Journal of Transport & Health 3 (2016) 107–113

Contents lists available at ScienceDirect

Journal of Transport & Health

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

Bicycle route preference and pollution inhalation dose: Comparing exposure and distance trade-offs

Alexander Y. Bigazzi [a,*], Joseph Broach [b,1], Jennifer Dill [b,2]

[a] Department of Civil Engineering, School of Community and Regional Planning, University of British Columbia, 2029 – 6250 Applied Science Lane, Vancouver, BC, Canada V6T 1Z4
[b] Nohad A. Toulan School of Urban Studies and Planning, Portland State University, PO Box 751, Portland, OR 97207-0751, United States

ARTICLE INFO

Article history:
Received 11 August 2015
Received in revised form
13 November 2015
Accepted 10 December 2015
Available online 28 December 2015

Keywords:
Bicycles
Route choice
Air pollution
Inhalation dose

ABSTRACT

Do bicyclist preferences for low-traffic facilities lead to route choices that minimize air pollution inhalation doses? For both preferences and doses a routing trade-off can exist between exposure to motor vehicle traffic and trip duration. We use past studies of bicycle route preferences and pollution exposure levels to estimate exposure/distance trade-offs among roadway facility types. Exposure/distance trade-offs for preferences and doses are found to be similar when comparing off-street paths, bike boulevards, and low-to-moderate traffic streets with or without bike lanes; when choosing a route among these facilities we expect bicyclists to approximately minimize inhalation doses. Compared to dose-minimizing behavior, bicyclists tend to use high-traffic streets too often if there is a bike lane and not enough if there is not. The recommendation for practice is to provide low-traffic routes wherever possible in bicycle networks, not to limit bicycle facilities on high-traffic streets. Networks with extensive low-traffic bicycle facilities are robust to misalignments between preferences and doses because they reduce both the likelihood and severity of excess (non-minimum) doses.

1. Introduction

Long-term exposure to traffic-related air pollution is associated with increased mortality (Hoek et al., 2013); short-term exposure during travel also has acute health effects (Peters et al., 2013). Although the long-term health impacts of exposure during travel specifically have not been established, it is often assumed in health impact assessments that the effects of changes in pollution inhalation during regular (commuting) travel, as a percent of daily inhalation, are similar to the effects of a proportional change in long-term exposure level (de Hartog et al., 2010; Schepers et al., 2015). Hence, routing behavior that minimizes pollution inhalation dose during travel can also be expected to minimize the pollution-related health risk of that travel.

Bicyclists choose routes based on a range of factors, including a preference for lower-traffic and off-street facilities, possibly motivated by considerations such as perceived safety, comfort, noise, and vehicle exhaust (Broach et al., 2012; Kang and Fricker, 2013; Sener et al., 2009; Tilahun et al., 2007; Winters and Teschke, 2010). But bicyclists will only accept a limited amount of additional travel duration or distance in order to use lower-traffic facilities. Use of low-traffic and off-street facilities reduces air pollution exposure for urban bicyclists (Bigazzi and Figliozzi, 2014); but if low-exposure bicycle routes require longer exposure duration, total inhaled pollutant dose for the trip can increase despite lower pollutant concentrations. For both preferences and pollution doses a routing trade-off can exist between exposure to motor vehicle traffic and trip duration.

A study of bicycle trips in Montreal found lower-pollution-exposure alternatives to shortest-distance routes for 57% of surveyed origin/destination pairs (Hatzopoulou et al., 2013a). Minimum-exposure routes had on average 5% lower modeled concentrations of nitrogen dioxide (NO_2) and 1% longer distance than shortest routes, with a net reduction in cumulative exposure (as concentration × distance) of 4%. A similar study of bicycle trips in Copenhagen estimated larger differences: 20–40% lower carbon monoxide (CO) and nitrogen oxides

---

[*] Corresponding author. Tel.: +1 604 822 4426.
E-mail addresses: abigazzi@civil.ubc.ca (A.Y. Bigazzi), jbroach@pdx.edu (J. Broach), jdill@pdx.edu (J. Dill).
[1] Tel.: +1 503 725 8204.
[2] Tel.: +1 503 725 5173.

http://dx.doi.org/10.1016/j.jth.2015.12.002

(NO_x) concentrations and 15% longer duration on low-exposure vs. shortest routes, with a net reduction in cumulative exposure (as concentration × time) of 10–30% (Hertel et al., 2008). Neither study included actual traveled routes nor route preferences, so willingness to detour to low-exposure routes was not addressed.

Route recall surveys and portable GPS devices have allowed researchers to identify and analyze the actual routes taken by urban transportation bicyclists. Observed routes commonly deviate from the shortest path, with mean distance deviations of 7% to 12% (Aultman-Hall et al., 1997; Broach et al., 2012; Winters and Teschke, 2010). Both revealed preference (RP) and stated preference (SP) data have been used to develop models of route choice that estimate the attributes that affect the attractiveness of travel routes. In addition to distance, RP-based models have found significant effects of upslope, bike facilities (e.g. bike paths, bike lanes, and signed bike routes), and delay factors (e.g. turns, traffic controls, busy crossings) (Broach et al., 2012; Hood et al., 2011; Menghini et al., 2010). Broach et al. (2012) reported strong and significant effects of traffic volumes greater than 10,000 vehicles per day for streets without bike lanes. Hood et al. (2011) did not find a significant effect of traffic volume, but this may be because they did not distinguish between busy streets with and without bike lanes.

