and habits. The data are vulnerable to response bias, particularly for questions about self-reported cycling and physical activity. Still, because the questionnaire was administered during a cycling trip, respondents had a specific context for questions about their considerations in routing decisions, and so the data are likely more robust than would be obtained through a more abstract instrument. Revealed preference data could support the findings with less vulnerability to hypothetical bias (Fifer, Rose, & Greaves, 2014), but separation of these concerns would be difficult without direct questioning. A choice experiment could be used to elicit value trade-offs among these factors, with the caveat that valuing health outcomes from choice experiments is challenging and vulnerable to framing of attributes and risk (Howard & Salkeld, 2009; Lloyd, 2003), and the conception of energy expenditure and air pollution risk by cyclists is still unclear. Further research is needed to examine how travellers ascertain both air pollution (smell, smoke, noise, public data, etc.) and energy expenditure (pedal torque, power output, total energy expenditure, perspiration, etc.).

Another limitation of the study is the indicators of latent concerns. Safety concern can be elicited in various ways, and testing different manifestations of safety perception was not the focus of this paper (Chataway et al., 2014; Sanders, 2015; Vilela da Silva & Braga, 2018). In addition to safety, cyclist comfort can be used to refer to various factors, including road grade and weather (Deenihan & Caulfield, 2015), hills and shade (Fu & Farber, 2017), and biomechanical ergonomic factors such as frame geometry, saddle position, and handlebars (Ayachi, Dorey, & Guastavino, 2015). Cycling comfort levels on four different facilities with varying levels of traffic exposure were significant indicators of the latent safety concern, but comfort on off-street facilities was not, which suggests that the factor is indeed traffic safety-related and not representative of more general comfort associated with hills, weather, or bicycle fit. Still, it is possible that some respondents associated comfort cycling near motor vehicle traffic with non-safety issues – even air pollution.

The study relies on data from a single population of cyclists, and transferability to other contexts is likely limited, particularly for locations with vastly different traffic safety or air pollution risks. Cyclists in heavily polluted cities, for example, may be more deterred by the consideration of air pollution. The sample also excludes non-cyclists, for whom energy expenditure and air pollution may be stronger deterrents. The exclusion of non-cyclists precludes analysis of barriers to cycling, but increases confidence in the validity of the response data. Questions about consideration of energy expenditure and air quality in cycle routing decisions would be highly abstract for people without urban cycling experience.

The sample demographics compare well to cyclists in a regional survey, but representativeness of the Vancouver cycling population is still uncertain. Not all cyclists had the opportunity to participate in the study, and even for cyclists present during sampling, participation could vary with factors such as time constraints, agency, and interest in cycling. These potential sample biases could affect the findings if they mediate the relationships among energy, air quality and safety considerations and are independent of the demographic and other control variables in model.

Future work should attempt to disaggregate cyclists' air pollution considerations by examining the relative importance of noxious fumes, visible smoke, noise, and air toxics (Cole-Hunter et al., 2015). Energy consideration could also be further disaggregated by separating perspiration, fatigue, and exercise motivations. Probably the least is known about urban cyclists' valuation of energy expenditure, and further investigation of this topic is crucial for evaluating and forecasting the impacts of electric-assist bicycles and other human-electric hybrid vehicles on our transportation systems. This study provides insights about the importance of energy expenditure and air pollution to different types of cyclists that can help guide these efforts.

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