Green Infrastructure: The Effects of Urban Rail Transit on Air Quality*

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Abstract

The transportation sector is a major source of air pollution worldwide, yet little is known about the effects of transportation infrastructure on air quality. In this paper we measure the effects of one major type of transportation infrastructure – urban rail transit – on air quality. Our approach uses the sharp discontinuity in transit utilization on the opening day of a completely new rail transit system in Taipei, Taiwan to identify the air quality effects of rail transit infrastructure. Using hourly air quality data from Taiwan we have three central findings. First, we find that the opening of the Metro reduced air pollution from one key tailpipe pollutant, carbon monoxide, by 5 to 15 percent. Second, we find little evidence that the opening of the Metro affected ground level ozone pollution. Third, we find little evidence suggesting that automobile travelers adjusted their time or route of travel to the availability of rail transit. These findings shed new light on the determinants of air quality, and suggest that environmental impacts are important components of the social value of transportation infrastructure.

Keywords: Air Pollution, Transportation Infrastructure, Automobile Externalities
JEL Classifications: R4, Q5, H4

1 Introduction

Exposure to airborne pollution has substantial adverse health consequences.[1] A recent WHO study has estimated that urban air pollution accounts for 6.4 million years of life lost worldwide annually (Cohen et al., 2004). Many harmful pollutants are emitted by automobiles. For example, Currie and Walker (2009) estimate that prenatal exposure to traffic congestion alone reduces welfare in the US by $557 million per year. However, while the adverse health consequences of automobile pollution are widely acknowledged, little is known about the effects of transportation infrastructure on air pollution. In this paper we ask whether the air quality effects of one major type of transportation infrastructure – urban rail transit – represent significant benefits.

Conceptually, whether rail transit infrastructure has any meaningful effects on air quality is unclear. On the one hand, a rich theoretical literature following Mohring (1972) has argued that rail transit is subject to increasing returns to scale. Ridership increases engender higher service frequencies, reduce the average waiting times at stops, thus encouraging further ridership. The 'Mohring Effect' implies that investments in rail transit infrastructure divert marginal automobile travelers away from their vehicles resulting in a traffic diversion effect, and thereby reduce air pollution. On the other hand, another highly influential literature following Vickery (1969) argues that investments in transportation infrastructure simply induce demand for travel, resulting in a traffic creation effect. As rail transit infrastructure investments are likely to both divert travelers away from automobile travel, as well as induce more travel, the net effect on automobile travel – and air pollution – is unclear.

Beyond an obvious interest for transportation and environmental economists, the question of whether rail transit infrastructure has meaningful air quality effects has tremendous practical relevance. Every day 155 million people travel on urban rail transit systems in over 110 cities throughout the world and publicly subsidized investments in rail transit infrastructure continue to grow (International Association of Public Transport, 2009). Since the year 2000 alone, urban rail transit systems in 37 cities have opened, including

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[1] For recent examples, see Currie and Neidell (2005) and Chay and Greenstone (2003) for evidence on the infant mortality effects of exposure to air pollution.

Delhi, Dubai, and most recently Shenyang, China. Indeed, rail transit advocates and policy makers often point to the environmental benefits of rail transit infrastructure to justify these substantial investments. For example, an initiative to transform Beijing into a 'public transport city' by doubling the size of the metro system from 224 km to 554 km of track by 2015 is based on the goal of reducing air pollution below 2008 levels (CCTV, 2009). Similarly, in the United States, the Obama administration recently announced that the environmental effects of rail transit will be taken into account in the allocation of federal funding (Cooper, 2010).

While environmental impacts often feature prominently in transportation policy debates, traditional estimates of the benefits of transportation infrastructure have focused largely on the value of reduced travel time.[2] More recently the literature has used two approaches to incorporate a broader set of effects in cost-benefit estimates.[3] A first approach uses a hedonic method based on differences in house prices in neighborhoods with and without access to rail transit to value rail transit infrastructure.[4] A recent example of this approach is Gibbons and Machin (2005) who study the effects of the expansion of the London underground system and find a 7 to 20 percent shift in house prices for a one-standard-deviation reduction in distance to the rail transit. However, as the air quality effects of rail transit infrastructure are likely to be citywide, neighborhood comparisons

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[2] Seminal contributions on the effects of transportation infrastructure include Fernald (1999). For a few recent examples see papers such as Baum-Snow and Kahn (2005) on modes of travel, Baum-Snow (2007) on suburbanization, and Michaels (2008) on trade. See Small and Verhoef (2007) for an excellent overview of the economics of urban transportation. See Mackie et al. (2001) and also Small and Verhoef (2007) for discussions of the traditional approach.