SP work has found additional factors predicting route choice such as: adjacent vehicle parking, pavement condition, and traffic speed. Among SP studies, Sener et al. (2009) reported significant negative effects of increasing traffic, while Stinson and Bhat (2003) established negative correlations between higher-order streets (minor and major arterials) and stated route choices. In addition to route choice models, SP-based “level of service” (LOS) studies have often found traffic volume and the presence of bicycle facilities to be key determinants of perceived cycling quality (Jensen, 2007; Landis et al., 1997; Petritsch et al., 2007).

To our knowledge, low-pollution-exposure bicycle routing has not been compared with route preferences. It is unknown whether bicyclists tend to make route choices that minimize inhalation doses (and by extension minimize pollution-related health effects), or if they under-avoid or over-avoid high-traffic roadways compared to minimum-dose routes. The goal of this paper is to improve understanding of the air pollution risk implications of bicycle route preferences – information that is potentially important to the health-conscious design of bicycle networks and bicycle route guidance. The primary research questions are: (1) is the strength of bicyclist preferences for low-traffic facilities consistent with inhalation dose-minimizing behavior, and (2) what types of facilities most likely lead to route choices with excess (non-minimum) inhalation doses? These research questions are addressed by comparing route trade-offs between traffic exposure and travel distance for both preferences and inhalation doses (a more generalizable approach than a case study of a specific network). Future work will incorporate bicycle power and respiration models to estimate the effects of other route attributes (such as stops and grades), and examine route choices and doses in real-world transportation networks.

2. Methods

Routing preference trade-offs between two route attributes can be represented by the marginal rate of substitution (MRS): the change in one attribute that exactly offsets a change in another attribute. The MRS between a route attribute and distance can be expressed as an equivalent distance for preference (ED_p): the relative change in travel distance that has an equivalent effect on route preference as a change in another route attribute – see Broach et al. (2012). For example, a bicyclist might be ambivalent about the choice between a 10% longer route and a route with 5000 vehicles per day (veh/day) higher average daily traffic (ADT), all other factors being the same. This ED_p of 10% implies that the bicyclist would accept a route of up to 10% longer distance to avoid an increase of 5000 ADT.

Inhalation dose (I) in pollutant mass for a trip or trip segment is the product of the ventilation (breathing) rate of the traveler (V_E) in volume per unit time, the pollutant concentration in breathing-zone air (C) in mass per volume, and the trip duration, which is distance (d) divided by travel speed (v): $I = V_E C \frac{d}{v}$. We define the equivalent distance for inhalation dose, ED_d, as the % change in travel distance d that has an equivalent effect on trip inhalation dose I as some change in exposure level C. ED_d is also the maximum additional distance that can be traveled on a lower-exposure route while still achieving a lower total inhalation dose than a higher-exposure alternative. Calculation of ED_d is described in the next section.

Consider a shortest-path route compared with a lower-traffic but longer alternative route (detour), as illustrated in the left side of Fig. 1. If the difference in distances between the routes (Δd) is less than ED_d, then the detour is the lower-dose route (and vice-versa). If Δd is less than ED_p then the detour is also the preferred (and presumably traveled) route (and vice-versa).

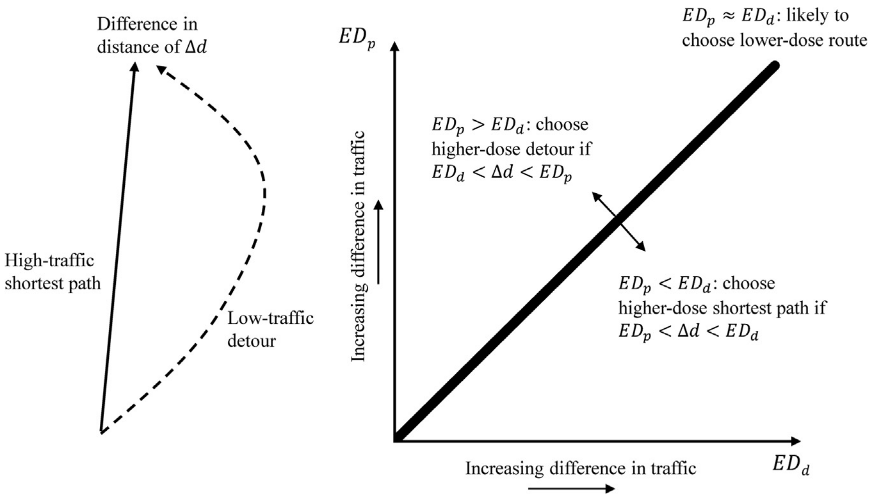

Fig. 1. Illustration of equivalent distance comparisons.

The right side of Fig. 1 illustrates a comparison of ED_p and ED_d . All other things being equal, ED_d and ED_p increase with the difference in traffic levels between the routes. If $ED_d \approx ED_p$ (the 45° line), then bicyclists are likely to choose the lower-dose route for any Δd because they make distance/traffic exposure trade-offs that align with trade-offs for inhalation doses. If $ED_p < ED_d$ (the lower right portion of the graph in Fig. 1) bicyclists are willing to accept less additional distance to avoid traffic than the dose-minimizing trade-off. If $ED_p > ED_d$ (the upper left portion of the graph) bicyclists are willing to accept more additional distance to avoid traffic than the dose-minimizing trade-off.

