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Dedicated bus lanes, bus speed and traffic congestion in Rome*

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Abstract. Buses are the mainstay of public transport systems in many cities but are typically subject to significant delays due to traffic congestion. We examine the welfare effects of providing dedicated bus lanes in the city of Rome, Italy. We demonstrate that a dedicated bus lane reduces bus travel time by about 18 percent. Our welfare analysis focuses on the situation where mixed road lanes are turned into dedicated bus lanes. We find that bus lanes are undersupplied, despite the additional time costs due to reducing road capacity available to cars.

JEL codes: H23, R41, H76
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1. Introduction

Road congestion is ubiquitous in major urban areas. To tackle this problem, governments discourage the use of private motorized transport (cars, motorbikes) and encourage the use of public transport. Putting this strategy into practice, however, typically requires improving the quality of public transport services (Proost, 2018), which is problematic because road congestion itself can hinder the speed and reliability of the public transport system. Rail-based public transport services operate on separate infrastructure and are thus insulated from road congestion, but buses - the mainstay of public transport system in most cities - mostly share the road with private vehicles and thus suffer from congestion delays. As a result, bus speed is typically quite low (Mohring, 1979).

A straightforward way to improve the speed and reliability of bus services is to provide dedicated bus lanes, where bus traffic is largely – though not always fully – separated from other vehicles.[1] The implementation of bus lanes is a relatively cheap option in congested cities. The main disadvantage is that road space available to cars is reduced, which potentially aggravates congestion and therefore car travel costs. In this paper, we examine the welfare effects of providing bus lanes in a city, based on data from Rome, Italy.

Broadly speaking, there exist two types of dedicated bus lane systems. The first is a Bus Rapid Transit (BRT) system, which is essentially a cost-effective alternative to rail-based mass transit. This type of system includes lengthy bus lanes which cut through the whole city and is particularly popular in South American and Asian cities, e.g. Bogota' and Jakarta. The literature evaluates the effects of BRT mainly by means of theoretical models and simulation exercises (Kutzbach, 2009; Basso et al., 2011; Basso and Silva, 2014). More recently, these effects have been analyzed with structural models (Tsivanidis, 2018; Gaduh et al., 2018). These models are appropriate for an empirical evaluation of the effects of this type of dedicated lanes as their introduction entails a structural, large-scale reorganization of a city's transportation system.

The second type of dedicated lanes are dedicated *sections* supplied on severely congested parts on the bus network. The length of a bus lane may therefore be as short as a few hundred meters, with most of the bus network running on non-dedicated lanes. The introduction or extension of this type of bus lanes implies a marginal, local, change in the city's transport system. Implementation costs are close to zero. The main social cost is due to reducing the number of lanes available to other traffic. This smaller-scale intervention is very widespread and is found in, e.g., London, Amsterdam, Rome, Zurich, New York and Los Angeles. To our

[1] In Rome dedicated lanes are shared with taxis, ambulances, police and other public service vehicles. Other cities (e.g. Zurich) adopt a starker separation of public transit vehicles.

knowledge, however, there is essentially no evidence of the effects of bus lane segments on the cost of travel and their implications for welfare.

We focus on this second type of bus lane in this paper. As far as we are aware, we provide the first estimates of the welfare effects of bus lanes, taking into account the travel time benefits to bus travelers as well as the change in travel costs to private motor vehicle users. Consistently with the idea that introduction of these bus lanes is a marginal, local change to the transportation system, we estimate these welfare effects on a road-by-road basis. Specifically, we follow the literature by estimating the effects of traffic density on travel time for private motor vehicles (Yang et al., 2020; Adler et al., 2020b) and on travel time of buses (Adler et al., 2020a). Our novel contribution is that we provide counterfactual travel times and demand (for car and bus travelers) for a policy where a dedicated bus lane is introduced.

We show that the provision of a dedicated bus lane reduces bus travel time on our roads by about 18 percent, and waiting time at stops by about 12 percent. We investigate the welfare implications in our counterfactual analysis. The welfare gains from the bus lane depend, quite intuitively, on the elasticity of demand by motor-vehicle travelers on the given road. We are able to single out roads for which the introduction of a bus lane would most likely increase welfare given a wide range of demand elasticities. Furthermore, for a few of these roads, under plausible conditions, the introduction of a bus lane would result in lower motor vehicle travel time in equilibrium. These findings suggest that dedicated lanes are undersupplied in Rome. Our results are consistent with previous theoretical literature (Basso et al., 2011; Basso and Silva, 2014) and have policy implications for large cities where buses are the mainstay of the public transport system.

2. Theoretical background

2.1 Setting

We consider a homogeneous road of fixed length (e.g. 1 km) with a given number of lanes and no bottlenecks. Individuals can travel either by private motor vehicles (cars, motorbikes) or public buses. We assume motor-vehicle and bus travel are substitutes, and both are decreasing in their own generalized price.

We assume the generalized price of motor vehicle travel consists only of travel time, T, which increases with road congestion. We take resource costs and fees as given and thus ignore them without loss. T is an increasing and convex function of motor vehicle density *per road* *lane*, D (Helbing, 2001; Yang et al., 2020, Adler et al., 2020b).[2] Drivers choose their speed based on the distance to the car in front of them, hence greater density implies lower speed. We estimate this "supply" relationship by assuming the following functional form (Underwood, 1961):

(1) $$T = \beta e^{\alpha D},$$

where α and β are positive parameters.[3] In the welfare analysis, we shall relate travel time to travel flow (or throughput), F, i.e. the number of motor vehicle travelling per unit of time.[4] Noting that density is just the product of travel time and flow, one can show that (1) implies a standard, upward-sloping, relation between travel time, T, and flow, F, as long as density is below a certain critical value (see Appendix A). This condition is almost always satisfied in our observations (more than 98.5 percent of the time). Therefore, we shall concentrate on the upward-sloping part of the travel time-flow relation.

The generalized price of bus travel is given by the fare and the generalized travel time, T_B^G. The fare is given in our analysis and can thus be ignored without loss. Hence, the generalized price of bus travel is T_B^G. The latter consists of in-vehicle travel time, T_B , and waiting time at stops, T_B^W. Bus travel time, T_B , consists in turn of two components: time *between* stops and time *at* stops. The latter increases with the number of boarding/alighting passengers at each stop, which we do not observe, and possibly with congestion of passengers inside buses and of vehicles on the road. We will assume that the time at stops is given which, as we argue later on, likely underestimates the welfare gains from dedicated bus lanes.

Just like motor vehicles, buses travel slower in heavy traffic. We will estimate the effect of road congestion -captured by traffic density- on bus users through changes in in-vehicle bus travel time, T_B as well as waiting time, T_B^W. The relationship between bus travel time and traffic density has the same functional form as (1):

(2) $$T_B = \gamma e^{\sigma D},$$

where γ and σ are positive parameters.

Road congestion also increases bus waiting time, T_B^W, because it decreases bus frequency, i.e. the average number of buses passing the road segment per unit of time. We do not observe waiting time, but we will estimate it by assuming that users arrive at bus stops

[2] We will measure T in minutes per kilometer, whereas we will measure D in vehicles per kilometer-lane.

[3] We focus on density of motor vehicles, ignoring that buses have a stronger effect on travel time delays than cars. In Rome, less than 1 percent of total traffic consists of buses, so there is little downside to ignoring this effect.

[4] We will measure F in vehicles per minute.

randomly (Jara-Diaz and Gschwender, 2009). Expected waiting time is then proportional to bus travel time (per kilometer):

$$T_B^W = \frac{0.5 \times T_B}{n_B}, \quad (3)$$

where n_B denotes the number of buses in operation. Given (2) and (3), it is straightforward to derive the marginal effect of road congestion, through higher levels of *D*, on bus waiting time T_B^W.