[3] While the literature on transportation infrastructure has generally not discussed environmental effects, there is now a substantial literature on automobile externalities and policies that incorporates environmental effects. Recent studies examining taxation of automobile travel include Feng, Fullerton and Gan (2005) and Fullerton and Gan (2005) who study whether second-best taxes on automobile travel can be similarly effective as a first-best tax. Similarly, Parry and Small (2005) study optimal gas taxes and find that gas taxes in the US are lower than the optimal gas tax, but higher in the UK. Davis (2008) demonstrates that regulations designed to reduce vehicle travel in Mexico City have virtually no effect on air quality. Similarly, Auffhammer and Kellogg (2009) show that gasoline content regulations are largely ineffective in reducing ground-level ozone pollution in the United States. See Parry, Walls, and Harrington (2007) for a survey of automobile externalities and policies.

[4] See Gibbons and Machin (2008) for a survey of the literature that uses the hedonic method to value transportation infrastructure.

may not fully capture the air quality effects.

A second approach uses the best available estimates of the many potential effects of rail transit in a highly complete model and computes optimal rail transit subsidies.[5] A recent example is Parry and Small (2009) who incorporate the costs of air pollution, among numerous other factors. They find that even starting with fares at 50 percent of operating costs, incremental fare reductions are welfare improving in almost all cases. Conclusions about the importance of air quality effects hinge crucially on the estimated behavioral responses and social costs of automobile travel incorporated into the models. As many key parameter estimates are subject to debate, whether this approach fully captures the air quality effects remains an open question.

The central empirical challenge in measuring the effects of rail transit infrastructure on air quality is one of identification. Variation in rail transit infrastructure that is not confounded with other factors, that also affect air pollution, is difficult to come by. For example, rail transit infrastructure is likely to be built in areas where the demand for automobile travel, and hence air pollution, is likely to be elevated anyway. Variation in the utilization of a particular rail transit system over time is similarly problematic. Times of the day when the utilization of rail transit infrastructure is especially high are also likely to be times when automobile travel, and air pollution are similarly elevated. Credible estimates of the air quality effects of rail transit infrastructure require a solution to the identification problem.

In this paper we tackle the identification challenge by exploiting exogenous variation in the availability of rail transit infrastructure from the opening of a new metro system in Taipei, Taiwan. We use the discontinuity in rail transit ridership on opening day of the Taipei Metro system to identify the effect of rail transit infrastructure on air pollution based on a discontinuity based (DB) approach. Because high frequency air pollution data for a range of pollutants were collected before and after the opening date of the Metro system, Taipei provides a uniquely compelling context to estimate these effects. Figure 1 displays the time series of Taipei Metro ridership and clearly shows the sharp discontinuity in ridership on opening day (March 28th 1996). It is this discontinuity in

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[5] See Parry and Small (2009) for a survey of the literature that computes optimal transit subsidies.

rail transit availability that forms the heart of our analysis.[6]

The identifying assumption underlying our ridership discontinuity approach is that in the absence of opening the Taipei Metro, air quality would have changed smoothly on March 28, 1996, in Taipei. More precisely, air pollution levels in Taipei on the days just before the opening of the Taipei Metro form a valid counterfactual for air pollution levels in Taipei on days just after the opening of the Taipei Metro, conditional on differences in weather, a host of time-specific fixed effects, and a very flexible smooth time trend. This assumption seems reasonable as construction delays and safety issues are highly uncertain, and Metro operators would have faced great difficulties in holding back the opening of the Taipei Metro from an expectant public for any strategic reasons.

