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Mitigating Increased Driving after the COVID-19 Pandemic: An Analysis on Mode Share, Travel Demand, and Public Transport Capacity

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Abstract

Reduced transit capacity to accommodate social distancing during the COVID-19 pandemic was a sudden constraint that along with a large reduction in total travel volume and a shift in activity patterns contributed to abrupt changes in transportation mode shares across cities worldwide. There are major concerns that as the total travel demand rises back toward prepandemic levels, the overall transport system capacity with transit constraints will be insufficient for the increasing demand. This paper uses city-level scenario analysis to examine the potential increase in post-COVID-19 car use and the feasibility of shifting to active transportation, based on prepandemic mode shares and varying levels of reduction in transit capacity. An application of the analysis to a sample of cities in Europe and North America is presented. Mitigating an increase in driving requires a substantial increase in active transportation mode share, particularly in cities with high pre-COVID-19 transit ridership; however, such a shift may be possible based on the high percentage of short-distance motorized trips. The results highlight the importance of making active transportation attractive and reinforce the value of multimodal transportation systems as a strategy for urban resilience. This paper provides a strategic planning tool for policy makers facing challenging transportation system decisions in the aftermath of the COVID-19 pandemic.

Keywords

planning and Analysis, transportation planning policy and processes, multimodal, multimodal planning, travel choices, public transportation, planning and development

Transportation systems are designed to supply physical connectivity for people, goods, and places within a given area so as to create "opportunities to participate in spatially disjointed activities" at various scales (*1*, *2*). In recent years, transportation systems have evolved, and they have extended their accessibility and reach; economical and time-affordable trips, both local and inter-city, are becoming available to increasingly larger numbers of people across the world (*3*).

Growth in transport supply has helped to grow wealth and economies, but has also generated a range of negative externalities such as crash fatalities and air pollution (*4*, *5*). The spread of COVID-19 might have been another unintended consequence of enhanced access to mobility and sharing of transport. On extended journeys in particular, people travel together for longer periods of time (*6*). Physical connectivity and sharing are key attributes of the transportation systems that have contributed to the pandemic and, as such, government travel restrictions were introduced as a pandemic mitigation strategy (*7–12*). In the COVID era, where possible, physical connectivity has been replaced with digital connectivity. People have been encouraged (or forced) to undertake work and educational activities remotely, exploiting telecommunication systems and related technologies (*13–15*).

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As the initial wave of the pandemic eased in some countries and travel restrictions were relaxed or have been lifted, overall transport demand has increased. It is not clear if demand will undergo a complete recovery to pre-COVID levels. Some suggest that the continuation of (promoted) remote educational and work activities will eliminate a proportion of commute (study and work) trips and trigger long-lasting societal change (*16*). In addition, fear of physical proximity may continue to reduce the number of recreational trips somewhat, especially in places where the pandemic hit hard or endures (*17*, *18*).

Figure 1 illustrates travel volumes by mode over time; the statistics have been derived from Apple Maps using a proxy measure of requests for directions (*19*). It can be seen that both the size of the initial reduction in travel and the speed of the recovery in volume varies by mode. In particular, in the recovery phase there is a faster increase in private (individual) transport mode usage, especially car usage, than in transit usage. Therefore, as overall travel demand has increased over the course of the recovery, transit demand has decreased as a proportion of all travel. Fear of sharing space with other passengers and reduced transit capacity because of social distancing requirements are two major contributors to this trend (*18*). Despite a link existing between transmission of airborne influenza-like illnesses and public transport usage (*20*), there is no clear evidence that public transportation spaces are environments where the virus has spread, when risks are mitigated by compulsory countermeasures such as user respiratory hygiene rules (e.g., wearing face masks), physical distancing, e-ticketing, and frequent hand sanitization (*21*, *22*).

Because of the differences in the speed of travel demand recovery among modes, there are concerns about overall transport supply, particularly in urban areas with high prepandemic transit mode shares. Overall transport supply comprises all system capacities (e.g., car, transit, active transportation); limitations to transit capacity can reduce the overall transport capacity both directly and indirectly. As a consequence, cities face the problem of environmental, social, and economic sustainability of transport systems in the postpandemic period, driven by the threat of a massive shift in travel from a sustainable mode of transport (transit) to private car.

Recent research on the pandemic has focused on the organizational and management-related policies that should be adopted in a qualitative way (*23*, *24*) during a pandemic to preserve a basic functioning system. However, little research has investigated methods or provided guidelines to policy makers with regard to action that should be taken during a pandemic to preserve the transport system and its sustainability goals in the light of a predictable end to the pandemic.

Transportation system modeling offers a viable tool for assessing scenarios given the reduction in transit capacity and upstream travel demand changes. Reports assessing various aspects of these scenarios, based on sophisticated transport simulations or exploiting big data analysis, are available (*25–27*). The challenge of using complex transport system models is that they require detailed localized information, and there is limited generalizability and substantial uncertainty in both parameter values and embedded assumptions when applying models built on prepandemic travel preferences and behavior. As an alternative approach, strategic planning models provide decision-makers with a way of exploring scenario spaces over a wide range of future conditions. Our exploratory approach relies on simple and clear assumptions and parameters, and can be useful for examining system responses to widescale abrupt changes. Compared with complex transportation models, such an approach requires less data and can be more transferrable.

This paper investigates solutions to an overall reduction in transport supply as travel demand experiences a resurgence during the COVID-19 recovery. The goal is to determine whether mode substitution of transit can be (sustainably) absorbed by the transport system given reductions in demand and a shift toward active transportation without increasing car usage in (already) congested cities. We apply a city-level scenario model that accounts for the most relevant variables at an urban scale (mode shares, transit capacity, and upstream travel demand), to provide planners, policy makers, and other professionals with a strategic planning tool and a glimpse of postpandemic mode shares and appropriate goals and strategies. In particular, we seek to answer the following question: What is the potential impact of a shift from transit to driving in different urban contexts, and what role can active transportation play in mitigating that impact?

Methodology

Framework: Mode Substitution of Transit

The extent of the resurgence in travel demand because of COVID-19 is still largely unknown, but across cities it seems that postpandemic mode shares will be substantially different from those prepandemic, with an increasing gap between private car and transit, in favor of the former (see Figure 1). In addition, transit travel demand is increasing more slowly (over time) than the demand for private car travel both because of the effect of legal constraints related to physical distancing, and because operators are still wary about (over)crowding, which in turn reduces capacity and, therefore, denies access (*18*).

