

TRANSPORT FINDINGS

Revealed Preferences for Utilitarian Cycling Energy Expenditure versus Travel Time

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Findings

This paper quantifies the perceived cost of utilitarian cycling energy expenditure as the marginal rate of substitution between energy expenditure and travel time (MRS_{et}). This trade-off manifests in, and can be inferred from cyclist cruising speeds. Median MRS_{et} values for observed cruising events in a naturalistic cycling dataset range from 0.05 to 0.95 min/km per kcal/min. The revealed cost of energy expenditure (relative to travel time) increases significantly with road grade, traffic controls, and certain facility types, and is also significantly higher for women, less-dedicated cyclists, and people riding on weekends and for non-commute purposes.

1. QUESTIONS

Cycling speed varies with individual, trip, and contextual factors, reflecting cyclists' trade-offs (Clarry, Imani, and Miller 2019; El-Geneidy, Krizek, and Iacono 2007; Yan, Maat, and van Wee 2024). Some of these trade-offs for cycling speed choice were modeled in a steady-state utility maximization framework considering travel time, energy expenditure, and bicycle stability/control (Bigazzi and Lindsey 2019). We use that modelling framework to investigate the relative perceived costs of energy expenditure and travel time for utilitarian cycling, quantified as the marginal rate of substitution between energy expenditure and travel time (MRS_{et}). MRS_{et} is the key behavioral parameter in the cycling speed choice model, and calibration allows the prediction of desired cycling speed when combined with three physical/physiological parameters: rider and equipment mass, effective frontal area, and coefficient of rolling resistance. Quantifying MRS_{et} also enables energy-sensitive analysis of cycling accessibility, infrastructure design, route and mode choices, and e-bike adoption.

2. METHODS

Speed choice model framework

In the model framework proposed by Bigazzi and Lindsey (2019), the utility-maximizing desired cycling speed v in m/s can be computed as:

$$v = \sqrt{\frac{1}{6\mu_3} \left(\sqrt{\mu_1^2 + \frac{200\mu_3}{\delta_1 MRS_{et}}} - \mu_1 \right)} \quad (\text{Eq.1})$$

where δ_1 is the rate of increase of energy expenditure with cycling work rate in kcal/min per W, μ_1 and μ_3 are the first- and third-order speed coefficients in the equation of cycling power in Ws/m and Ws³/m³, respectively, and MRS_{et} is the ratio of the marginal disutility of energy expenditure in kcal/min to travel time in min/km. MRS_{et} can be inferred from an observed cruising speed (desired speed in free-flow conditions) as:

$$MRS_{et} = \frac{1}{0.06v^2\delta_1(\mu_1 + 3\mu_3v^2)} \quad (\text{Eq.2})$$

The conditions for Eq. 1 and 2 include that the cyclist is not braking, and the speed is sufficiently moderate that it does not substantially affect the rider's ability to control the bicycle.

Data

The speed model was calibrated on GPS data from 256 participants in a 2017 active travel survey in metropolitan Vancouver, Canada (Mohamed and Bigazzi 2019). GPS data processing methods and supporting datasets (e.g., network, physical parameters) are described in the Supplemental Information. Cruising events were extracted from the GPS records of utilitarian cycling trips (excluding “exercise” trip purpose) using Toeplitz inverse covariance-based time-series clustering (Hallac et al. 2017), with cruising clusters identified as those with low fluctuations in the cycling speed and path based on speed, acceleration, heading change, grade, and the first differences of these variables with respect to time (Berjisian and Bigazzi 2024a- Manuscript in preparation). Record-level MRS_{et} during cruising events was calculated using Eq. 2. To satisfy the non-braking and moderate speed conditions, records with negative power ($\mu_1v + \mu_3v^3 < 0$) or non-moderate speeds (below 2 m/s or above 7 m/s) were excluded. The low and high-speed thresholds were based on bicycle stability (Wang and Yi 2015) and physiological stress responses (Fitch, Sharpnack, and Handy 2020), respectively. Median MRS_{et} was calculated for each cruising event, and outlier values (more than 1.5 times the interquartile range below the first or above the third quartile) were discarded (the Supplemental Information provides a comparison of aggregation methods).