Our analysis reveals three main findings. First, we find significant effects for transportation source air pollution. Our ridership discontinuity based analysis indicates that the opening of the Taipei Metro caused a meaningful reduction in the concentration of one tailpipe pollutant, carbon monoxide (CO). The effects appear to be both statistically and economically significant as the Taipei Metro opening caused a 5 to 15 percent reduction in CO across a range of estimation approaches. We also find similar point estimates for the effects on another tailpipe pollutant, nitrogen oxides (NO_x), but the estimates are less precise. Importantly, the estimates are highly stable across a variety of alternative specifications, approaches, and samples.

Second, we examine the effects of rail transit infrastructure on another harmful pollutant that is indirectly related to automobile emissions, ground level ozone (O_3). Controlling ground level ozone has proven very challenging as the highly non-linear process of ozone formation is not completely understood (Seinfeld and Pandis, 1998). As in many cities around the world, ground level ozone pollution is a problem in Taipei as the common violations of the World Health Organization maximum safe pollution thresholds indicate. Our analysis reveals that rail transit infrastructure has little detectable effect on ground level ozone formation. In this regard, our findings echo the recent work of Auffhammer

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[6] Our approach is similar in spirit to recent studies in the public health literature on the impact of transportation restrictions imposed during the Olympics on air quality and health outcomes. Examples include Friedman et al. (2001) who examine the effect of the 1996 Olympics in Atlanta on air quality and asthma, and Li et al (2010) who examine the effect of the 2008 Olympics in Beijing on asthma.

and Kellogg (2009) who find that gas content regulations have little effects on ground level ozone formation.

Third, having found evidence that rail transit reduces transportation source pollution, we seek to shed light on whether rail transit infrastructure alters the travel patterns of automobile travelers in other ways. To do so we examine evidence for heterogeneous responses to the opening of the Taipei Metro along two dimensions, by time of day and distance to the Metro track. Our results show little heterogeneous effects of the Taipei Metro opening. While these results are necessarily less definitive than our main results, they do suggest that the reduction of automobile travel in response to the opening of the Taipei Metro was not simply concentrated during a certain time of day or in a certain location.

Are the air quality effects we find economically meaningful? To answer this question we use estimates in the literature on the health impacts of exposure to air pollution to understand the health effects that our results would imply. The benefits of the implied health effects are significantly larger that those incorporated in prior work. Strikingly, our estimates are more than double those incorporated into the Parry and Small (2009) optimal rail transit subsidy calculations. Furthermore, the fact that our estimates account for at least 30 percent of the social value of rail transit infrastructure estimated by Parry and Small (2009) indicates that the air quality benefits we measure are a substantial component of the benefit of rail transit infrastructure.[7]

The availability of air pollution data from other sources and other cities in Taiwan provides a number of opportunities to evaluate the credibility of our identification strategy. We first examine whether other air pollutants closely related to industry activity (and presumably the demand for travel) also display a discontinuous change in Taipei on the day that the Taipei Metro opened. Comfortingly, we find little evidence that the Taipei Metro was opened on a day when local demand for travel appeared to be especially high or low. Second, we examine whether the same transportation source pollutants in two

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[7] Environmental effects are frequently included in the Environmental Impact Assessments (EIAs) required in many local planning processes. However, as the environmental effects incorporated in EIAs are often vague, difficult to verify, and subject to influence by interest groups (Dipper, 1998) economists have typically sought other methods to quantify the costs and benefits of transportation infrastructure.

other Taiwanese air sheds (Kaohsiung and the East Coast) also display a discontinuity on the day the Metro system opened in Taipei. Again we find little evidence that the Taipei Metro was opened on a day when automobile pollution was especially high or low in Taiwan. Lastly, we use the air pollution outcomes in Kaohsiung in the narrow window around the Taipei Metro opening date as a control to conduct a simple difference-in-differences analysis that also yeilds very similar conclusions. These tests and alternative approach estimates provide further support for the validity of our main findings.

The remainder of the paper is organized as follows: Section 2 provides the institutional setting and outlines the empirical approach. Section 3 describes the data. Section 4 presents the results. Section 5 concludes.