Figure 2 illustrates the mechanisms of mode shift from transit depending on local transport system

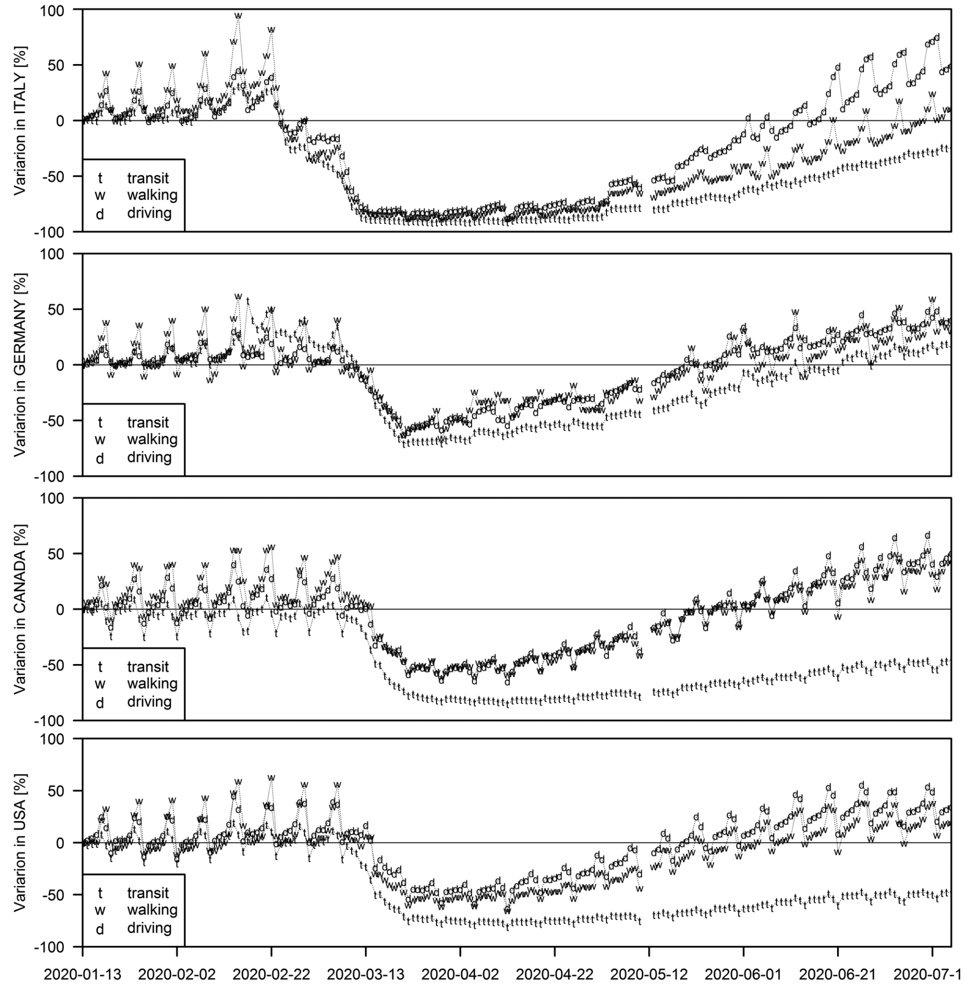

Figure 1. Mobility trends in Italy, Germany, Canada, and the U.S.A. based on requests for directions in Apple Maps. Elaboration based on data from Apple (*19*).

conditions and time windows: cases (1) and (2) represent prepandemic load factors during peak hours exceeding design capacity, more common in dense cities with high transit mode shares; cases (3) and (4) represent prepandemic transit demand below transit capacity, more common in most U.S. cities. The decrease in ridership is comprised of three components: (a) a reduction in upstream travel demand because of a decrease in activities; (b) users unwilling to use transit because they are wary of the possible consequences (fear of sharing because it could lead to infection, and lack or easing of prevention measures before a vaccine is available) or because an alternative mode is more convenient timewise (reduced driving times, if not captive users); and (c) "spillover transit users," that is, users willing to take transit but denied access because of reduced capacity. In the light of a ridership resurgence it is expected that "spillover transit users" should return to use transit sooner than those who changed because they were wary or for convenience. Transit retained ridership (new ridership) can be either equal or lower than COVID-19 design transit capacity, but likely not higher because of spillover transit users. Extended seat booking, passenger counting, on-demand reinforcement services, and manned physical distancing enforcement should prevent the COVID-19 design capacity threshold from being exceeded. Social (or physical) distancing acts as a top-down constraint on design capacity, being more severe in the case of peak load factors >1 (overcrowding), which can be allowed by design during peak hour (pre-COVID). On the other hand, where (and when) load factors are <1, social distancing constraints could affect capacity (and ridership) to a lesser extent.

In any of the four cases in Figure 2, the way in which mode shift from transit will affect other modes of

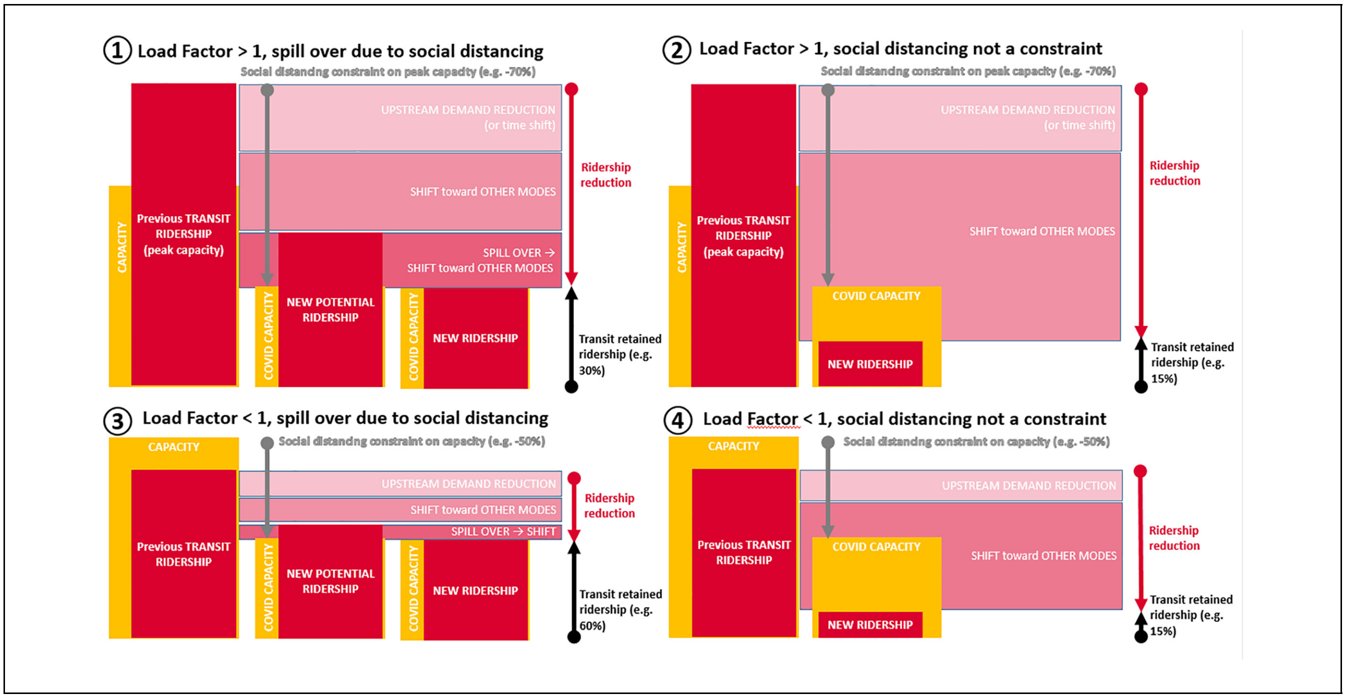

Figure 2. Transit ridership shift mechanisms because of the pandemic.

transport depends on the relative attractiveness of the alternatives, which vary with traveler and trip characteristics (e.g., purpose, distance, sociodemographics). In general, total travel demand is primarily determined by exogenous factors (activities), whereas mode shares are more dependent on the endogenous factors of the transportation system (affecting the relative costs of each mode). Postpandemic mode share will largely depend on which policies are adopted to support active transportation, public transportation, and to maintain policies that will result in a reduction in private car usage.