Misaligned *preferences* and doses ($ED_d \neq ED_p$) only materialize as *choice* of an excess (i.e. non-minimum) dose route if Δd is between ED_d and ED_p. Otherwise, bicyclists still choose the lower-dose detour (for small Δd) or shortest path (for large Δd). With a larger absolute difference $|ED_d - ED_p|$ there is greater opportunity for Δd to be between ED_d and ED_p (i.e. a preferred alternative to the minimum-dose route exists). The size of excess dose is the difference between Δd and ED_d, so the maximum possible excess dose for a chosen route is $|ED_d - ED_p|$. Hence, both the likelihood and potential severity of excess dose route choices increase with $|ED_d - ED_p|$.

2.1. *Equivalent distance for inhalation dose,* ED_d

We consider only differences in exposure level and distance; investigation of systematic route-level differences in bicyclist ventilation and speed is left for future work, as discussed in the final section. If V_E and v are static, the ED_d for two routes (low-traffic LT and high-traffic HT) can be calculated by setting $I_{LT} = I_{HT}$:

$$ED_d = \frac{d_{LT}}{d_{HT}} - 1 = \frac{C_{HT}}{C_{LT}} - 1$$

In words, the ED_d is equal to the fractional excess exposure concentration on the high-traffic route.

Exposure concentration ratios $\frac{C_{HT}}{C_{LT}}$ are determined by numerous route attributes such as traffic volume and composition, intersections and major road crossings, distance to major roads, bicycle facility type, near-road sources (i.e. land-use), etc. (Bigazzi and Figliozzi, 2014; Boogaard et al., 2009). This paper investigates the effects of traffic volume and facility type. Table 1 summarizes previously reported bicyclist exposure comparisons on roadways with varying ADT for volatile organic compounds (VOC), carbon monoxide (CO), and several sizes and types of particulate matter (PM). Bigazzi and Figliozzi (2015) provide a mathematical model of on-road exposure as a function of ADT: $\frac{C_{HT}}{C_{LT}} = \exp(\beta \bullet \Delta ADT)$, where β is a pollutant-specific coefficient and ΔADT is the ADT difference between facilities. The other studies in Table 1 report concentration ratios on high-traffic versus low-traffic facilities; ΔADT is calculated from the central values of each. The last column in Table 1 reports ED_d per 1000 ADT, computed for Bigazzi and Figliozzi (2015) as $\exp(\beta \bullet 1,000) - 1$ and for the other studies as $\frac{\left(\frac{C_{HT}}{C_{LT}} - 1\right)}{\left(\frac{\Delta ADT}{1,000}\right)}$.

Other studies have reported bicyclist exposure concentrations on different facility types, but without specific traffic data or with spatially aggregated traffic data (such as ADT/km^2 used in land use regression models). CO, black carbon particulate matter (BC), and ultrafine particulate matter (UFP) concentrations have been observed to be lower for on-street bicycle facilities that are more physically separated from motor vehicle traffic lanes (Hatzopoulou et al., 2013b; Kendrick et al., 2011). MacNaughton et al. (2014) measured 30% higher BC and NO_2 concentrations for on-street bike lanes than off-street paths. Bigazzi and Figliozzi (2015) suggest that CO and VOC concentrations for off-street paths parallel to roadways are similar to the lowest-traffic (i.e. zero-ADT) streets, while paths in more separated locations such as a park can be 20% lower. Assuming traffic volume effects of 1.5% and 3.0% per 1000 ADT for CO and UFP respectively (from the other studies in Table 1), the concentrations differences in Kingham et al. (2013) indicate off-street path concentrations 30% and 50% lower for CO and UFP respectively than the traffic volume effect alone (i.e. lower than a zero-ADT on-street facility).

Table 1
Reported exposure comparisons on facilities with ADT differences of ΔADT.

Source and setting	**Form**	**Comparison**	**Pollutant**[a]	C_{HT}/C_{LT}	**ED_d per 1000 ADT**
Bigazzi and Figliozzi (2015): AM peak periods, spring-summer, USA	Log-linear regression model	On-street facilities with varying ADT	VOC	$\exp(1.5e-5^*\Delta ADT)$	1.5%
			CO	$\exp(1.2e-5^*\Delta ADT)$	1.2%
Jarjour et al. (2013): AM peak periods, spring-summer, USA	Ratio	$\Delta ADT \approx 16,000$	UFP	1.48	3.0%
			CO	1.21	1.3%
			BC	1.21 (NS)	1.3% (NS)
			$PM_{2.5}$	0.93 (NS)	−0.4% (NS)
Kingham et al. (2013): AM and PM peak periods, autumn, New Zealand	Ratio	$ADT \approx 22,500$ (on-street vs. off-street routes)	UFP	2.2	5.3%
			CO	1.6	2.7%
			PM_1	1.2	0.9%
Zuurbier et al. (2010): AM peak periods, year-round, Netherlands	Ratio	$\Delta ADT \approx 10,000$	Soot	1.30	3.0%
			PNC	1.18	1.8%
			$PM_{2.5}$	1.08 (NS)	0.8% (NS)
			PM_{10}	0.96 (NS)	−0.4% (NS)
Strak et al. (2010): AM peak periods, spring, Netherlands	Ratio	$\Delta ADT \approx 17,750$	PNC	1.52	2.9%
			Soot	1.45	2.5%
Int Panis et al. (2010): unknown times, summer, Belgium	Ratio	$\Delta ADT \approx 35,000$ (different cities)	PNC	3.1	6.0%

NS: C_{HT} vs. C_{LT} difference not significant (not all studies included statistical comparisons).