Finally, we focus on steady-state relations, i.e. we assume that observed motor-vehicle travel time and flow are *each hour* and *for each road* in equilibrium, i.e. demand equals supply. The latter assumption is useful to identify road-hour specific demand shifters.[5]

2.2 Dedicated bus lanes

We are interested in the welfare effects of introducing dedicated bus lanes. To evaluate the potential travel time gains for bus travelers, we focus on roads where traffic is currently mixed (i.e., buses travel on the same lanes as other vehicles) and derive the counterfactual bus travel time with a bus lane. We assume the average speed of buses on the bus lane equals the speed on a mixed traffic lane when there is no traffic, i.e. *D=0*. Given (2), the counterfactual bus travel time on a dedicated bus lane, T_B^{DL}, is thus equal to γ. To obtain the bus waiting time, we replace $T_{Bi,t}^{DL}$ in expression (3) and assume the number of buses in operation, n_B, is invariant with respect to the status quo.[6]

Given a road of fixed size, introducing a bus lane entails closing a lane for motor vehicles. We aim to estimate how this reduction in capacity affects the relation between traffic density and motor vehicle travel time on this road. For concreteness, let us focus on a two-lane mixed traffic road (we shall focus on this kind of roads in the empirical analysis below). Given two lanes in the status quo, introducing the bus lane reduces the space available for motor vehicles by half. To obtain the counterfactual relationship between travel time, T^{DL}, and density on the remaining lane, we refer to equation (1). This equation characterizes the motor vehicle travel time in the status quo when there are *D* vehicles per kilometer *per lane* and hence, with a two-lane road, 2*D* per kilometer *in total*. We assume that, for any level of *D*, T^{DL} equals the travel time in the status quo given the same total number of vehicles, *2D*, but placed on a single

[5] While it would be desirable to model mode choice using a discrete choice setting, we do not have adequate data to estimate the parameters of such model, since we do not observe individual travel choices but only aggregate traffic and bus data.

[6] Bus travelers dislike waiting at stops, T_B^W, more than the time on the bus. In the welfare analysis, we will take this into account by assuming that the time cost of waiting time is twice the bus travel time (see, e.g. Basso and Silva, 2014).

lane. This assumption is fairly crude, but it is consistent with previous studies on the effects of road space allocation on travel time. See, e.g., Basso and Silva (2014, equation 7). Therefore, given the parameters α and β in expression (1), the relation between travel time and motor-vehicle density with the bus lane, is:

$$T^{DL} = \beta e^{2\alpha D}. \quad (4)$$

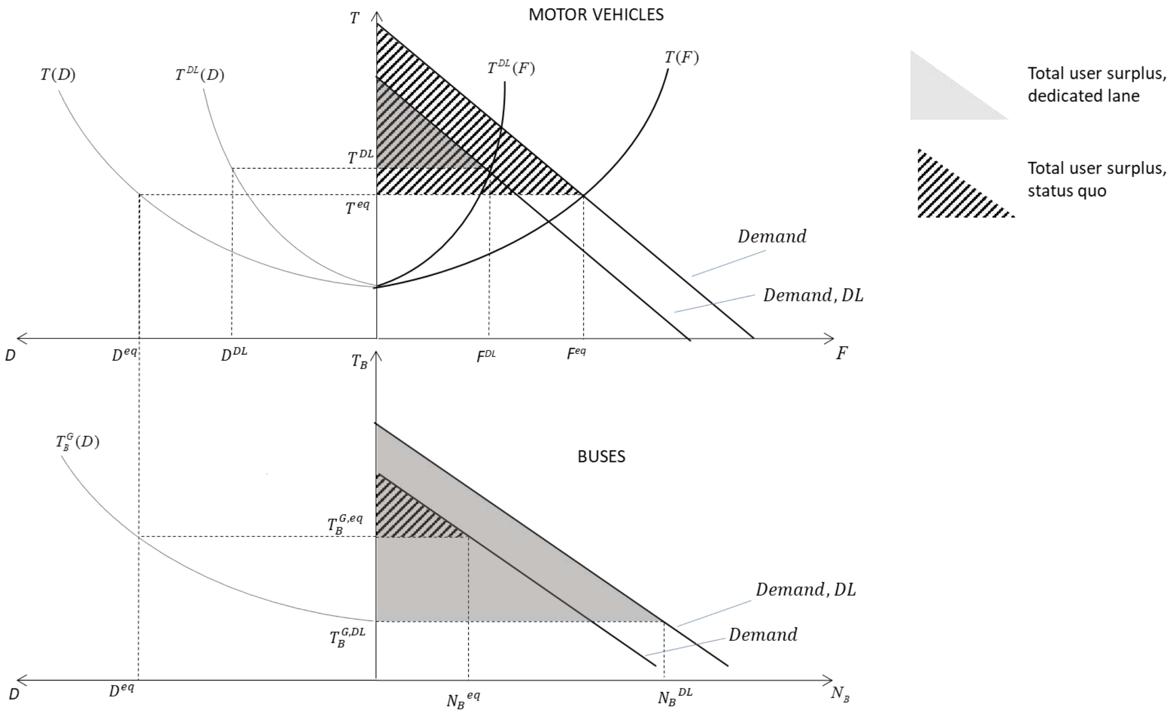
Intuitively, reducing the space available for motor vehicles implies a steeper relation between density and travel time. In Appendix A, we show that a reduction in the number of available lanes makes the *travel time-flow* relation steeper as well (to be precise, more than twice as steep).

Figure 1 summarizes the effects of introducing a bus lane. The top panel refers to motor-vehicles, with the relationship between travel time and density depicted on the left and the relationship between travel time and flow on the right. The decreasing lines on the right panel represent the demand for motor-vehicle travel, which increases with the generalized price of travel by bus (see equations (9) and (10) below). Starting from the status-quo equilibrium (superscript "eq."), we expect the counterfactual (with a bus lane) motor-vehicle flow, F^{DL}, to decrease as fewer users travel on the road by motor vehicle. Travel time, T^{DL}, is however likely to be higher than in the status quo due to the reduction in capacity. Nonetheless, it is possible that T^{DL} is *smaller* than in the status quo, if (i) demand for motor vehicle travel decreases due to the improvement in bus travel time (so that in equilibrium motor vehicle density on the remaining lanes decreases) and (ii) the restriction to capacity available to motor vehicles from introducing a bus lane is sufficiently mild. We argue in Section 5 that, under reasonable assumptions, these conditions apply for some of the roads in our sample.

The bottom panel of Figure 1 refers to bus travel. Following the introduction of the dedicated lane (superscript DL), demand increases given the increase in motor vehicle travel time. Generalized bus travel time drops from $T_B^{G,eq}$ to $T_B^{G,DL}$ with the introduction of a bus lane[7] and the number of bus users increases from N_B^{eq} to N_B^{DL}. The figure also shows the net user surplus (which is our measure of welfare) in the status-quo (black dashed area) and bus-lane (grey area) equilibria. The net effect on welfare from introducing the bus lane is the difference between these areas.

[7] Recall that we assumed bus travel time at stops (loading and unloading passengers), is given. Hence, we characterize the relationship between bus travel time and the number of bus passengers as flat since the speed of buses between stops does not depend on the number of passengers carried.

Figure 1: Effects of providing dedicated bus lanes



3. Empirical approach

In order to estimate the parameters in (2), we estimate the effect of traffic density, D, on log bus travel time, $logT_B$. We estimate separate models for each road in our sample, using a range of time (hour-of-the-day, day-of-the-week and week-of-the-year fixed effects). These controls aim to capture unobserved supply shocks that affect bus speed. Furthermore, we include weather controls and bus stop fixed effects. We estimate:

(5) $$logT_{Bi,t} = \pi_i + \sigma_i D_{i,t} + \vartheta_i{}' X_t + v_{i,t},$$

where $v_{i,t}$ is the error term. Importantly, X_t includes three other types of time fixed effects – hour-of-the-day, day-of-the-week and week-of-the-year dummies – as controls. We estimate these models using OLS as well as with IV to deal with potential endogeneity issues. For example, many unobserved supply shocks, such as road closures, accidents or bad weather, may simultaneously affect density and bus travel time. Hence, the key requirement that $E(D_{i,t} v_{i,t} | X_t) = 0$ may fail.