Mathematical Model

The analysis is based on two key effects of the pandemic on transportation systems: a decrease in upstream travel demand and reduced transit capacity. Considering only mode share distribution across private car, transit, and active transportation (primarily walking and cycling), we simulate scenarios of the effect of the pandemic on mode share depending on actions taken that have an impact on the reduction of upstream travel demand (e.g., telework), transit capacity (e.g., social distancing requirements, service cuts), and the attractiveness of active transportation (enhanced traffic calming and protected facility provision). The analysis is carried out by exploiting city-level trip balancing based on mode shares, peak hour transit capacity, and upstream travel demand, as explained in the following subsections.

Pre/Postpandemic Mode Shares. Pre- and postpandemic mode shares are defined as:

c_i and c_f are private car mode share initial (prepandemic) and final (postpandemic), respectively.
t_i and t_f are transit mode share initial (prepandemic) and final (postpandemic), respectively
a_i and a_f are active transportation mode share initial (prepandemic) and final (postpandemic), respectively.

Prepandemic refers to a time when travel behavior was not influenced by travel restrictions or fear of infection. Postpandemic refers to a time after the initial wave of the pandemic, before a vaccine was available. Mode shares are calculated for a given area of analysis, for example, a city or region.

Transit Ridership Retention Factor. The variable R_t represents the retained portion of public transport ridership because of the pandemic. It is estimated as a ratio of post-to-previous transit ridership, which relates to transit capacity according to the mechanism illustrated in Figure 2. Depending on the case, it is calculated considering physical distancing restrictions (i.e., maximum on-board density allowance [28]), frequency of services (depending on finance and grants made to the public transport sector, available workforce, vehicles, and infrastructure capacity), given prepandemic ridership as the 100% R_t baseline. Easing physical distancing constraints would increase R_t; varying frequencies on certain services, at the expense of others, could lead to higher or lower R_t.

Active Transportation Shift Factor. The variable S_a represents the proportion of transit and automobile trips that are shifted to active transportation modes (walking, cycling, and micromobility means of transportation). S_a can be selected, for example, according to planned cycling- and walking-friendly policies, given total feasible trips based on distance requirement (e.g., <10 km).

Upstream Demand Reduction Factor. The variable V_d is introduced to account for the variation in upstream travel demand in relation to a reduction in trips undertaken. It has been shown that fear of the pandemic, travel restrictions, curfews, shutdown of commercial activity, and other measures determined a reduction in upstream travel demand (see Figure 1), especially during peak periods. In some countries, as restrictions were eased, travel demand increased, but it is still unknown whether values will go back to prepandemic levels (*10*, *29*).

Exogenous factors relating to the transportation system are determinants of a reduction in upstream travel demand in a pandemic (*30*). Figure 3 illustrates a conceptual summary of factors affecting changes in travel demand. Commute trips are particularly affected by conversion to remote activities such as telecommuting and online teaching. For recreational, shopping, and other occasional trips, the behavioral change is concerned with the transition from bricks-and-mortar shops to online shops and e-commerce, a reduction in in-person business meetings/conferences, and cancellation of events.

In addition, a resurgence in travel demand depends on travelers' willingness to be exposed to the risk of infection, which is related to medical research and innovation. Availability of vaccines and effective treatments for the pandemic will likely increase travel demand. Moreover, job losses and economic recovery are factors affecting the generation of work trips, availability of time for discretionary trips, and willingness to pay for recreational trips. Finally, transport system policies adopted in the pandemic (changes in transport supply) can induce an increase (or decrease) in transport demand.

Trip Balancing Equations. In line with a mass balance, the transportation system is analyzed with the constraint that the postpandemic number of trips (postpandemic travel demand) equals the prepandemic number of trips minus trips lost because of reduced demand, as illustrated in Figure 4. In addition to the reduction in total trips, there is expected to be a mode shift, particularly away from transit because of the constraints described above.

Transit trips are reduced according to $t_f = R_t t_i$, where R_t is the transit retained ridership factor. The motorized trip balancing is then Equation 1:

$$(c_i + t_i)(1 + V_d + S_a) = c_f + R_t t_i \quad (1)$$

where V_d is the demand variation factor ($V_d > 0$ for demand increases, $V_d < 0$ otherwise) and S_a is the active transportation shift factor ($S_a < 0$ for shift toward active transportation, $S_a > 0$ otherwise). Rearranging Equation 1, we can calculate the percentage increase in demand for car usage, the target shift to active transportation and the reduction in upstream demand based on prepandemic mode shares and assumptions with regard to transit capacity and the reduction in travel demand. It is assumed that the upstream travel demand reduction factor V_d and the active transportation shift factor S_a are