Regression modelling

A mixed effects regression model was estimated to examine the relationships between MRS_{et} (the dependent variable) and route, trip, and person characteristics. The model was specified using stepwise addition of independent variables, retained at a statistical significance threshold of 95% confidence (Table 1). Both trip-level and person-level random effects were included in the specification. Similar models estimated with MRS_{et} aggregated up from cruising events to the trip and person levels are reported in the Supplemental Information.

Table 1. Independent variables included in the model specification process

Variable	Definition	Descriptive statistic ^a
Cycling facility type	Predominant cycling facility type for records in the event; facility data from (Ferster et al. 2023)	25% local street bikeway, 4% bike path, 9% cycle track, 9% multi-use path, 14% painted bike lane, 7% non-conforming trail, 7% non-conforming major road, 23% non-conforming other, 2% none
Ln(traffic volume)	Natural log of median average daily traffic (ADT) on the map-matched links; ADT data from multiple sources – see (Berjisian and Bigazzi 2024a- Manuscript in preparation)	5.34 (3.72)
Road grade	Road grade for the median MRS _{et} record in the event	0.01 (0.02)
Traffic controls	Traffic signal or stop sign located within 40 meters of most records in the event; traffic control data from OSM	33%
Crash risk	Median number of reported bicycle-involved crashes in 2017 in a buffer of 50 meters around the map-matched links, divided by median volume of Strava-recorded cyclists on those links; crash data from Insurance Corporation of British Columbia (2017) and bicycle volume data from STRAVA (2019)	0.0003 (0.0026)
Greenery	Majority vegetation land cover classification in a buffer of 50 meters around the map-matched links; land cover data from Metro Vancouver (2014)	19%
Traversed percentage	Median % of trip distance traversed in the event	49.6 (30.4)
Trip purpose	Self-reported trip purpose	70% commute, 10% errands, 13% leisure, 8% other
Weekend	Trip occurred on a weekend day	12%
Peak hour	Start of trip between 6 and 10 hr or between 15 and 18 hr	73%
Weather: precipitation and temperature	Hourly precipitation (mm) and temperature (degrees C) recorded at the closest station with non-missing data to the start of the trip; weather data from Government of Canada (2017), Pacific Climate Impacts Consortium (2017), and Weather Underground (2017)	Precipitation 0.6 (3.4); temperature 19.3 (5.3)
E-bike	Motorized bicycle or e-bike	8%
'Dedicated' cyclist type	Probability of a cyclist belonging to the 'Dedicated' type (versus 'Casual') of a binary latent class typology based on preferences and self-reported behavior (Berjisian and Bigazzi 2024b)	0.57 (0.46)
Age group	Cyclist's age group in low (≤ 30), middle (30 to 50), high (> 50)	27% low, 50% middle, 23% high
Gender	Woman (binary)	35%
Household bicycle ownership	Number of non-motorized bicycles in the household (capped at 4)	17% 1, 25% 2, 16% 3, 42% 4 or more
Household e-bike ownership	At least one e-bike in the household (binary)	13% ^b
Household motor vehicle ownership	At least one motor vehicle in the household (binary)	70%
Household income	Annual pre-tax total	25% $< \$50k$, 42% $\$50k$ - $\$100k$, 33% $> \$100k$ ^c
Educational attainment	Highest degree obtained	22% college degree or less, 41% bachelor's degree, 37% graduate degree

^a % or mean (standard deviation)^b Assumed false for 3 participants with missing data who did not report any e-bike trips^c Assumed $\$50k$ - $\$100k$ for 1 participant with missing data (based on other respondents with similar demographics)

3. FINDINGS

The dataset contained over 2 million 1-second GPS records, 974,268 of which (48%) were identified as belonging to a cruising event. Of those, 352,801 (36%) were discarded due to negative power or control-relevant speed. The remaining records occurred during 9506 unique cruising events, of which 806 were discarded as outliers. The 8700 remaining cruising events had a mean MRS_{et} of 0.31 and standard deviation of 0.19, and range of 0.05 to 0.95 min/km per kcal/min. For comparison, Bigazzi and Lindsey (2019) reported MRS_{et} values centering around 0.3.