In the IV estimates, we use *hour-of-the-week* dummies, z_t, as instruments for density (e.g. a dummy for Monday morning between 9 and 10 AM is one instrument). This means effectively that we estimate the following equation in the first step:

(6) $$D_{Bi,t} = \Upsilon_i + \varrho_i z_{,t} + \varpi' X_t + u_{i,t},$$

and the following in the second step:

(7) $$logT_{Bi,t} = \pi_i + \sigma_i \widehat{D}_{i,t} + \vartheta_i{}' X_t + v_{i,t},$$

where $\widehat{D}_{i,t}$is the predicted density level from the first step.

Hence, we assume that $E(z_t v_{i,t}|X_t) = 0$. That is, conditional on our controls, these hour-of-the-week dummies do not have any effect on travel time of buses in operation, *except through changes in congestion (i.e. motor vehicle density)*. This assumption is reasonable for bus travel time between stops, but unlikely to hold for travel time at stops.[8] We shall therefore focus only on the former as our dependent variable.

Note that given our vector of controls, X_t, the variation we exploit for our instrument is that demand is higher during a certain hour of the week, but we control for the hour of the day (i.e., we control for daily variation in sunlight or policies that apply only on certain hours of the day, e.g. traffic light changes), day of the week and week of the year (i.e., we control for roadworks that tend to occur only on certain days or that are specific to a certain period of the year). Our controls also take care of environmental conditions that affect driving speed for given density at certain hours of the day, as well as weather conditions (rain and temperature).

Note also that our estimates of σ_i $a$re road specific. Having road specific estimates is useful as it makes the counterfactual analysis (which is based on the estimate of σ_i) arguably more convincing. For instance, we do not have to make the implausible assumption that the travel time gains from a dedicated bus lane are the same for each road.

To measure the time gains for bus travelers due to bus lanes, we employ these road-specific estimates of the effect of motor-vehicle density on bus travel time (i.e., σ_i and other parameters) from equation (5). Assuming zero motor-vehicle traffic density on newly introduced dedicated lanes (*D=0)*, we obtain the counterfactual bus travel time, $T^{DL}_{Bi,t}$. Combining this information with equation (3) provides the counterfactual waiting time of dedicated lanes (we keep the number of buses in operation, n_B, constant).

We measure the cost of introducing a (counterfactual) dedicated bus lane for a subsample of two-lanes mixed traffic roads (i.e. roads that do not include a bus lane already), by calculating the expected increase in motor-vehicle travel time when closing one lane to motor-vehicles. To this end, we estimate the effect of motor-vehicle density on motor-vehicle travel time based on (1). Specifically, after taking logs, and adding controls, we estimate:

(8) $$logT_{i,t} = \mathcal{K}_i + \alpha_i D_{i,t} + \vartheta_i X_t + \varepsilon_{i,t},$$

[8] For example, bus service frequency changes systematically over the course of the day. Changes in service frequency implies different levels of bus occupancy and thus affect boarding times for buses in operation.

where $D_{i,t}$ is the density of vehicles per road lane. Our specification includes the same set of controls as for (5). Furthermore, because one can also expect similar endogeneity issues, as in (5), we rely on IV estimates using the same demand shifting instrument, z_t.[9] Given estimates of α_i and $\mathcal{K}_i$, we predict the counterfactual relationship between motor-vehicle travel time and density on road i when one lane is converted into a bus lane, $T_{i,t}^{DL}$, using equation (4).

We aim to characterize the counterfactual equilibria when converting a standard road lane to a bus lane, as depicted in Figure 1, and compute the associated welfare changes. To do so, one needs to combine the estimated relations (1)-(4) with information about demand. We assume the following inverse linear demand for motor-vehicle travel:

$$T_{i,t} = \mu_{i,t} + \theta_{i,t} T_{B_{i,t}}^{G} - \varphi F_{i,t}, \tag{9}$$

where $\mu_{i,t} > 0$, $\theta_{i,t}$ and $\varphi > 0$. The fundamental assumption we make is that the slope of the demand for motor-vehicle travel, φ, is invariant across roads and hours, whereas we let $\mu_{i,t}$ and $\theta_{i,t}$ vary by road and hour. We consider several values of φ , such that demand ranges from almost perfectly elastic to almost perfectly inelastic. We estimate $\mu_{i,t}$ and $\theta_{i,t}$, which is possible given our assumption that each hourly observation of motor-vehicle travel time and flow on a road describes an equilibrium. Similarly, we assume a linear (inverse) demand for bus travel:

$$T_{B_{i,t}}^{G} = \varsigma_{i,t} + \varrho_{i,t} T_{i,t} - \rho_{i,t} N_{B_{i,t}}, \tag{10}$$

where $\varsigma_{i,t}$, $\varrho_{i,t}$ and $\rho_{i,t}$ are positive parameters. We calculate the value of $\varrho_{i,t}$ and $\rho_{i,t}$ based on elasticities reported in the literature and estimate $\varsigma_{i,t}$ by road and hour accordingly. Appendix B provides a detailed description of this procedure.

[9]Adler et al. (2020b) show that use hourly information on public transport supply during strikes as demand-shifting instruments for density when estimating (8), obtaining similar results. Yang et al. (2020) also use demand-shifting instruments to estimate a similar relationship.

4. Data

4.1 Motor-vehicle traffic data

To obtain information about motor-vehicle traffic (including motorcycles) on mixed traffic roads, we use information from loop detectors provided by Rome's Mobility Agency. We focus on 27 road segments, labeled as roads, of which 23 are mixed traffic, whereas the other four include a dedicated bus lane (as well as a lane available to car traffic). For roads with a dedicated bus lane, we have information about motor traffic on the lane parallel to the dedicated bus lane. We employ information on hourly travel time and flow for measurement points on these roads between 5am and midnight for 769 workdays, during a period from the 2nd of January 2012 to the 22nd of May 2015.

Travel time is measured in minutes per kilometer. We calculate density based on the observed flow and travel time and measure it as the number of motor vehicles per kilometer of road lane. After excluding extreme outliers, we have in total about 350,000 hourly observations for motor vehicle travel time, flow and density. We provide descriptive information in Table 1.

On average, travel time of private motor vehicles on mixed traffic roads is 1.41 min/km, which corresponds to an average (instantaneous) speed of almost 45 km/h. This speed is far above the average speed of an entire trip, e.g. because our measurement locations are not close to traffic lights, which means we do not account for speed reductions at traffic lights.[10] Flow is on average about 9.2 vehicles per lane per minute. Density is on average about 14.8 motor vehicles per kilometer-lane. Car traffic conditions are fairly similar on roads that contain a dedicated bus lane.

4.2 Bus travel data

For our sample of 27 roads used by the city's bus network we have information for each bus line *section,* i.e., the segment between two successive stops. We use information from about 58 bus line sections, located on the same road segments for which we observe motor-vehicle traffic data. Using bus microdata available for the months of March 2014 and 2015, we calculate *i)* the bus travel time between stops (in minutes per km), *ii)* time at stops (in minutes per stop), for each bus line section and *iii)* the total bus travel time – including time at stops (in minutes per km). 44 bus line sections are located on mixed traffic roads (i.e., that do not include a

[10] The main consequence of this is that we exclude time delays of motor vehicles at intersections. As pointed out by a referee, intersection delays play an important role for time delays in cities. Consequently, as dedicated bus lanes reduce road capacity and therefore increase time delays for motor-vehicle users, we have overestimated the *percentual* increase in overall travel time experienced by these motor-vehicle users implying that we have underestimated the welfare gains of dedicated bus lanes.

dedicated bus lane). The remaining bus line sections are on roads with bus lanes. In total, we have 71,645 hourly observations for mixed traffic roads and 31,024 observations for dedicated bus lanes.