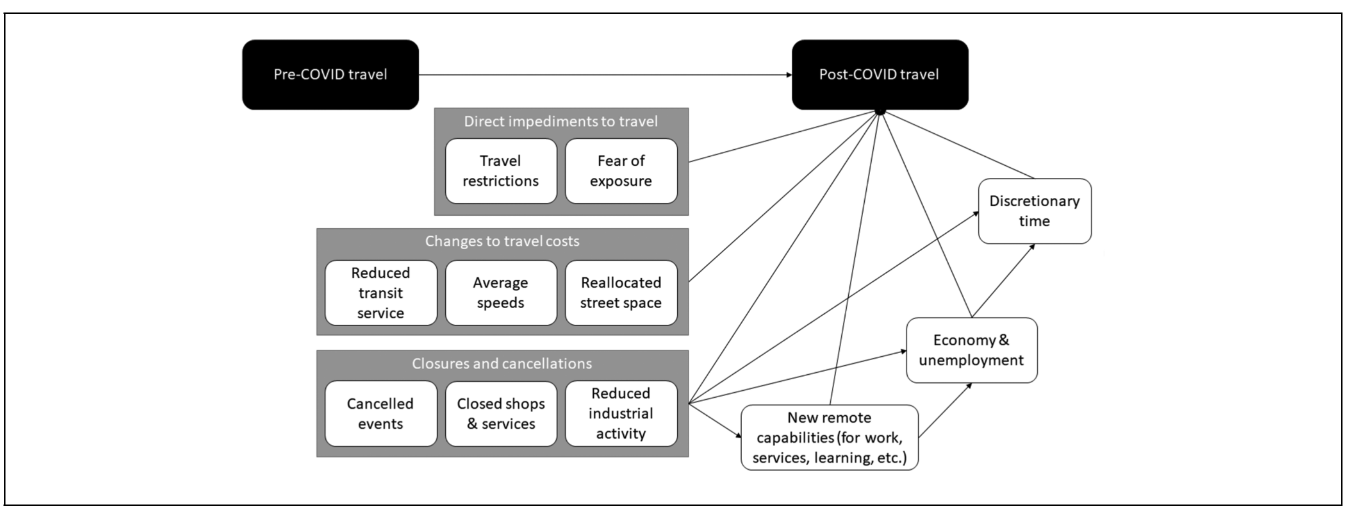

Figure 3. Determinants of variation in travel demand because of the COVID-19 pandemic.

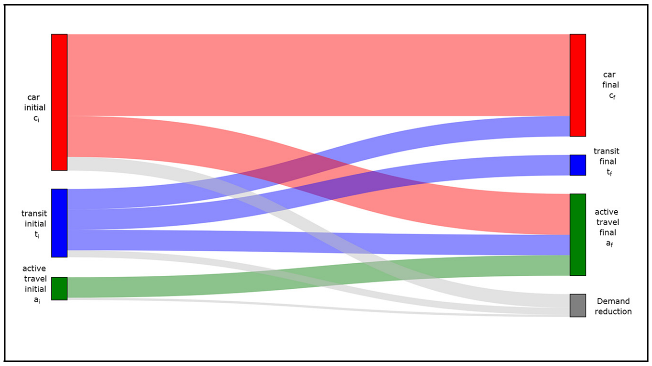

Figure 4. Mode share balancing scheme. Red is private car (***c**$_i$* initial and ***c**$_f$* final), green is active transportation (***a**$_i$* initial and ***a**$_f$* final), blue is public transportation (***t**$_i$* initial and ***t**$_f$* final), and gray is reduced demand.

applied uniformly to t_i and c_i for a trade-off between simplicity and accuracy. In fact, there is not enough evidence to foresee which mode will be hit proportionally the most by a reduction in upstream demand (V_d). In addition, S_a is assumed to be uniform based on a similar proportion of trips <10 km by car and transit (73% trips by car <10 km and 75% transit trips <10 km in Italian municipalities with more than 250,000 inhabitants [*31*]).

Scenario Analysis

The overall capacity of a transportation system depends on design sustainability criteria. The primary aim of such a system is to supply mobility for all. However, in a dense urban environment where space is critical, a massive shift toward private cars leads to congestion and to an overall reduction in the capacity of the transport system for all users regardless of their mode. One driver of a huge shift to car usage can be physical distancing enforcement without urban space reallocation, generating a vicious circle in which urban space for transit and active transportation (e.g., cycle paths, sidewalks, bus priority lanes, transit stops, access paths to stations) is reduced. To prevent an overall reduction in transport supply and maintain the sustainability goals of transportation, it is in the best interests of policy makers to understand the magnitude of shifts from transit to car and compare them with the effectiveness of countermeasures introduced to avoid an increase in private car usage.

Car-only Substitution

The assumption in the first scenario is that mode substitution of transit goes entirely to car use, that is, there is no shift toward active transportation ($S_a = 0$). Rearranging Equation 1 to obtain the percentage increase in car use results in Equation 2:

$$\Delta c_{\%} = \frac{c_f - c_i}{c_i} = \frac{t_i}{c_i}(1 + V_d - R_t) + V_d \qquad (2)$$

Figure 5 depicts the behavior of Equation 2, according to different values of V_d and R_t. For example, a city with $t_i/c_i = 1$ (i.e., same share of car and transit use pre-COVID) with transit running at 35% of its capacity and an overall reduction of 20% in travel demand would generate about a 15% increase in car traffic, whereas with no reduction in demand the increase in car traffic would be higher than 50%. It should be noted that for simplicity's sake, the scale of the increase in traffic is not limited by a road capacity constraint. Most urban environments were already congested during peak hours before the pandemic. If all transit users exceeding constrained capacity were to shift to cars during the period in which overall demand returns to prepandemic values, there would be a net gain of car users with a substantial increase in congestion in urban environments. When sharing the same infrastructure with cars, the effect on transit would be a reduction in speed (and frequency, therefore capacity) and the effect on active transportation would be a decrease in comfort and safety, and an increase in exposure to air pollution, leading to a further reduction in the attractiveness of both these forms of transportation. A further increase in car usage would then negatively affect transit and active transportation, which are the antidotes to car congestion.

Car and Active Transportation Substitution

When a proportion of car and transit trips shifts to active transportation, $S_a < 0$, the percentage change in car trips is calculated by rearranging Equation 1 as Equation 3:

$$\Delta c_{\%} = \frac{c_f - c_i}{c_i} = \frac{t_i}{c_i}(1 + V_d + S_a - R_t) + V_d + S_a \qquad (3)$$

Figure 6 illustrates Equation 3 with varying levels of transit capacity and a reduction in overall demand. Trends are in line with Figure 5, but now a shift in active transportation contributes to mode substitution from car and transit. As a consequence, cities with high transit shares that are disproportionately affected by a reduction in transit, can mitigate an increase in car traffic by mixing measures related to travel reduction (exogenous factors) and active transportation.

Maximum Transport Demand to Achieve No Increase in Driving

This scenario sets prepandemic car usage as the capacity limit of the road system as a strategic policy reference point, to calculate a target total reduction in demand (and, subsequently, a target active transportation shift). It is of interest to examine what level of reduction in

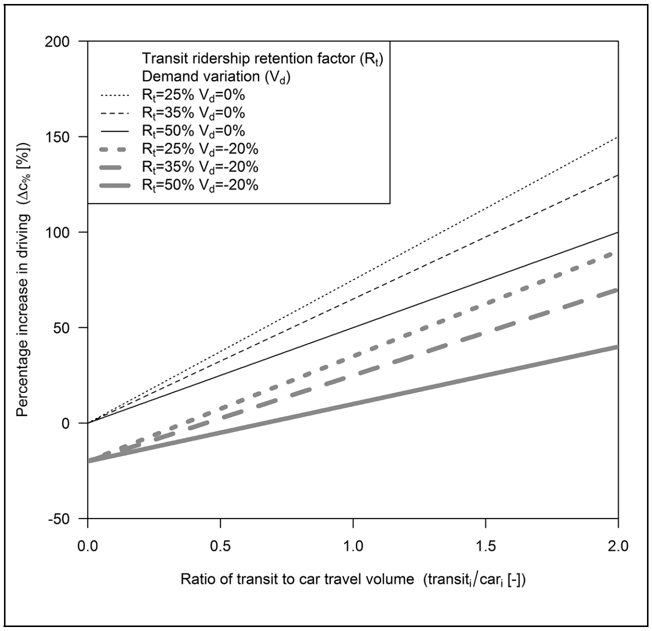

Figure 5. Percentage increase in driving for $\mathbf{R_t}$ = 25%, 35%, 50% (transit ridership retention factor) and $\mathbf{V_d}$ = 0%, 20% (demand variation), assuming $\mathbf{S_a} = 0$ (shift toward active transportation).