[a] Pollutants: volatile organic compounds (VOC), carbon monoxide (CO), particle number concentration (PNC), particulate matter with aerodynamic diameter less than $X \in 1, 2.5, 10$ microns (PM_x), black carbon particulate matter (BC), and ultrafine particulate matter (UFP)

Table 2
ED_p Calculated from Broach et al. (2012).

Facility[a]	ADT[b]	Reference: off-street path		Reference: bike boulevard	
		Commuter (%)	Non-commuter (%)	Commuter (%)	Non-commuter (%)
Off-street path	NA	0	0	−5.8	−9.8
Bike boulevard	0–5000	6.2	10.9	0	0
Bike lane	0–57,000	19.1	35.1	12.2	21.8
Mixed traffic	0–10,000				
Mixed traffic	10,000–20,000	63.0	65.2	53.5	49.0
Mixed traffic	20,000–30,000	186	221	170	189
Mixed traffic	30,000–72,000	876	872	819	776

[a] “Mixed traffic” is a roadway without separate bike lanes: bicycles share the roadway with motor vehicles. “Bike boulevard” (a type of mixed traffic facility) is on low-traffic streets, usually in residential areas, with traffic calming and control devices that reduce the speed and volume of motor vehicle traffic.

[b] ADT values reflect the range of data used in model estimation.

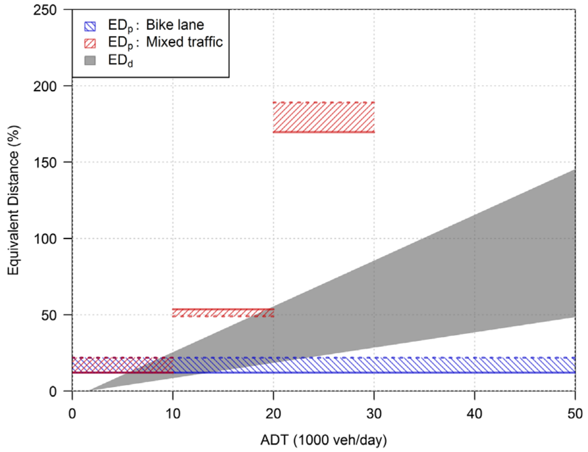

Fig. 2. ED_p and ED_d for on-street facilities with varying ADT vs. a bike boulevard (ED_p ranges from the commuter value (solid line) to the non-commuter value (dashed line)).

Similar to the approach in this paper, ADT was previously used as an indicator of pollution exposure levels on bicycle routes (Hertel et al., 2008). Applied in this way, ADT represents the effects of not just the traffic volume (i.e. total on-road vehicle emissions) but also roadway and built environment characteristics that correlate with ADT and influence on-road exposure. Arterial roadways likely have more near-road stationary emissions sources, a higher percentage of trucks, and a wider cross-section than low-traffic local streets, and so ADT also acts as a proxy for these factors in the analysis. Another factor that is wrapped into the exposure-ADT relationship is the relative contribution of on-road sources to ambient concentrations of each pollutant: higher background concentrations lead to smaller percentage impacts of ADT on C, as can be observed for fine and coarse PM in Table 1. Due to these conflated factors the relationships summarized in Table 1 are context- and pollutant-dependent. Still, this approach is appropriate for the analysis because those factors would also be correlated in other, similar settings. The exposure-ADT relationships in Table 1 are expected to represent trip-average exposure differences during peak periods in developed countries (based on the study settings described in the first column); future work should examine these relationships in other contexts.

2.2. *Equivalent distance for route preferences,* ED_p

ED_p can be extracted from estimated route choice model coefficients as $\mathrm{ED}_p = \exp\left(\frac{\beta_{alt} - \beta_{ref}}{\beta_d}\right) - 1$, where β_d is the estimated coefficient on ln(distance) and β_{ref} and β_{alt} are estimated coefficients for the proportion of route on reference and alternative facilities, respectively (Broach et al., 2012). Table 2 gives ED_p for various (alternative) facilities, calculated from Broach et al. (2012), using off-street path and low-traffic bike boulevard as reference facilities. The on-street facility types are: bike boulevard (on-street, no bike lane, traffic calmed), bike lane (on-street, paint-separated lane), and mixed traffic (on-street, no bike lane).

Broach et al. (2012) developed the route choice model from GPS data collected by 164 adult bicyclists recruited using a variety of non-random methods from throughout the Portland, Oregon metropolitan area (the same city used to develop the exposure model in Bigazzi and Figliozzi (2015)). The participants were primarily experienced cyclists who reported riding weekly throughout the year; female cyclists were purposely oversampled. Cyclists on commute trips (defined by the authors as any direct trip between home and work in either direction) were relatively more sensitive to distance but also more sensitive to traffic, perhaps because travel was more likely during peak periods. These offsetting preferences resulted in commuting cyclists being either more or less willing to avoid traffic, depending on the specific traffic level.