Table 1 – Bus and motor vehicle travel

	Mixed Traffic	Dedicated Bus Lanes		Mixed Traffic	Dedicated Bus Lanes
Bus travel time between stops [min/km]	1.56	1.08	Bus users per section [pass-km/min]	5.16	9.96
Bus time at stops [min/stop]	0.69	0.78	Travel time motor veh. [min/km]	1.41	1.20
Bus travel time (incl. at stops) [min/km]	3.02	1.99	Density motor veh. [veh/lane-km]	14.8	13.5
Bus waiting time [min]	7.69	4.34	Flow motor veh [veh/min]	9.20	8.46
Line section length [km]	0.47	0.85	Number of roads	23	4
Bus flow per lane [veh/min]	0.08	0.24	Number of bus lines	15	2
Bus flow per road [veh/min]	0.12	0.24	Number of bus line sections	44	14

Summary information in Table 1 shows that the average bus travel time is almost 2 minutes per km (speeds of about 30 km/h) on dedicated lanes, where it is slightly above 3 minutes per km on mixed traffic roads (about 20 km/h). This difference is due to a higher driving speed on dedicated lanes (1.08 minutes per km versus 1.56 minutes per km in mixed traffic) and fewer stops on dedicated lanes (the average distance between stops is 0.47 km on mixed traffic roads, whereas it is 0.85 km on bus lanes). Note that buses tend to spend slightly more time at stops on dedicated lanes (the difference is 0.09 minutes per stop, so about six seconds) most likely because of higher passenger demand.

Bus travelers care about the in-vehicle bus travel time, but also about the waiting time at stops. Waiting time is substantially smaller when buses travel on bus lanes (4.34 versus 7.69 minutes), because bus frequency is two times higher than on mixed traffic roads (0.24 compared to 0.12 buses per minute). This difference is partly due to the higher speed of buses on dedicated lanes, but the primary reason is that, as one would expect, the public transport agency tends to use roads with dedicated lanes more intensively. Accordingly, the total number of bus users is higher for bus sections on dedicated lanes.

Bus travel time tends to be more variable on mixed traffic lanes: the average standard deviation (computed by line section and per each hour) of travel time between stops is 0.54 min/km, compared to 0.27 min/km on dedicated lanes. Variability in travel time at stops is slightly higher on dedicated lanes than on mixed traffic roads (the standard deviations are 0.25 and 0.20 min/stop respectively). Motor-vehicle traffic conditions are quite similar for both types of roads: roads with dedicated bus lanes have similar, but slightly lower, motor-vehicle travel times and densities than mixed traffic roads.

5. The effects of providing dedicated bus lanes

In Table C1 of Appendix C, we provide the estimates (and standard errors) of σ_i and α_i, i.e. the road-specific effects of density on motor-vehicle and bus travel time respectively.[11] On average, estimates of σ_i and α_i on mixed roads are around 0.02, whereas on roads with dedicated bus lanes, as one might expect, α_i is also on average about 0.02 whereas σ_i is equal to zero for each road. Hence, these results indicate that on mixed lanes travel time by motor vehicles as well as buses increase by about 2% for one additional car (per kilometer), whereas on dedicated bus lanes, travel time of buses is not affected by traffic conditions.[12]

Given this information, we are able to evaluate the effects of separating buses from other traffic. The beneficial effect of providing a separate lane for buses is that bus speed increases, whereas the detrimental effect for motor vehicles is that number of lanes is reduced. We focus on the beneficial effect first. The counterfactual reduction in bus travel time due to the introduction of separate dedicated bus lane on current mixed roads can be calculated by assuming that the motor-vehicle density is reduced towards zero. The estimates imply that providing a (fully-separate) dedicated bus lane on a road where traffic is currently mixed reduces bus travel time between stops by 0.56 min/km on average, i.e. about 32 percent of the travel time between stops and 18 percent of the average bus travel time overall (including time idle at stops). Furthermore, expression (3) implies that, assuming the supply of buses does not change, the introduction of a bus lane reduces waiting time by about 0.86 minutes, i.e. about 12 percent. These figures support the findings of previous literature that relies on simulation models (e.g. Basso and Silva, 2014).

Focusing now on the losses to motor-vehicle users due to reduced road capacity. We exclude roads that only have a single lane per direction (our methodology is unsuitable for such roads) and focus on a subsample of ten two-lane mixed-traffic roads.[13] For these roads, we compare the status quo to the counterfactual equilibrium where one lane is closed to motor vehicles and reserved to buses, applying the methodology illustrated in Section 2.2 and Figure

[11] For a more exhaustive discussion of these results, see Adler et al. (2020b). A slight difference is that the latter study includes 5 additional roads which we have excluded as they are not used by buses.

[12] These numbers imply a critical value of traffic density (beyond which the road becomes hypercongested) of about 48 vehicles/lane-km. This number tends to be higher than the values commonly estimated in the engineering literature. The most likely explanation relates to the relatively small size of cars in Rome and to the high share of motorcycles among motor vehicles (about 25%, see (ATAC SpA, 2013).

[13] The set of roads we consider in this exercise are quite similar to the average road in our sample, although traffic tends to be slightly slower (travel time is 1.49 min/km versus 1.33 min/km for the full sample). Bus travel conditions are also quite similar.

1. See Appendix B for a formal characterization of the equilibrium. We report the results (averaged for all hours and roads) in Table 2, given different assumptions on the slope of the demand for motor-vehicle travel, denoted by φ in expression (9). On these ten roads, the provision of dedicated bus lanes brings substantial benefits to bus travelers, as travel time decreases by about 18 percent and waiting time by about 12 percent. Frequency increases by about 20 percent as a result of the higher bus speed. Demand for public transport is quite sensitive to time improvements: following Parry and Small (2009), we assume an elasticity with respect to the generalized price of bus travel of -2.2. Thus, the provision of a bus lane causes a substantial increase in the number of bus users, by about 26 percent. The public transport modal share increases to about 40 percent, from an initial share of 29 percent. Note that these gains are calculated assuming no other changes in the supply of bus services as demand conditions change.[14]

One of the key parameters to determine the net welfare effects of introducing the bus lane is the own-price elasticity of the demand for motor-vehicle travel. We consider a range of values for the slope, ranging from $\varphi = 1$ to $\varphi = 0.1$, corresponding to an implied elasticity of -0.12 to -2.53 (which largely encompass existing elasticities in the literature. See, e.g., Litman, 2019). When $\varphi = 1$, demand is highly inelastic and few motor-vehicle users can avoid the road considered, despite the reduction in the available capacity. Hence, this reduction causes a severe increase in motorists' travel time, by about 150 percent. The result is a net loss of welfare equal to about 29 passenger-minutes per minute. It seems however reasonable to assume that demand *at the level of a road* is quite elastic (e.g., because there are alternative routes). When demand is sufficiently elastic ($\varphi \leq 0.3$), i.e. the implied elasticity is less than -1, motorists can more easily avoid this road resulting in a relatively small increase in the equilibrium travel time. Therefore, the net welfare change from bus lanes is positive.

The averaged results mask significant differences between roads (see Appendix D). For one out of ten roads the travel time gains on buses are large, while the increase in motor-vehicle travel time is relatively small. Hence, the net welfare effect of the dedicated lane is positive even when demand is highly inelastic ($\varphi = 1$). By contrast, four other roads are so prone to congestion that reallocating space to buses results in travel delays for motor vehicles that are

[14] That is, we ignore several modifications that a welfare-maximizing public transit agency would probably adopt in response to the increase in user demand such as increasing the number of operating buses, with a further increase in frequency (Mohring, 1972). Furthermore, the agency could adjust the size of buses and the distance between stops (Basso and Silva, 2014). Recall also that we treat idle time at stops as given. Therefore, we may slightly underestimate the welfare gains of bus lanes, as it seems plausible that buses on these lanes need less time to move into heavy traffic. However, it is also possible that we slightly overestimate the welfare gains, as the stop time increases because of increased number of passengers that enter or leave the bus.

very large even when demand is quite elastic ($\varphi = 0.3$). Hence, not all roads are good candidates for introducing a dedicated lane. Nonetheless, it appears that the introduction of dedicated lanes would increase welfare in about 10 percent of roads in our sample, *without requiring any other changes to the transport system*.[15]

Table 2 – Effects of provision of dedicated bus lanes

	Status quo (mixed traffic)	Introducing a Bus Lane			
		$\varphi = 1$	$\varphi = 0.5$	$\varphi = 0.3$	$\varphi = 0.1$
Motor-vehicle flow [veh/min-lane]	9.20	6.96	6.50	6.37	6.04
Motor-vehicle travel time [min/km]	1.49	4.10	2.61	2.16	1.76
Bus flow [veh/min]	0.13	0.16	0.16	0.16	0.16
Bus travel time [min/km]	3.06	2.50	2.50	2.50	2.50
Bus travel time, between stops [min/km]	1.76	1.20	1.20	1.20	1.20
Waiting time [min]	7.21	6.35	6.35	6.35	6.35
Bus users [pass/min]	5.41	6.86	7.07	7.20	7.34
Motor-vehicle modal share [% pass-km]	71.16	59.53	57.13	56.19	54.41
Bus modal share [% pass-km]	28.84	40.47	42.87	43.81	45.59
Welfare gain [pass-min]	/	-29.39	-7.60	1.14	7.31

Note: To compute the modal shares, we assume an average occupancy of 1.45 passengers per motor-vehicle. Bus travel time includes travel time between stops and time at stops.