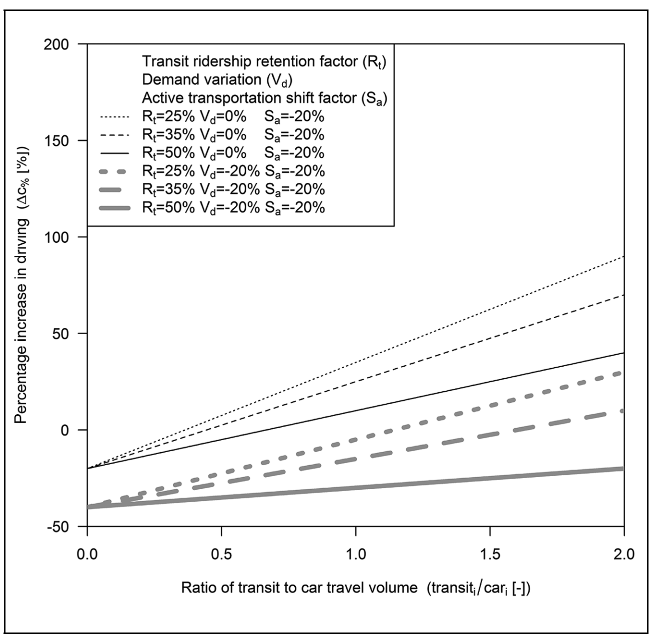

Figure 6. Percentage increase in driving for $\mathbf{R_t}$ = 25%, 35%, 50% (transit ridership retention factor) and $\mathbf{V_d}$ = 0%, 20% (demand reduction), assuming $\mathbf{S_a} = -20\%$ (shift from car and transit toward active transportation).

overall travel demand would lead to no increase in trips by car with the transit capacity constraint in place. This scenario shows the maximum reduction in transport demand to achieve no increase in driving, and is called target demand variation $V_{d,\,target}$. It is calculated enforcing a zero increase in trips by car, as per Equation 4:

$$\Delta c_{\%} = 0 \rightarrow V_{d,\,target} = \frac{1 + \frac{t_i}{c_i} R_t}{1 + \frac{t_i}{c_i}} - S_a - 1 \qquad (4)$$

Figure 7 illustrates the result of Equation 4 with varying transit capacity and a shift in active transportation mode. The results show nonlinear behavior; with increasing values of transit-to-car ratios, the target reduction in demand levels off, because initial car mode share decreases. A shift in active transportation contributes to a decrease in the target demand value. For example, assuming $R_t = 25\%$, a city with a 0.5 transit-to-car ratio could aim for a 25% decrease in travel demand, or if this were to prove too challenging, promote active transportation measures (20% shift) and a 5% only reduction in travel demand reduction to meet a zero gain in private car transportation.

Target Shift to Active Transportation to Achieve No Increase in Driving

Another strategic planning value of interest is the mode shift to active transportation needed to prevent an increase in trips by car with the transit capacity constraint in place. This value, $S_{a,\,target}$, is calculated from the constraint of a zero increase in trips by car, as per Equation 5:

$$\Delta c_{\%} = 0 \rightarrow S_{a,\,target} = \frac{1 + \frac{t_i}{c_i} R_t}{1 + \frac{t_i}{c_i}} - V_d - 1 \qquad (5)$$

Figure 8 illustrates the nonlinear behavior of Equation 5. In line with Figure 7, achieving no increase in driving can be done by aiming for a mixed reduction in demand and promoting active transportation policies. In addition, as initial transit mode shares increase, so does the importance of the transit capacity reduction factor. Positive S_a values (below 0 in Figure 8) mean no shift toward active transportation is needed as long as the reduction in travel demand is higher than the shift from transit to driving.

It is also of interest to contextualize the increase in the target active transportation shift factor $S_{a,\,target}$. To do so, active transportation mode share a_i, is used as a baseline to report the percentage increase in active transportation needed. This estimation can help policy makers understand the effectiveness, feasibility, and adequacy of transportation measures for avoiding an increase in car traffic during recovery from the pandemic. Equation 6 is used to calculate the percentage increase in the active transportation mode share needed to mitigate increased driving:

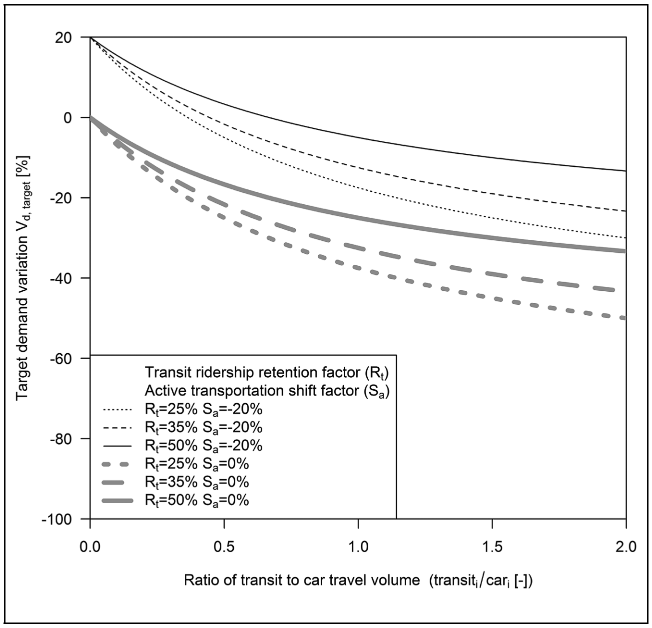

Figure 7. $\mathbf{V_{d,\,target}}$ (target demand variation) to achieve no increase in driving, in case of $\mathbf{S_a}$ = 0%, -20% (shift factor toward active transportation modes) and $\mathbf{R_t}$ = 25%, 35%, 50% (transit ridership retention factor).