Due to missing survey data for independent variables, 341 cruising events from 5 people were excluded from the regression analysis. [Table 2](#) gives the model results, estimated on 8359 events over 1518 trips by 135 people. The mean residual sum of squares for the model is 0.023. Leave-one-out cross-validation yielded a mean residual sum of squares of 0.026, indicating minimal overfitting. Positive parameter values in [Table 2](#) indicate conditions in which cyclists are less willing to exchange energy for time (i.e., unwilling to pedal harder to go faster and save travel time). This might occur when the perceived cost of energy expenditure is high (e.g., because they are already at a high exertion level), or because the perceived cost of travel time is low (e.g., because they are in a more comfortable environment). In addition to energy-time trade-offs, preferred speeds will be lower, inflating the measured MRS_{et} , where speed has a non-negligible negative impact on perceived safety (Bigazzi and Lindsey 2019).

Non-cycling facilities, major roads, painted bike lanes, and cycle tracks have lower MRS_{et} than local street bikeways, indicating that cyclists prefer to ride harder on these facilities. In contrast, cyclists have higher MRS_{et} on multi-use paths, non-conforming trails (often unpaved), and non-conforming ‘other’ (mostly local streets without traffic calming), suggesting that cyclists prefer a more leisurely riding style on these facilities. These results are likely due to a combination of factors including comfort, speed adaption, and facility design.

Steeper uphill gradients correspond to higher MRS_{et} , indicating greater perceived marginal energy costs at higher exertion rates. Errand and leisure trips were associated with higher relative energy costs than commute trips, and cyclists tended to ride harder on weekday trips. E-bike trips had lower MRS_{et} because we did not differentiate human from motor inputs, hence e-bikers are more willing to exchange energy for time.

‘Dedicated’ cyclists had lower MRS_{et} , which is likely co-causal: cycling is more attractive as a travel mode because these riders perceive energy costs to be lower. Women had higher MRS_{et} , possibly due to a combination of physiological factors (e.g., lower maximal metabolic rates (Robertson et al. 2000)), social factors (e.g., more trip chaining (Noland and Thomas 2007)), and psychological factors (e.g., more sensitive to motor vehicle traffic

Table 2. Estimated mixed effects regression model of MRS_{et} for cruising events

Variable	Estimated parameter
Intercept	0.35
Cycling facility type (reference level: local street bikeway)	
Bike path	-0.00444 ^a
Cycle track	-0.0244
Multi-use path	0.016
Painted bike lane	-0.0456
Non-conforming trail	0.0758
Non-conforming major road	-0.0305
Non-conforming other	0.0126
None	-0.0482
Road grade	1.59
Traffic controls	0.0219
Crash risk	1.40
Traversed percentage	-0.000164
Trip purpose (reference level: commute)	
Errand	0.0344
Leisure	0.0565
Other	0.0159 ^a
Weekend	0.0221
E-bike	-0.0591
'Dedicated' cyclist type	-0.0647
Woman	0.0737
Household owns motor vehicle	-0.0469
Standard deviation for person-level random intercept	0.08
Standard Deviation for trip-level random intercept (nested in persons)	0.05
R ² (marginal, conditional)	0.14, 0.38

^a Not statistically significant at $p < 0.05$ but retained as part of a categorical variable

(Heesch, Sahlqvist, and Garrard 2012)); this finding could relate to gender disparities in cycling participation. Riders from households who own motor vehicles had lower MRS_{et} , possibly indicating more 'choice' riders who preferentially ride when they are less energy-conservative.

These findings support the novel behavioural approach to speed modelling for cyclists, and provide insights into how perceived energy costs vary across cyclists, trips, and facilities. Further calibration with other datasets will illuminate the transferability of energy preferences. Future research should explore the application of the calibrated model for speed simulation, and incorporate non-free-flow speeds and motor energy for e-bikes.

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SUPPLEMENTARY MATERIALS

Supplemental Information

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Figure S.1. Distributions of event-level MRS aggregated from records by mean, median, and mode

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Figure S.2. Distributions of within-person variability (standard deviation) of event-level MRS aggregated from records by mean, median, and mode

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Figure S.3. Distribution of MRSet within the street network

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