Broach et al. (2012) is the only known study to report bicyclist preferences with specific traffic levels (ADT). Sener et al. (2009) used stated preference data to estimate a route choice model with travel duration as the measure of route length. They report MRS of different facility characteristics with travel time, which can be translated to ED_p using the mean trip duration (30 min) and assuming constant travel speeds: 37% for moderate versus light traffic and 103–130% for heavy versus light traffic. Specific thresholds for light, medium, and heavy traffic are not provided. Other bike route choice models did not generate traffic-based parameters which could be used for this analysis.

3. Results

From Table 1, 1–3% per 1000 ADT appears to be a good estimate of ED_d between on-street facilities for strongly traffic-related pollutants (UFP or PNC, BC or soot, CO, and VOC). This range of values is small considering the variety of pollutants and study conditions in Table 1. Higher ED_d of up to 6% per 1000 ADT was reported for UFP in cross-city and on-street/off-street comparisons. Lower ED_d (0–1% per 1000 ADT) was reported for larger particle sizes ($\text{PM}_{2.5}$ and PM_{10}) which are more widely distributed in an urban area. Based on the facility comparison studies, we estimate ED_d for on-street facilities compared to off-street paths as the traffic volume effect (due to ΔADT) plus an additional reduction of 0–50%.

Fig. 2 shows ED_p and ED_d for on-street facilities with varying ADT versus a low-traffic bike boulevard with 1500 ADT (Broach et al., 2012; National Association of City Transportation Officials, 2014). The upper limit of 50,000 ADT reflects the traffic volume range from the studies in Table 1. ED_d is plotted for the range 1–3% per 1000 ΔADT (grey area). ED_p is plotted for a range from the commuter value (solid line) to the non-commuter value (dashed line) in Table 2. ED_p is similar to or slightly higher than ED_d for streets with or without bike lanes up to $\sim$20,000 ADT. Over 20,000 ADT, $\text{ED}_p < \text{ED}_d$ with bike lanes and $\text{ED}_p > \text{ED}_d$ dramatically without bike lanes; the area for mixed traffic and $\text{ADT} > 30,000$ is off the figure at $\text{ED}_p \approx 800\%$. The ED_p and ED_d comparisons show that bicyclists might be unwilling to detour on a lower-dose bike boulevard when presented with a shorter route using bike lanes on arterials (especially commuters), and they might be willing to take a higher-dose detour on a bike boulevard when presented with a shorter route using arterials without bike lanes (especially non-commuters).

Fig. 3 shows ED_p and ED_d for on-street facilities with varying ADT versus an off-street path, again using ED_p from Table 2 ranging from the commuter to non-commuter values. ED_d is plotted as the traffic volume effect of 1–3% per 1000 ΔADT (as in Fig. 2) plus two different off-street reductions: 0–50% (lighter grey) and a fixed 25% (darker grey). The comparisons are similar to Fig. 2 – and almost exactly aligned if the off-street reduction is 10%. Preference and dose trade-offs are misaligned for high-traffic streets with a bike lane ($\text{ED}_p < \text{ED}_d$) or without ($\text{ED}_p > \text{ED}_d$); mixed traffic with $\text{ADT} > 30,000$ is again out of the range of the plot. ED_p for bike boulevards is at the low end of the ED_d range, implying some potential unwillingness to detour to a lower-dose off-street path when presented with a shorter route using bike boulevards.

Fig. 4 shows ranges of the difference $\text{ED}_d - \text{ED}_p$ for the facility comparisons in the previous two figures. The off-street path comparisons use the wider ED_d range from Fig. 3; mixed traffic with $ADT > 30,000$ is excluded because it is out of the range of the figure ($\sim$800%). Value ranges toward the right in Fig. 4 indicate $ED_d > ED_p$: less willingness to detour than dose-minimizing trade-offs. Value ranges toward the left in Fig. 4 indicate $ED_d < ED_p$: greater willingness to detour than dose-minimizing trade-offs. The distance from 0 in Fig. 4 is the maximum potential excess dose due to misalignment of preference and dose trade-offs, i.e. $|ED_d - ED_p|$.

From Fig. 4, preferences for bike lane routes can more than double inhaled doses compared to lower-exposure detours on bike boulevards or off-street paths. Preferences for low-traffic detours from more direct routes on mixed traffic facilities with ADT of 20,000–30,000 can double or triple inhaled doses. Inhaled doses can be up to nine times higher if the high-traffic direct route is on mixed traffic facilities with $\text{ADT} > 30,000$. The differences between ED_d and ED_p among off-street paths, bike boulevards, and streets with $\text{ADT} < 20,000$ (with or without bike lanes) are generally under 50%; if bicyclists choose an excess-dose route among these facilities, the magnitude of the excess dose is expected to be relatively small.

The figures in this section use ED_d estimated for CO, VOC, BC, and UFP. Fine and coarse particulate matter is expected to have lower ED_d, which would exacerbate the excess doses due to over-detouring from arterials without bike lanes ($\text{ED}_p > \text{ED}_d$), but reduce or eliminate the risks of $\text{ED}_p < \text{ED}_d$ for bike lanes on high-traffic streets. ED_p for the preceding figures was based on Broach et al. (2012); using ED_p from Sener et al. (2009) likely also results in $\text{ED}_p > \text{ED}_d$ for high-traffic versus low-traffic roadways (ED_p of 100–130%), depending on the ADT thresholds.