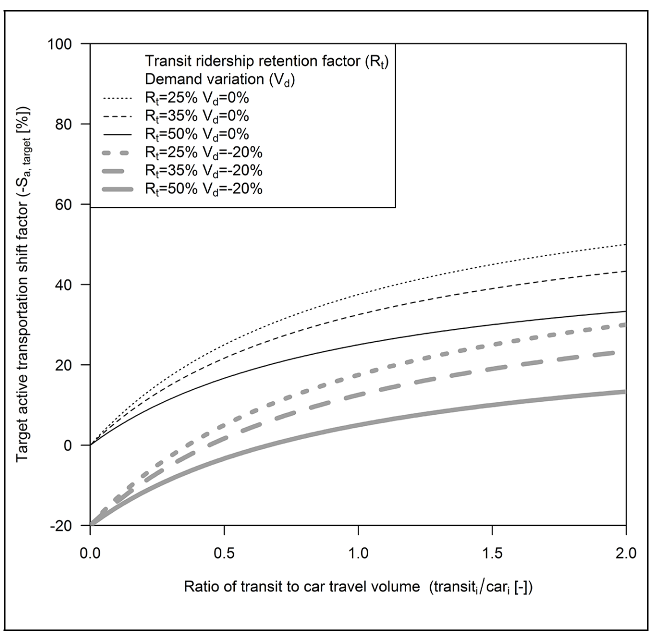

Figure 8. $\mathbf{S_{a,\,target}}$ (target active transportation shift factor) not to increase traffic, in case of $\mathbf{V_d}$ = 0%, 20% (demand reduction) and $\mathbf{R_t}$ = 25%, 35%, 50% (transit ridership retention factor).

$$\Delta a_{\%} = \frac{a_f - a_i}{a_i} = \frac{-S_{a,\,target}(1 - a_i)}{a_i} \tag{6}$$

Figure 9 illustrates the behavior of Equation 6 for values of prepandemic active transportation mode share a_i from 10% to 60%. For high a_i, the percentage increase is slightly higher than zero, meaning that high initial active transportation mode shares, determined by a good cycling infrastructure and human-centric urban planning, would need a relatively low increase of share to absorb former transit users.

Equation 6 was also applied to selected cities across Europe and North America to create the positioning map in Figure 10. This highlights clusters of cities that share similar transportation characteristics. Elaboration is based on the following data: Canadian cities 2016 work trips (*32*); United States 2018 work trips (*33*); European cities all trips (*34–36*). In particular, cities with higher initial transit shares require higher active transportation mode substitution to achieve no increase in driving (e.g., New York), unless they start with high prepandemic rates of active transportation (e.g., London or Paris). Cities that invested in active transportation are in a favorable position because their active transportation percentage target increase is lower and because they likely have a vulnerable user-friendly road environment and efficient active transportation system, which can welcome more users (from transit and car) without time- and resource-consuming interventions. It can be argued that these cities have a more resilient transportation system because reduced transit capacity can be supplied by an already effective active transportation system.

Given the calculated required increases in active transportation above, the question is, are these magnitudes of increase possible? Because of the nature of active transportation in that it requires effort by the traveler, it is more feasible to accomplish shorter trips by walking, cycling, or micromobility, provided that a well-designed active transportation network exists. Despite trip length variability according to trip purpose (*37*), it is reasonable to consider trips under 10 km as suitable for active transportation, particularly as e-bikes are becoming increasingly available (*38*). In Italy, about 70% of motorized trips (cars, motorbikes, transit) are potentially suitable for undertaking by active transportation because they are less than 10 km. Furthermore, about 33% of all trips are less than 2 km, by any mode (*31*). In Canada, the median commute distance by any mode in the eight largest metropolitan areas was between 6.6 km and 10.5 km (*32*). In the U.S.A., nearly 60% of all privately operated motorized vehicle trips are under 6 mi (9.7 km) (*39*). Because there is a high potential to shift "suitable" motorized trips to active transportation, it would be worthwhile to investigate trip distance distributions for transit and driving, and compare these with the target shift in active

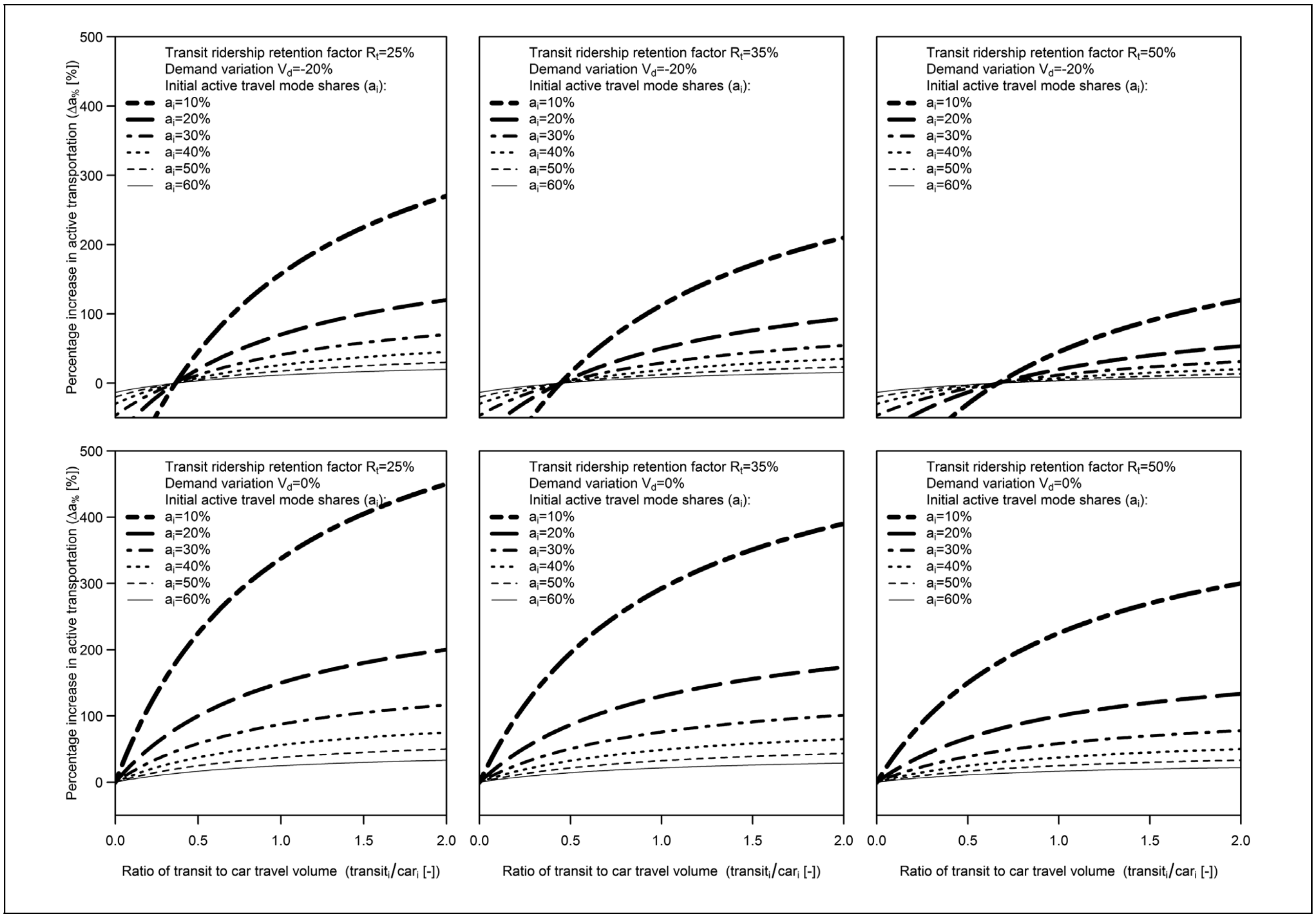

Figure 9. $\Delta a_{\%}$ (percentage increase in active transportation) needed to achieve no increase in driving, for a_i = 10% to 60% (initial active transportation mode shares).