Reducing the space available to motor-vehicles on a road may cause some motorists to switch to other roads, increasing travel times there as well (Wardrop, 1952). To check the robustness of our findings to the presence of alternative routes, we have also carried out the analysis under the alternative assumption that each road we consider is parallel to another road with one lane (with traffic conditions in the status quo being identical on each lane). We assume that these two roads are perfect substitutes for motor vehicle users. Although motor-vehicle travel time on the parallel road may increase (though not necessarily, see below), there are two countervailing effects that reduce the associated welfare losses. First, some motor vehicle users who do not switch to public transport when the bus lane is introduced can use another road, instead of being priced out. Furthermore, introducing the bus lane on one of the two roads implies a smaller reduction in total capacity for motor vehicles than when considering each road

[15] As a consistency check, we performed a counterfactual analysis of removing bus lanes from the few roads in our sample that already include one. One difficulty is that we do not have information about the counterfactual bus travel time delay for each removed dedicated lane. We address that issue by using the average proportional bus travel time gains for the introduction of a dedicated lane on current mixed roads to calculate the counterfactual bus travel time delay. We find that removing current dedicated lanes reduces welfare, which makes us more confident in our procedure.

in isolation.[16] Therefore, the increase in motor-vehicle travel time tends to be smaller. In fact, on at least two of our ten roads, motor-vehicle travel time *decreases* after introducing the bus lane. As discussed in Section 2, given the reduction in demand for motor-vehicle travel (due to the improvement in bus travel time), and the relatively limited restriction to overall capacity, motor-vehicle travel time on the remaining lanes decreases in the new equilibrium with a dedicated lane.[17] Under this alternative assumption, we find that introducing a bus lane increases welfare on at least three out of ten roads. We report these results in Appendix D (Tables D5). We find even more favorable welfare effects of dedicated lanes when we assume the parallel road has two lanes, rather than one (see Table D6).

A potential concern is that we ignore possible increases in bus idle time at stops due to higher passenger demand when dedicated lanes are introduced. We cannot address this concern directly because we do not observe bus travel demand nor the number of passengers boarding/exiting the bus at each stop. However, back-on-the-envelope calculations show that even if the transit agency does not change other supply conditions (e.g. the supply of buses on the road), this effect is unlikely to overturn our results.[18] We also ignore congestion on bus lanes since we assume that frequency of buses in the counterfactual is the same as in the status quo. Our data suggests that bus congestion in the roads we consider that include a bus lane is negligible. While it is possible that greater bus congestion arises when a dedicated lane is introduced, higher bus frequency would also bring benefits in the form of lower waiting times.

Finally, we ignore additional factors that may affect users' travel cost, such as discomfort, transfers and access time, because we do not have sufficient data to meaningfully evaluate the impact of such factors. To the extent that the expansion of dedicated lanes allows to increase frequency, it should help alleviating crowding and discomfort, as well as reduce the time spent waiting for a bus connection when transferring.

[16] For example, if the parallel road has one lane, there are three lanes available to motorists in total. Introducing the bus lane implies a reduction in capacity by one third. By contrast, if one considers a single two-lane road in isolation, the bus lane implies a reduction of capacity by one half.

[17] If we assume the alternative road has a single lane, travel time decreases in two out of ten roads after the introduction of the dedicated lane. If we assume the alternative road has two lanes, travel time decreases on six out of ten roads.

[18] On average, bus occupancy is 42 passengers per km in the status quo on the roads we consider. Occupancy increases by about 4 passengers per km with the dedicated lane given our results. Assuming 20 stops per line and supposing (conservatively) that each extra passenger travels 4 stops on average, there are 2 additional entry/exits to/from the bus per each stop. Table 2 indicates that placing the bus on a dedicated lane brings to a reduction in travel time of 0.56 minutes per kilometer, or 33.6 seconds per kilometer. Given there about 2 stops per kilometer on mixed traffic roads (see Table 4), this implies a reduction in travel time by 16.8 seconds per stop. Assuming each extra passenger entering/exiting generates a time loss of 2.5 seconds (Basso and Silva, 2014), the net decrease in travel time would still be equal to 11.8 seconds per stop, i.e. more than 70% of what we find. We also ignore the increase in crowding due to higher bus demand (De Palma et al., 2015). Table 2 reports that the frequency (flow) of bus increases by about 20 percent, while the number of bus users increases by 26 percent. Therefore, one can expect a small increase in crowding.

6. *Conclusion*

Urban and transport economists typically advise road pricing to address road externalities, but this is often politically unfeasible. An often-suggested alternative is to subsidize public transit and/or improve its quality. In this paper, we have focused on the effects of introducing dedicated bus lanes, which have received little attention in the literature so far. Our findings suggest that dedicated bus lanes may bring substantial welfare gains.

We show that the provision of a dedicated bus lane reduces bus travel time on our roads by about 18 percent and waiting time by about 12 percent. Frequency increases by about 20 percent as a result of the higher bus speed. We also find a substantial increase in the number of bus users, by about 26 percent. The public transport modal share increases to about 40 percent, from an initial share of 29 percent. Note that these gains are calculated assuming no other changes in the supply of bus services as demand conditions change. The averaged results mask significant differences between roads. Although some roads are not suitable to introducing a bus lane, the latter would increase welfare in about 10 percent of roads in our sample, *without requiring any other changes to the transport system.* When considering a simple network of roads (two roads in parallel) we find that the introduction of a bus lane on one road can result in lower travel time for motor vehicles as well.

Overall, the findings suggest that the introduction of dedicated lanes for some roads should be a priority in Rome, as road congestion has a strong effect on travel time delays of buses in line with previous literature (Basso and Silva, 2014; Börjesson et. al, 2017).

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Appendix

Appendix A: Deriving the relation between travel time and flow of motor-vehicles

We now derive the relation between motor vehicle travel time and flow, i.e. the quantity of vehicles per unit of time on our (one-km) road segment. Given the fundamental relation between density, flow and travel time, D=FT, and equation (1), it can be shown that

$$\text{(A1)} \qquad \frac{dT}{dF} = \frac{\frac{\partial T}{\partial D}T}{1 - \frac{\partial T}{\partial D}F} = \frac{\alpha T^2}{1 - \alpha \mathrm{D}}.$$

which is positive whenever $\alpha \mathrm{D} < 1$.

Now suppose that we introduce a dedicated bus lane on a given road with 2 lanes by reducing the number of lanes for mixed traffic by one. This makes the relationship between travel time and flow more than twice as steep:

$$\text{(A2)} \qquad \frac{dT^{DL}}{dF} = \frac{2\alpha {T^{DL}}^2}{1 - 2\alpha \mathrm{D}} > 2\frac{\alpha T^2}{1 - \alpha \mathrm{D}} = 2\frac{dT}{dF},$$

where we have assumed that there exists a positive relationship between travel time and flow which implies that $2\alpha \mathrm{D} < 1$.