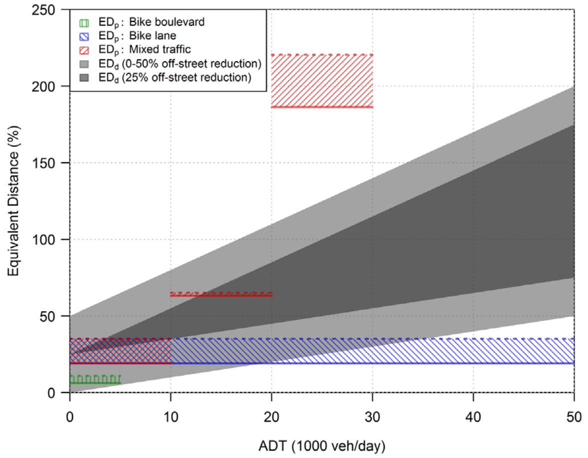

Fig. 3. ED_p and ED_d for on-street facilities with varying ADT vs. an off-street path (ED_p ranges from the commuter value (solid line) to the non-commuter value (dashed line)).

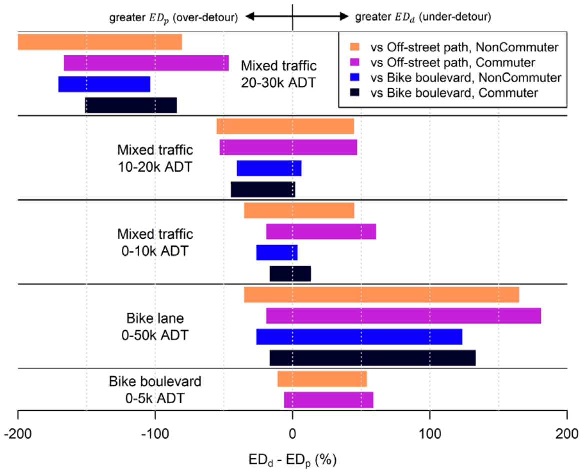

Fig. 4. Ranges of $ED_d - ED_p$ for different facilities vs. bike boulevards and off-street paths; distance from 0 is maximum excess dose.

4. Discussion

Traffic exposure/distance trade-offs are similar between bicyclists' preferences and inhalation doses of VOC, CO, UFP, and BC when comparing off-street paths, bike boulevards, and low-to-moderate traffic streets with or without bike lanes. Thus, there are many situations where we expect bicyclists to make route choices with approximately minimum inhalation doses (and pollution-related health risks) due to their preferences for low-traffic facilities. High-traffic arterial streets above 20,000 ADT are the main exception: compared to dose-minimizing behavior, bicyclists tend to choose these facilities too often if there is a bike lane and not enough as a more direct alternative if there is not a bike lane.

Misalignment of preference and dose trade-offs only leads to actual excess doses if (1) bicyclists encounter traffic exposure/distance trade-offs in their route choice set (i.e. a low-traffic route deviates from the shortest path) and (2) the distance trade-off is between the preference and dose trade-offs. Networks with more extensive low-traffic routes are robust to misalignments between preferences and doses because they decrease the likelihood of encountering an exposure/distance trade-off. In previous work most bicycle trips had low-exposure route options that deviated from the shortest path, although the amount of additional distance was inconsistent between studies, likely due to different network configurations and exposure modelling approaches (Hatzopoulou et al., 2013a; Hertel et al., 2008). A large difference between preference and dose trade-offs increases the opportunity for an excess-dose route to be preferred and increases the potential size of excess doses.

The implication of these findings for practice is to provide low-traffic routes wherever possible in bicycle networks, not to limit bicycle facilities on high-traffic streets. An extensive grid of low-traffic bicycle facilities: (1) minimizes doses between any two points on the transportation network, (2) reduces the likelihood of bicyclists encountering an exposure/distance trade-off (the shortest route is likely low-exposure), and (3) reduces the likelihood of an exposure/distance trade-off leading to an excess-dose route choice (Δd is likely smaller than both $\mathrm{ED}p$ and ED_d). This approach will be most successful in areas with a well-connected street network and reinforces the value of policies aimed at improving network connectivity. Although high-traffic streets with or without bike lanes can lead to excess doses, the upper-limit size of excess dose $|\mathrm{ED}_p - \mathrm{ED}_d|$ is about five times higher for high-traffic streets without bike lanes than with (even more if considering fine and coarse PM, with lower ED_d). If there is an excess-dose route choice, a smaller required detour distance (Δd) from a high-traffic street without bike lanes decreases the size of excess dose. Some bicyclists will be on high-traffic streets regardless of the bicycle facilities (inadequate low-traffic alternatives, low marginal rates of substitution of distance for traffic ("vehicular cyclists"), and/or trip ends on arterials), and bicycle facilities can provide safety benefits. Physically separated bicycle facilities on high-traffic arterials can reduce exposure levels by lateral separation (Hatzopoulou et al., 2013b; Kendrick et al., 2011) and avoidance of traffic queues; this type of facility was not included in the data used for this paper, but warrants further research. In addition, there are many strategies for mitigating pollution risks for bicyclists that are not facility- or route-based and outside the scope of this paper, such as travel time shifts, traffic management, and low-emissions vehicle technology.