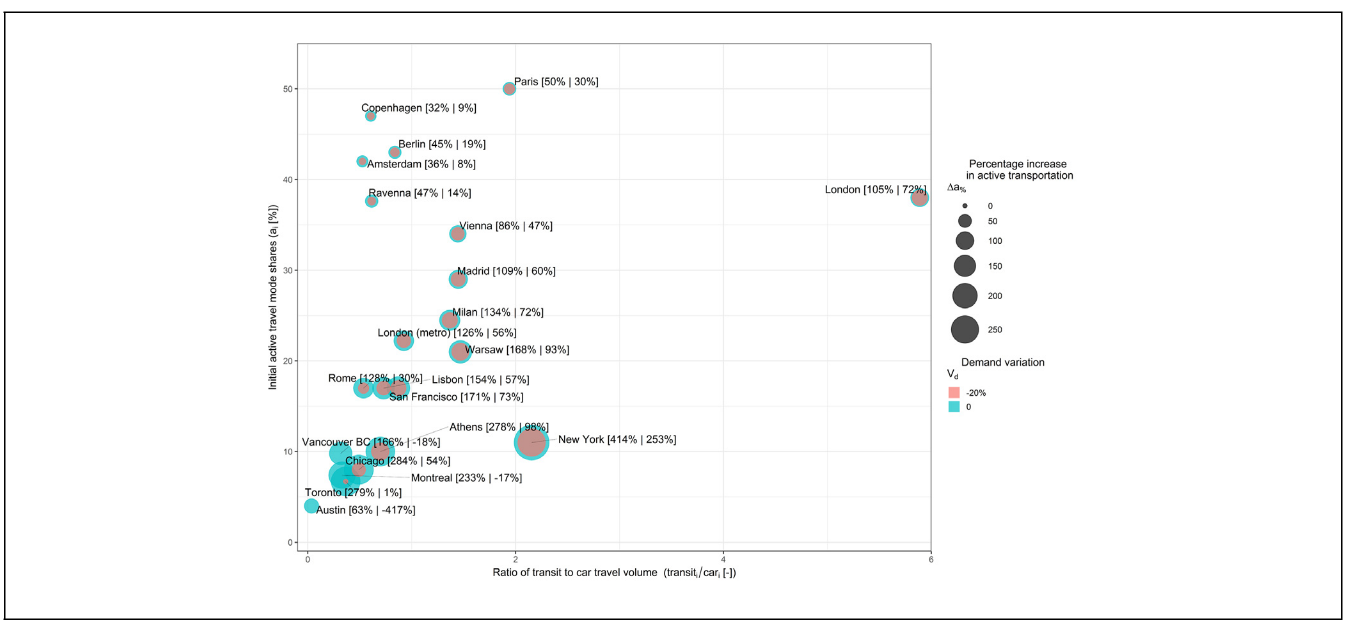

Figure 10. Positioning map of cities showing $\Delta a_{\%}$ (percentage change in active transportation) needed to avoid increased driving. Labels show, in order, $\Delta a_{\%}$ needed for V_d = 0%, -20% (demand reduction) and R_t = 25% (transit ridership retention factor) in all cases. a_i is the initial active transportation mode share.

transportation required to achieve no increase in driving (Figure 8).

Figure 11 shows the eight largest metropolitan cities in Canada and four demographic clusters of municipalities in Italy (by population) according to the percentage of car and transit trips below 10 km and prepandemic transit/car mode share ratio. Elaboration is based on data from ISFORT (*31*) for Italian clusters of municipalities by population (all trips), and Savage (*32*) for Canadian cities (work trips).These cities are compared with $S_{a,\,target}$ for a 25% retained transit ridership factor and no variation in upstream demand (the black line). A "feasibility" region (white area above the $S_{a,\,target}$ curve) is thus determined: cities in the region that have (potentially) sufficient short car and transit trips that can be converted to active transportation to achieve no increase in driving. The gray "infeasibility" region shows conditions for which insufficient suitable car and transit trips exist to offset the mode shift from transit. In this region, a reduction in upstream demand could still help to avoid increased driving, as could an increase in the postpandemic transit capacity (and, thus, the retained transit ridership factor). In the feasible region, cities closer to the line would have to convert a larger proportion of their suitable trips to active transportation (a greater challenge), whereas those farther from the line (higher up) have the easier task of converting a smaller number of short car and transit trips. For example, it will be more difficult to offset transit capacity reductions with a shift to active transportation in Toronto than in Vancouver or Winnipeg. Italian municipalities are better positioned than Canadian cities, with shorter motorized trips prepandemic. The importance of short trip distances in relation to the feasibility of off-setting pandemic-reduced transit capacity with active transportation supports the idea of compact, mixed-use development as a strategy for urban resilience.

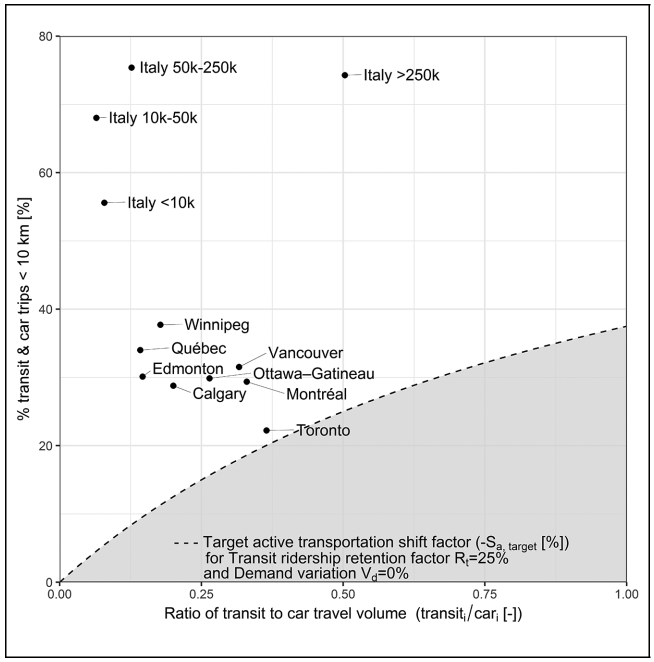

Figure 11. Percentage of motorized (car and transit) trips <10 km compared with $\mathbf{S_{a,\,target}}$ (target active transportation shift factor) to avoid increased driving. V_d = 0% (demand reduction) and R_t = 25% (transit ridership retention factor).