Appendix B: Characterizing the counterfactual equilibria with dedicated bus lanes

We characterize the counterfactual equilibria in Figure 1. Inverting (9) we get:

(B1) $$F_{i,t} = \frac{\mu_{i,t}}{\varphi} + \frac{\theta_{i,t}}{\varphi} T^G_{B_{i,t}} - \frac{T_{i,t}}{\varphi},$$

which implies that the cross-price elasticity of demand for motor vehicle travel with respect to the price of bus travel is:

(B2) $$\varepsilon_{F,B\,i,t} \equiv \frac{dF_{i,t}}{dT^G_{B_{i,t}}} \frac{T^G_{B_{i,t}}}{F_{i,t}} = \frac{\theta_{i,t}}{\varphi} \frac{T^G_{B_{i,t}}}{F_{i,t}}.$$

In a companion paper, using data on monetary price changes in public transport on travel demand for Rome, see Adler et al. (2020a), we find that $\varepsilon_{F,B}$ is about 0.1. We assume the same elasticity applies for travel time changes in public transport. Given the assumed φ, and given hourly observations of $F_{i,t}$ and $T_{B\,i,t}$ for each road, we compute the value of $\theta_{i,t}$ for the given road-hour pair as follows:

(B3) $$\theta_{i,t} = \frac{0.1\varphi F_{i,t}}{T^G_{B_{i,t}}}.$$

The value of $\mu_{i,t}$ can be calculated given the assumption that, on a given road-hour pair, the market is in equilibrium. Specifically, Given φ, $\theta_{i,t}$ and information on $T_{i,t}$, $T_{B\,i,t}$ and $F_{i,t}$, one calculates $\mu_{i,t}$ using (9).

Consider now the demand for bus travel. Inverting (10) we get:

(B4) $$N_{B\,i,t} = \frac{\varsigma_{i,t}}{\rho_{i,t}} + \frac{\varrho_{i,t}}{\rho_{i,t}} T_{i,t} - \frac{T^G_{B_{i,t}}}{\rho_{i,t}}.$$

To determine $\rho_{i,t}$, we assume the price elasticity of bus travel in Rome is -2.2 (this is the value that Parry and Small (2009) assume for peak-hour travel in London). This elasticity writes:

(B5) $$\varepsilon_{B\,i,t} \equiv \frac{dN_B}{dT_B} \frac{T^G_{B_{i,t}}}{N_{B\,i,t}} = -\frac{1}{\rho_{i,t}} \frac{T^G_{B_{i,t}}}{N_{B\,i,t}}.$$

Using this expression and our observations of $N_{B\,i,t}$ and $T_{B\,i,t}$ we can calculate $\rho_{i,t}$ for the given hour and road as:

(B6) $$\rho_{i,t} = \frac{T^G_{B_{i,t}}}{2.2 \times N_{Bi,t}}.$$

We can then calculate $\varrho_{i,t}$ as follows. We assume the cross-price elasticity of public transport (bus) with respect to motor vehicles is about 0.14, an average reported in Litman (2015) for other cities (and similar to what Adler et al. (2020) find for Rome). We then get:

$$\varrho_{i,t} = \frac{0.14 \times \rho_{i,t} \times N_{B_{i,t}}}{T^G_{B_{i,t}}}. \tag{B7}$$

We then determine the intercept $\varsigma_{i,t}$ using (10) and information on $T^G_{B_{i,t}}$, $T_{i,t}$, $N_{B_{i,t}}$ as well as the parameters determined previously.

To obtain the counterfactual bus travel time between stops on dedicated lanes, we substitute $D_{i,t} = 0$ in (2), so this travel time equals γ. The counterfactual bus travel time, $T^{DL}_{Bi,t}$, is thus given by the sum of travel time between stops and time at stops, where the latter is assumed not to change with respect to the status-quo equilibrium. Combining this information with equation (3) provides the counterfactual waiting time of dedicated lanes (we keep the number of buses in operation, n_B, constant).

Given the above information, we can characterize the counterfactual equilibria with dedicated lanes for each road-hour pair. In the counterfactual equilibrium, the private supply cost of travel by motor-vehicle (conditional on the reduction in road space) must equal demand. Hence, $\mu_{i,t} + \theta_{i,t} T_{B}{}^{G,DL}_{i,t} - \varphi F_{i,t} = T^{DL}_{i,t}$ holds. We find road traffic density in the counterfactual by solving the following for $D_{i,t}$:

$$\mu_{i,t} + \theta_{i,t} T_{B}{}^{G,DL}_{i,t} - \varphi\left(D_{i,t} / \beta e^{2\alpha D_{i,t}}\right) = \beta e^{2\alpha D_{i,t}}, \tag{B8}$$

Given the counterfactual density, we calculate the corresponding travel time and flow of motor vehicles. Finally, we calculate the welfare change on the motor-vehicle and bus market, respectively, computing the areas of the greyed areas in Figure 1.

Appendix C: Results by road

Table C1 – Motor vehicle and bus travel time effect of density

				Mixed Traffic Roads				
Road	α OLS	Se OLS	α IV	Se IV	σ OLS	Se OLS	σ IV	Se IV
1	0.0118	0.0001	0.0124	0.0008	0.0199	0.0030	0.0071	0.0096
2	0.0081	0.0001	0.0107	0.0005	0.0070	0.0015	0.0015	0.0038
3	0.0330	0.0001	0.0311	0.0009	0.0345	0.0010	0.0277	0.0035
4	0.0286	0.0001	0.0274	0.0006	0.0381	0.0010	0.0356	0.0029
5	0.0184	0.0001	0.0128	0.0007	0.0182	0.0011	0.0244	0.0031
6	0.0219	0.0001	0.0199	0.0008	0.0208	0.0020	0.0266	0.0057
7	0.0344	0.0001	0.0340	0.0005	0.0229	0.0022	0.0211	0.0042
8	0.0161	0.0002	0.0150	0.0007	0.0119	0.0040	0.0053	0.0098
9	0.0099	0.0001	0.0119	0.0010	0.0139	0.0027	0.0305	0.0072
10	0.0190	0.0002	0.0200	0.0006	0.0168	0.0042	0.0198	0.0074
11	0.0178	0.0005	0.0458	0.0029	0.1250	0.0094	0.1331	0.0213
12	0.0393	0.0003	0.0199	0.0026	0.0009	0.0054	-0.0021	0.0159
13	0.0191	0.0002	0.0180	0.0010	0.0112	0.0045	0.0035	0.0102
14	0.0161	0.0001	0.0143	0.0009	0.0027	0.0068	0.0169	0.0148
15	-0.0190	0.0006	0.0183	0.0059	0.0136	0.0089	0.0473	0.0268
16	0.0059	0.0001	0.0121	0.0014	0.0023	0.0018	0.0025	0.0053
17	0.0259	0.0001	0.0260	0.0005	0.0107	0.0011	0.0101	0.0032
18	0.0218	0.0001	0.0193	0.0010	0.0092	0.0045	0.0075	0.0116
19	0.0281	0.0002	0.0203	0.0014	-0.0132	0.0027	0.0125	0.0081
20	0.0291	0.0001	0.0279	0.0005	0.0004	0.0017	0.0003	0.0033
21	0.0295	0.0001	0.0279	0.0006	0.0092	0.0009	0.0114	0.0021
22	0.0340	0.0003	0.0211	0.0033	0.0191	0.0052	0.0293	0.0072
23	0.0271	0.0002	0.0114	0.0016	0.0132	0.0050	0.0273	0.0153
Average	0.0208	0.00004	0.0200	0.0004	0.0160	0.0009	0.0195	0.0023

				Roads with Dedicated Bus Lanes				
Road	α OLS	Se OLS	α IV	Se IV	σ OLS	Se OLS	σ IV	Se IV
24	0.0344	0.0002	0.0297	0.0011	0.0035	0.0024	0.0059	0.0048
25	0.0334	0.0005	0.0244	0.0040	0.0029	0.0032	-0.0063	0.0095
26	0.0053	0.0001	0.0054	0.0007	0.0045	0.0056	0.0068	0.0086
27	0.0114	0.0003	0.0022	0.0013	-0.0018	0.0036	0.0041	0.0060
Average	0.0211	0.0002	0.0157	0.001	0.0023	0.0019	0.0026	0.0037

Note: in the headers, "OLS" stands for the Ordinary Least Squares estimates for equations (5)-(8), whereas "IV" stands for Instrumental Variables estimates for such equations.