This paper examines whether preferences implied by observed routing behavior leads to minimum-dose route choices, but does not address the rationality or optimality of the behavior. Bicyclists make routing decisions by weighing many factors, of which pollution is potentially one. Little is known about the role of pollution in route choices – which could be difficult to disentangle from other factors strongly correlated with traffic such as safety, noise, and stress. Further research on these choices would be useful, including whether providing information about pollution and crash risk exposure would change behavior and reduce negative health impacts. Heterogeneity of routing preferences was not addressed in this paper, nor was generalizability of route preferences from the sample population of riders, or the effect of the route choice set on the decision to bicycle at all.

The existing literature on bicyclist pollution exposure lacks information on the intra-modal, roadway determinants of exposure (Bigazzi and Figliozzi, 2014). A wide range of bicycle exposure concentrations have been reported on varying route types in cities around the world in more than 40 published studies, but there is little consistency in the roadway data that are reported, precluding comparisons across studies and meta-analyses of transportation network effects. In this paper we used six studies that reported varying bicyclist exposure concentrations and ADT on sampled routes (Table 1); studies of the net health impacts of bicycle facilities have similarly relied on a small subset of the bicyclist exposure literature (Schepers et al., 2015). We recommend ADT as a minimum bicycle sampling route metric to report in future exposure studies, as well as background concentrations for context.

This paper presents a comparison of preference and dose trade-offs in the abstract; an advantage of this approach is that the findings are not specific to a network configuration. Future work will investigate the prevalence of excess-dose route choices in real-world networks. The next step in this research is to employ bicycle power and physiology models to incorporate the influences of road grade and intersections on route choices and doses. Additional future work will estimate absorbed doses and include route choice effects on physical activity and safety.

Acknowledgmenets

The data for this analysis was supported by the following grants: Robert Wood Johnson Foundation, Active Living Research (Grant no. 51711) and National Institute for Transportation and Communities (NITC) (Grant nos. 560, 849), a university transportation center funded by the US Department of Transportation (Grant no. DTRT12-G-UTC15). The research sponsors had no role in the study design, the collection, analysis and interpretation of data, the writing of the report, or the decision to submit the article for publication.

References

Aultman-Hall, L., Hall, F., Baetz, B., 1997. Analysis of bicycle commuter routes using geographic information systems: implications for bicycle planning. Transp. Res. Rec.: J. Transp. Res. Board 1578, 102–110. http://dx.doi.org/10.3141/1578-13.

Bigazzi, A.Y., Figliozzi, M.A., 2015. Roadway determinants of bicyclist exposure to volatile organic compounds and carbon monoxide. Transp. Res. Part D: Transp. Environ. 41, 13–23. http://dx.doi.org/10.1016/j.trd.2015.09.008.

Bigazzi, A.Y., Figliozzi, M.A., 2014. Review of urban bicyclists' intake and uptake of traffic-related air pollution. Transp. Rev. 34, 221–245. http://dx.doi.org/10.1080/01441647.2014.897772.

Boogaard, H., Borgman, F., Kamminga, J., Hoek, G., 2009. Exposure to ultrafine and fine particles and noise during cycling and driving in 11 Dutch cities. Atmos. Environ. 43, 4234–4242. http://dx.doi.org/10.1016/j.atmosenv.2009.05.035.

Broach, J., Dill, J., Gliebe, J., 2012. Where do cyclists ride? A route choice model developed with revealed preference GPS data. Transp. Res. Part A: Policy Pract. 46, 1730–1740. http://dx.doi.org/10.1016/j.tra.2012.07.005.

de Hartog, J.J., Boogaard, H., Nijland, H., Hoek, G., 2010. Do the health benefits of cycling outweigh the risks? Env. Health Perspect. 118, 1109–1116. http://dx.doi.org/10.1289/ehp.0901747.

Hatzopoulou, M., Weichenthal, S., Barreau, G., Goldberg, M., Farrell, W., Crouse, D., Ross, N., 2013a. A web-based route planning tool to reduce cyclists' exposures to traffic pollution: A case study in Montreal, Canada. Environ. Res. 123, 58–61. http://dx.doi.org/10.1016/j.envres.2013.03.004.

Hatzopoulou, M., Weichenthal, S., Dugum, H., Pickett, G., Miranda-Moreno, L., Kulka, R., Andersen, R., Goldberg, M., 2013b. The impact of traffic volume, composition, and road geometry on personal air pollution exposures among cyclists in Montreal, Canada. J. Expo. Sci. Env. Epidemiol. 23, 46–51. http://dx.doi.org/10.1038/jes.2012.85.

Hertel, O., Hvidberg, M., Ketzel, M., Storm, L., Stausgaard, L., 2008. A proper choice of route significantly reduces air pollution exposure – a study on bicycle and bus trips in urban streets. Sci. Total Environ. 389, 58–70. http://dx.doi.org/10.1016/j.scitotenv.2007.08.058.

Hoek, G., Krishnan, R.M., Beelen, R., Peters, A., Ostro, B., Brunekreef, B., Kaufman, J.D., 2013. Long-term air pollution exposure and cardio-respiratory mortality: a review. Env. Health 12, 43.

Hood, J., Sall, E., Charlton, B., 2011. A GPS-based bicycle route choice model for San Francisco, California. Transp. Lett.: Int. J. Transp. Res. 3, 63–75. http://dx.doi.org/10.3328/TL.2011.03.01.63-75.