Strategies to Avoid Increased Driving

The analysis above shows the vulnerability of transport systems with regard to a reduction in transit capacity and a potential subsequent increase in driving. This is especially critical in urban environments where prepandemic transit shares were high, and this includes most major metropolitan areas (*31–33*). Of particular concern is the estimated 70% of public transit users who are "captive," and not able to change modes readily (*40*). As long as the overall travel demand remains low, because of travel restrictions and a reduction in activity, transit mode substitution is mitigated; however, as the overall travel demand increases toward prepandemic levels, policy makers must develop plans to accommodate travel by former transit users. A further increase in private car users is not sustainable and could lead to a reduction of overall transport system capacity both because of the reduced performance of transit and hostile environments for active transportation (*41*, *42*).

Figure 12 gives a conceptual illustration of the mode substitutions that can be targeted to mitigate increased driving. As shown in the analysis, many cities have a "feasible" number of trips that can be shifted from motorized to active transportation to avoid a net increase in driving after a reduction in transit capacity. However, the analysis does not determine how to bring about those shifts. For this, cities must turn to the large body of literature on strategies for promoting active transportation. These may be included in emergency mobility plans as a pandemic response or as a long-term proactive measure. The key determinants of mode shift toward active transportation can be divided into infrastructure factors (e.g., active network connectivity, provision of trip-end facilities, a reduction in car parking spaces, road space reallocation), promotional programs (e.g., education, promotional campaigns), governance (e.g., policy implementation, stakeholder involvement, leadership) and exogenous factors (e.g., sociodemographic factors, trip distances, topography, physical environment, climate) (*43*). Many cities across the world have already undertaken initiatives in the midst of the pandemic: bike network development, pop-up bike lanes, pedestrian priority areas, traffic calming measures,

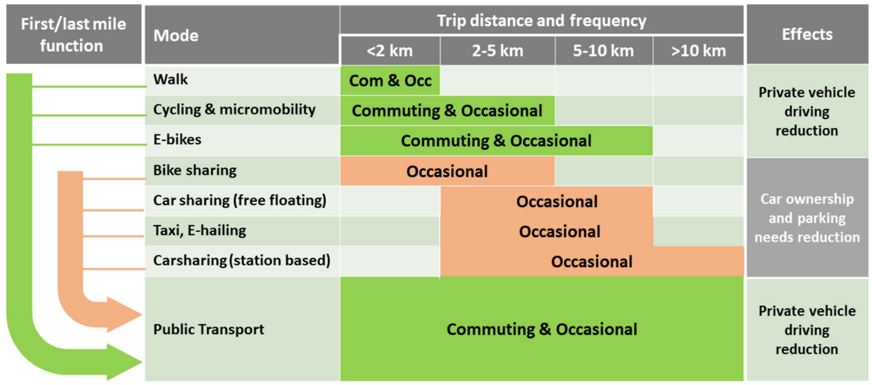

Figure 12. Illustration of potential trip mode matching based on distance and frequency.

20 km/h neighborhoods, folding/e-bike subsidies, bike/walk to work paybacks, bike parking and trip-end facilities, bus priority lanes, and (re)introducing congestion and parking charges (*44–47*). Furthermore, the promotion of active transportation can be a key support factor for transit and vice versa, because the services can be complementary and synergic (*45*, *48*, *49*). Active transportation is an important access mode (first/last mile) for transit, and it contributes to reducing transit load factors and private car traffic, thereby increasing transit speed (and capacity).

Limitations and Future Research

Limitations of this work include the use of a high-level strategic planning model, rather than a detailed travel demand model, which was necessitated by the scale of analysis. Although highly aggregate and simplified, this analysis offers insights to policy makers with regard to the many transit users who were unable to access the facilities because of reduced capacity, and in relation to the feasibility of using active transportation policies to offset the "unsupplied" transit users. Regardless of the existence of a sufficient number of feasible trips that could be shifted to active transportation, further research with regard to the number and quality of active transportation incentives needed to bring about such shifts is needed.

There is also a need to address the economic sustainability of public transportation with reduced ridership. Transit agencies are experiencing low load factors and reduced revenues, and also increased costs because of sanitization requirements and other expenses related to the protection of transit workers. This is partially mitigated by a reduction in service. However, as the service recovers (or increases), ridership may not attain prepandemic levels, and this may limit revenues.

As the pandemic progresses (and demand evolves), new public transport measures to deal with its effects are being implemented, and it is important to evaluate them to gather insights for long-term decisions. Examples are as follows: in Italy, train operator Trenord and bus operator Tper share real-time vehicle crowding information to help travelers plan trips better in accordance with social distancing; to overcome a shortage of vehicles and improve social distancing, ATAC (metro, bus, and train operator in Rome) will be using private buses on low ridership routes; in the UK, Transport for London has extended operating bus lanes to 24 h, effectively reducing capacity for private vehicles; in the U.S.A., Houston METRO has added extra buses to many busy routes to encourage social distancing; in Vancouver, Canada, TransLink monitors and modifies load targets based on the infection rate in the region on a daily basis; and in other cities, on-demand service extensions (e.g., Berlin BVG with BerlKönig, Miami-Dade Transit with Uber and Lyft, Los Angeles Metro with Via) have been used to mitigate underperforming routes because of disinfection activities and vehicle reallocations.

In addition, with regard to productivity, there could be an increase in operational costs because of delays caused by increased congestion in areas in which transit shares infrastructure with private traffic. During the lockdown phase of the pandemic, transit agencies experienced significant travel time savings because of reduced interaction with private vehicle traffic (*50*). Although not always immediately "cashed" to optimize fleet and crew scheduling because of system design constraints, travel time savings and an increase in average transit speed show the potential effects of a reduction in private vehicle traffic and the usefulness of bus-only lanes.

During this pandemic, countries have the opportunity to redefine strategic goals to reduce the risk of reduced mobility for all as private vehicle traffic increases. The path of sustainability could start and then accelerate with temporary measures enabling structural change and equitable mobility. Policy makers, and private and public authorities should embrace the opportunity to rethink the space and time in which we live our lives in the urban environment, reallocating and rebalancing that space to allow lesser proximity (*51*) and greater ease for people to participate in activities (work, study, shop, play, etc.) safely. Actions taken now should be the basis of a far-sighted paradigm shift in the concept of the livability of our urban environments.

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The authors confirm contribution to the paper as follows: study conception and design: F. Ciuffini; data collection: F. Ciuffini, S. Tengattini; analysis and interpretation of results: F. Ciuffini, A. Y. Bigazzi, S. Tengattini; draft manuscript preparation: F. Ciuffini, A. Y. Bigazzi, S. Tengattini. All authors reviewed the results and approved the final version of the manuscript.

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