Table C2 – Bus travel time gain with dedicated lanes

			Mixed Traffic Roads				
Road	Bus Flow	Bus Users	T_B	T_B^{DL}	T_B -T_B^{DL}	Passenger time gain	Lanes
1	10.11	6.87	2.07	1.73	0.34	2.36	1
2	12.05	8.28	2.38	2.12	0.26	2.13	1
3	8.45	5.72	0.63	0.45	0.18	1.03	2
4	8.52	5.79	1.43	0.83	0.60	3.48	2
5	2.90	2.01	1.79	1.13	0.66	1.32	1
6	3.02	2.09	1.41	0.84	0.57	1.19	1
7	2.79	1.93	1.64	1.17	0.47	0.91	2
8	2.44	1.69	1.74	1.67	0.07	0.12	2
9	3.48	2.35	2.78	1.52	1.26	2.96	2
10	6.08	4.18	1.20	0.89	0.31	1.30	1
11	4.76	3.25	2.71	1.36	1.35	4.39	1
12	17.14	11.64	1.10	1.03	0.07	0.79	2
13	7.93	5.38	1.07	0.92	0.15	0.82	1
14	7.65	5.23	1.31	0.85	0.46	2.42	1
15	3.79	2.68	0.92	0.54	0.38	1.01	1
16	4.08	2.88	0.45	0.29	0.16	0.45	1
17	17.42	12.02	1.31	1.10	0.20	2.44	2
18	7.80	5.31	1.29	1.05	0.24	1.27	2
19	16.29	11.10	1.38	1.09	0.29	3.24	2
20	7.56	5.11	1.41	1.11	0.30	1.53	2
21	4.99	3.46	1.79	1.40	0.38	1.33	2
22	5.29	3.67	1.58	0.99	0.59	2.16	2
23	9.03	6.10	2.53	1.87	0.66	4.02	2
Average	7.55	5.16	1.56	1.12	0.44	1.90	/

Note: Road-specific values, averaged over all observations. We consider only roads that do not already include a dedicated lane and for which we have bus travel information. Bus flow is the number of vehicles per hour. Bus users is the number of bus travellers per minute on the road segment. T_B is the observed bus travel time (min/km), considering only travel time between stops (ignoring time at stops). T_B^{DL} is the counterfactual travel time (between stops) with a fully dedicated lane (i.e. zero density). Passenger time gain is the reduction in travel time, times the number of bus users per minute.

Appendix D: Effect of dedicated lanes

Table D1– Results with $\varphi = 1$

$\varphi = 1$	Road										
	1	2	3	4	5	6	7	8	9	10	Average
<u>Status quo</u>											
Motor-vehicle flow [veh/min]	7.38	8.33	7.36	5.83	8.88	8.86	10.06	14.25	10.61	10.44	9.20
Motor-vehicle travel time [min/km]	1.61	1.31	1.81	1.28	2.41	1.58	1.38	1.34	1.19	0.99	1.49
Bus flow per lane [veh/min]	0.07	0.07	0.02	0.02	0.03	0.15	0.14	0.04	0.04	0.08	0.066
Bus travel time, total [min/km]	2.31	2.91	2.26	2.46	4.85	4.05	4.28	2.37	1.77	3.34	3.06
Bus travel time at stops [min/km]	1.64	1.48	0.61	0.71	1.13	2.75	2.96	0.57	0.29	0.81	1.30
Waiting time [min]	3.73	4.25	17.35	16.71	10.13	1.84	1.94	6.49	6.17	3.49	7.21
Bus users [pass/min]	5.73	5.85	1.95	1.70	2.38	12.17	11.03	3.49	3.71	6.05	5.41
<u>Dedicated Lane</u>											
Motor-vehicle flow [veh/min]	5.64	6.63	4.93	6.28	7.04	6.36	7.49	5.70	8.51	10.98	6.96
Motor-vehicle travel time [min/km]	3.50	3.34	4.86	1.50	4.42	4.23	4.14	10.01	3.76	1.22	4.10
Bus flow [veh/min]	0.29	0.27	0.06	0.06	0.14	0.56	0.55	0.18	0.21	0.34	0.16
Bus travel time, total [min/km]	2.03	2.31	1.79	2.39	2.64	3.84	4.05	1.98	1.28	2.69	2.50
Waiting time [min]	3.49	3.75	15.68	16.34	7.53	1.80	1.83	5.66	4.80	2.70	6.36
Bus users [pass/min]	6.77	7.97	2.90	1.83	4.15	13.24	12.40	4.73	5.85	8.72	6.86
Welfare gain [pass-min]	-17.5	-16.4	-21.0	-2.5	-7.3	-34.2	-42.5	-128.0	-27.9	3.76	-29.39

Table D2– Results with $\varphi = 0.5$

$\varphi = 0.5$	Road										
	1	2	3	4	5	6	7	8	9	10	Average
<u>Status quo</u>											
Motor-vehicle flow [veh/min]	7.38	8.33	7.36	5.83	8.88	8.86	10.06	14.25	10.61	10.44	9.20
Motor-vehicle travel time [min/km]	1.61	1.31	1.81	1.28	2.41	1.58	1.38	1.34	1.19	0.99	1.49
Bus flow per lane [veh/min]	0.07	0.07	0.02	0.02	0.03	0.15	0.14	0.04	0.04	0.08	0.066
Bus travel time, total [min/km]	2.31	2.91	2.26	2.46	4.85	4.05	4.28	2.37	1.77	3.34	3.06
Bus travel time at stops [min/km]	1.64	1.48	0.61	0.71	1.13	2.75	2.96	0.57	0.29	0.81	1.30
Waiting time [min]	3.73	4.25	17.35	16.71	10.13	1.84	1.94	6.49	6.17	3.49	7.21
Bus users [pass/min]	5.73	5.85	1.95	1.70	2.38	12.17	11.03	3.49	3.71	6.05	5.41
<u>Dedicated Lane</u>											
Motor-vehicle flow [veh/min]	4.84	6.05	4.43	5.35	6.16	6.00	7.26	6.79	8.29	9.80	6.50
Motor-vehicle travel time [min/km]	2.70	2.18	3.11	1.48	3.36	2.77	2.51	4.73	2.07	1.16	2.61
Bus flow [veh/min]	0.29	0.27	0.06	0.06	0.14	0.56	0.55	0.18	0.21	0.34	0.16
Bus travel time, total [min/km]	2.05	2.31	1.78	2.39	2.63	3.84	4.04	1.97	1.28	2.69	2.50
Waiting time [min]	3.49	3.75	15.58	16.34	7.33	1.80	1.83	5.66	4.80	2.90	6.35
Bus users [pass/min]	7.02	8.27	2.99	1.88	4.27	13.64	12.77	4.87	6.03	8.98	7.07
Welfare gain [pass-min]	-8.13	-1.2	-2.98	-1.64	11.5	-13.3	-16.29	-51.3	-1.09	8.51	-7.6