Int Panis, L., de Geus, B., Vandenbulcke, G., Willems, H., Degraeuwe, B., Bleux, N., Mishra, V., Thomas, I., Meeusen, R., 2010. Exposure to particulate matter in traffic: a comparison of cyclists and car passengers. Atmos. Environ. 44, 2263–2270. http://dx.doi.org/10.1016/j.atmosenv.2010.04.028.

Jarjour, S., Jerrett, M., Westerdahl, D., Nazelle, A., de, Hanning, C., Daly, L., Lipsitt, J., Balmes, J., 2013. Cyclist route choice, traffic-related air pollution, and lung function: a scripted exposure study. Environ. Health 12. http://dx.doi.org/10.1186/1476-069X-12-14.

Jensen, S., 2007. Pedestrian and bicyclist level of service on roadway segments. Transp. Res. Rec.: J. Transp. Res. Board 2031, 43–51. http://dx.doi.org/10.3141/2031-06.

Kang, L., Fricker, J.D., 2013. Bicyclist commuters' choice of on-street versus off-street route segments. Transportation. 40, 887–902. http://dxdoi.org/10.1007/s11116-013-9453-x.

Kendrick, C., Moore, A., Haire, A., Bigazzi, A., Figliozzi, M.A., Monsere, C., George, L., 2011. Impact of bicycle lane characteristics on exposure of bicyclists to traffic-related particulate matter. Transp. Res. Rec.: J. Transp. Res. Board 2247, 24–32. http://dx.doi.org/10.3141/2247-04.

Kingham, S., Longley, I., Salmond, J., Pattinson, W., Shrestha, K., 2013. Variations in exposure to traffic pollution while travelling by different modes in a low density, less congested city. Environ. Pollut. 181, 211–218. http://dx.doi.org/10.1016/j.envpol.2013.06.030.

Landis, B., Vattikuti, V., Brannick, M., 1997. Real-time human perceptions: toward a bicycle level of service. Transp. Res. Rec.: J. Transp. Res. Board 1578, 119–126. http://dx.doi.org/10.3141/1578-15.

MacNaughton, P., Melly, S., Vallarino, J., Adamkiewicz, G., Spengler, J.D., 2014. Impact of bicycle route type on exposure to traffic-related air pollution. Sci. Total Environ. 490, 37–43. http://dx.doi.org/10.1016/j.scitotenv.2014.04.111.

Menghini, G., Carrasco, N., Schüssler, N., Axhausen, K.W., 2010. Route choice of cyclists in Zurich. Transp. Res. Part A: Policy Pract. 44, 754–765. http://dx.doi.org/10.1016/j.tra.2010.07.008.

National Association of City Transportation Officials, 2014. Urban Bikeway Design Guide, 2nd ed. Island Press, Washington, DC.

Peters, A., Klot, S., von, Mittleman, M.A., Meisinger, C., Hörmann, A., Kuch, B., Wichmann, H.E., 2013. Triggering of acute myocardial infarction by different means of transportation. Eur. J. Prev. Cardiol. 20, 750–758. http://dx.doi.org/10.1177/2047487312446672.

Petritsch, T., Landis, B., Huang, H., McLeod, P., Lamb, D., Farah, W., Guttenplan, M., 2007. Bicycle level of service for arterials. Transp. Res. Rec.: J. Transp. Res. Board 2031, 34–42. http://dx.doi.org/10.3141/2031-05.

Schepers, P., Fishman, E., Beelen, R., Heinen, E., Wijnen, W., Parkin, J., 2015. The mortality impact of bicycle paths and lanes related to physical activity, air pollution exposure and road safety. J. Transp. Health Forthcom. 2, 460–473. http://dx.doi.org/10.1016/j.jth.2015.09.004.

Sener, I.N., Eluru, N., Bhat, C.R., 2009. An analysis of bicycle route choice preferences in Texas, US. Transportation 36, 511–539. http://dx.doi.org/10.1007/s11116-009-9201-4.

Stinson, M., Bhat, C., 2003. Commuter bicyclist route choice: analysis using a stated preference survey. Transp. Res. Rec.: J. Transp. Res. Board 1828, 107–115. http://dx.doi.org/10.3141/1828-13.

Strak, M., Boogaard, H., Meliefste, K., Oldenwening, M., Zuurbier, M., Brunekreef, B., Hoek, G., 2010. Respiratory health effects of ultrafine and fine particle exposure in cyclists. Occup. Environ. Med. 67, 118–124. http://dx.doi.org/10.1136/oem.2009.046847.

Tilahun, N.Y., Levinson, D.M., Krizek, K.J., 2007. Trails, lanes, or traffic: Valuing bicycle facilities with an adaptive stated preference survey. Transp. Res. Part A: Policy Pract. 41, 287–301. http://dx.doi.org/10.1016/j.tra.2006.09.007.

Winters, M., Teschke, K., 2010. Route preferences among adults in the near market for bicycling: findings of the cycling in cities study. Am. J. Health Promot. 25, 40–47. http://dx.doi.org/10.4278/ajhp.081006-QUAN-236.

Zuurbier, M., Hoek, G., Oldenwening, M., Lenters, V., Meliefste, K., Van Den Hazel, P., Brunekreef, B., 2010. Commuters' exposure to particulate matter air pollution is affected by mode of transport, fuel type, and route. Environ. Health Perspect. 118, 783–789.