Table D3– Results with $\varphi = 0.3$

$\varphi = 0.3$	Road										
	1	2	3	4	5	6	7	8	9	10	Average
Status quo											
Motor-vehicle flow [veh/min]	7.38	8.33	7.36	5.83	8.88	8.86	10.06	14.25	10.61	10.44	9.20
Motor-vehicle travel time [min/km]	1.61	1.31	1.81	1.28	2.41	1.58	1.38	1.34	1.19	0.99	1.49
Bus flow per lane [veh/min]	0.07	0.07	0.02	0.02	0.03	0.15	0.14	0.04	0.04	0.08	0.066
Bus travel time, total [min/km]	2.31	2.91	2.26	2.46	4.85	4.05	4.28	2.37	1.77	3.34	3.06
Bus travel time at stops [min/km]	1.64	1.48	0.61	0.71	1.13	2.75	2.96	0.57	0.29	0.81	1.30
Waiting time [min]	3.73	4.25	17.35	16.71	10.13	1.84	1.94	6.49	6.17	3.49	7.21
Bus users [pass/min]	5.73	5.85	1.95	1.70	2.38	12.17	11.03	3.49	3.71	6.05	5.41
Dedicated Lane											
Motor-vehicle flow [veh/min]	4.63	5.83	4.35	5.01	5.93	5.91	7.19	7.54	7.99	9.30	6.37
Motor-vehicle travel time [min/km]	2.19	1.86	2.53	1.46	3.01	2.30	2.09	3.23	1.74	1.14	2.16
Bus flow [veh/min]	0.29	0.27	0.06	0.06	0.14	0.56	0.55	0.18	0.21	0.34	0.16
Bus travel time, total [min/km]	2.04	2.32	1.78	2.38	2.63	3.85	4.05	1.98	1.28	2.69	2.50
Waiting time [min]	3.49	3.75	15.58	16.34	7.33	1.80	1.83	5.66	4.80	2.90	6.35
Bus users [pass/min]	7.11	8.37	3.05	1.92	4.36	13.90	13.02	4.97	6.14	9.16	7.20
Welfare gain [pass-min]	-0.62	6.19	3.74	-1.01	18.18	-4.78	-7.14	-21.10	6.96	10.94	1.14

Table D4– Results with $\varphi = 0.1$

$\varphi = 0.1$	Road										
	1	2	3	4	5	6	7	8	9	10	Average
Status quo											
Motor-vehicle flow [veh/min]	7.38	8.33	7.36	5.83	8.88	8.86	10.06	14.25	10.61	10.44	9.20
Motor-vehicle travel time [min/km]	1.61	1.31	1.81	1.28	2.41	1.58	1.38	1.34	1.19	0.99	1.49
Bus flow per lane [veh/min]	0.07	0.07	0.02	0.02	0.03	0.15	0.14	0.04	0.04	0.08	0.066
Bus travel time, total [min/km]	2.31	2.91	2.26	2.46	4.85	4.05	4.28	2.37	1.77	3.34	3.06
Bus travel time at stops [min/km]	1.64	1.48	0.61	0.71	1.13	2.75	2.96	0.57	0.29	0.81	1.30
Waiting time [min]	3.73	4.25	17.35	16.71	10.13	1.84	1.94	6.49	6.17	3.49	7.21
Bus users [pass/min]	5.73	5.85	1.95	1.70	2.38	12.17	11.03	3.49	3.71	6.05	5.41
Dedicated Lane											
Motor-vehicle flow [veh/min]	4.51	5.34	4.17	4.48	5.44	5.46	6.50	8.35	7.37	8.76	6.04
Motor-vehicle travel time [min/km]	1.95	1.55	2.09	1.39	2.70	1.85	1.66	1.86	1.46	1.11	1.76
Bus flow [veh/min]	0.29	0.27	0.06	0.06	0.14	0.56	0.55	0.18	0.21	0.34	0.16
Bus travel time, total [min/km]	2.10	2.31	1.79	2.39	2.65	3.85	4.05	1.98	1.28	2.69	2.51
Waiting time [min]	3.49	3.75	15.58	16.34	7.33	1.80	1.83	5.66	4.80	2.90	6.35
Bus users [pass/min]	7.24	8.53	3.10	1.96	4.44	14.17	13.27	5.06	6.26	9.33	7.34
Welfare gain [pass-min]	1.47	11.05	8.87	0.11	26.12	1.38	0.42	-0.77	12.11	12.39	7.31

Table D5– Results with one-lane parallel road

One-lane parallel road	Road										
	1	2	3	4	5	6	7	8	9	10	Average
Status quo											
Motor-vehicle flow [veh/min-lane]	7.11	8.45	7.35	5.87	8.77	8.91	10.04	14.21	10.40	10.73	9.19
Motor-vehicle travel time [min/km]	1.61	1.32	1.82	1.28	2.42	1.57	1.38	1.34	1.18	0.99	1.49
Bus flow per lane [veh/min]	0.07	0.07	0.02	0.02	0.03	0.15	0.14	0.04	0.04	0.08	0.07
Bus travel time, total [min/km]	2.25	2.94	2.26	2.45	4.91	4.04	4.27	2.36	1.75	3.36	3.06
Bus travel time at stops [min/km]	1.58	1.49	0.61	0.71	1.12	2.74	2.96	0.57	0.29	0.81	1.29
Waiting time [min]	3.75	4.13	17.27	16.88	10.17	1.86	1.92	6.55	6.35	3.45	7.23
Bus users [pass/min]	5.67	5.85	1.94	1.68	2.38	12.04	11.10	3.47	3.64	6.16	5.39
Dedicated Lane											
Motor-vehicle flow [veh/min]	10.49	11.69	10.70	8.52	9.58	12.87	11.74	20.69	14.97	14.92	13.20
Motor-vehicle travel time [min/km]	2.82	2.41	2.79	1.66	2.21	2.60	1.10	1.91	2.43	1.05	2.10
Bus flow [veh/min]	0.29	0.27	0.07	0.06	0.14	0.56	0.55	0.17	0.21	0.35	0.27
Bus travel time, total [min/km]	2.06	2.30	1.79	2.38	2.64	3.83	4.08	1.98	1.28	2.69	2.50
Waiting time [min]	3.47	3.74	15.25	16.29	7.16	1.78	1.81	5.73	4.80	2.86	6.29
Bus users [pass/min]	6.79	8.06	2.89	1.80	4.15	13.40	12.67	4.82	5.92	8.88	6.94
Welfare gain [pass-min]	-19.60	-8.00	-9.73	-8.25	22.48	-20.49	3.21	-17.97	-17.30	8.51	-6.71

Table D6– Results with two-lane parallel road

Two-lane parallel road	Road										
	1	2	3	4	5	6	7	8	9	10	Average
Status quo											
Motor-vehicle flow [veh/min-lane]	7.11	8.45	7.35	5.87	8.97	8.91	10.04	14.21	10.40	10.73	9.19
Motor-vehicle travel time [min/km]	1.61	1.32	1.82	1.28	2.42	1.57	1.38	1.34	1.18	0.99	1.49
Bus flow per lane [veh/min]	0.07	0.07	0.02	0.02	0.03	0.15	0.14	0.04	0.04	0.08	0.07
Bus travel time, total [min/km]	2.25	2.94	2.26	2.45	4.91	4.04	4.27	2.36	1.75	3.36	3.06
Bus travel time at stops [min/km]	1.58	1.49	0.61	0.71	1.12	2.74	2.96	0.57	0.29	0.81	1.29
Waiting time [min]	3.75	4.13	17.27	16.88	10.17	1.86	1.92	6.55	6.35	3.45	7.23
Bus users [pass/min]	5.67	5.85	1.94	1.68	2.38	12.04	11.10	3.47	3.64	6.16	5.39
Dedicated Lane											
Motor-vehicle flow [veh/min]	7.24	10.76	9.57	6.50	10.26	11.58	13.09	15.66	13.38	13.67	11.90
Motor-vehicle travel time [min/km]	1.46	1.73	2.79	1.16	1.92	2.60	1.35	1.00	2.89	0.98	1.78
Bus flow [veh/min]	0.29	0.28	0.07	0.06	0.14	0.56	0.55	0.18	0.20	0.35	0.27
Bus travel time, total [min/km]	2.03	2.32	1.79	2.38	2.64	3.84	4.05	1.97	1.28	2.69	2.50
Waiting time [min]	3.44	3.61	15.24	16.55	7.02	1.78	1.83	5.68	4.92	2.84	6.29
Bus users [pass/min]	6.74	8.12	2.91	1.81	4.27	13.40	12.41	4.75	5.81	8.95	6.92
Welfare gain [pass-min]	3.87	5.73	-4.74	-0.37	34.15	-15.45	2.65	12.24	-21.21	12.25	2.91