2 Institutional Setting and Empirical Approach

2.1 Institutional Setting

Simple comparisons suggest that Taipei is most comparable to highly dense cities in the emerging economies of East Asia. The metropolitan Taipei area is located in the Taipei Basin in northern Taiwan, stretching over approximately 900 square miles. In 2009, the total population was 2.7 million in Taipei city, with nearly 6.5 million in the greater metro area. The country's per capita income was US$ 15,000 in 2009, compatible with other countries such as South Korea and about one third of that of the US (International Monetary Fund, 2009). The Taipei Metropolitan area is highly populated with a density of approximately 25,000 people per square mile, roughly comparable to New York City.

The public transportation system in Taipei has improved substantially since the Taipei Metro (TM) system began operating in 1996. The planning and construction of the Metro was a lengthy and highly uncertain process that involved the displacement of various communities, numerous protests, and wrestling among competing interest groups. The original concept for the Metro was initiated in 1967 in anticipation of the increasing traffic congestion and resulting air pollution problems expected in a rapidly growing economy. However, it was not until twenty years later that the master plan specifying the routes, transportation capacity, and other engineering details was completed. The official construction began in December 1988. The first line was opened on March 28th 1996. Importantly for the empirical analysis, the planning and announcement of the precise route occurred many years in advance of the actual opening day, allowing time for households and firms to undertake substantial adjustments.

After construction began, the initial opening day of the Taipei Metro was scheduled to be on December 31, 1992. However, opening day was soon postponed to August 12, 1993 as delays in construction as well as difficulties in integrating communication and operation systems lead to slow progress. The project also experienced further setbacks. For example, during an operating test on May 5, 1993, one train caught fire due to the overheating of the brake system upon attempting to enter a station. A similar accident resulting in trains being derailed and burned occurred on September 24, 1993 due to a malfunction of the automatic-control system. As the numerous safety issues has become apparent government regulators took an even larger in determining when the metro was safe to operate. Ultimately, the TM was not fully inspected and certified by the government until May 5, 1995. The opening date of TM was finally set to be March 28, 1996 after a successful public test ride on February 27, 1996.

There were of course other public transport alternatives to a metro system available in Taipei. One prominent alternative was high speed busses. As a number of authors have argued that high speed buses are more likely to pass the cost-benefit test than a subway system (see for example Kain, 1992 and Gordon and Kolesar, 2010) it is worthwhile to discuss the decision to invest in a metro system in Taipei. One key reason was the international rivalry with mainland China. The fact that Beijing was due to open a subway system in 1971 led to public pressure to plan a similar system in Taipei, which opened long after it was initially planned. The international rivalry rationale for the Metro is reflected in how the project was funded. The central Taiwanese government contributed two thirds of the costs, and the city government contributed only one third of the total costs. A second reason for the construction of a subway rather than utilizing high speed busses was the lack of a road network in Taipei capable of handling high speed busses. The pre-metro road network consisted of many narrow short streets that frequently turned at sharp angles due to a poorly organized city planning process. To implement a meaningful high speed bus system an entirely new network of high speed roads would first have to be constructed. Thus, it seems that the decision to construct the Taipei Metro rather then invest in high speed busses was primarily driven by international rivalry and a lack of a road network capable of handling high speed busses rather than air pollution concerns.

As shown in Figure 2, the original Taipei Metro system began with a single route. The dotted line in the figure indicates the first route, Muzha, that was opened on March 28th 1996, with 14.8 km of track and 12 stations.[8] The Taipei Metro network is centered at the Taipei Train Station in Taipei city and operates daily from 6:00am to midnight, with an interval of 1.5-15 minutes. In terms of pricing, the Taipei Metro fare is a function of distance between stations, ranging from 70 cents to 2 dollars, comparable to the bus fare of approximately 50 cents per trip. The Taipei Metro system was also linked to bus routes as bus travel is a frequently used mode of travel. The travel mode shares in 2001 were 8.8 percent Taipei Metro, 16.1 percent bus, 34 percent car and 41.1 percent motorbike (Jou et al., 2010). The Taipei Metro has been ranked as one of most reliable systems in the world (Railway and Transport Strategy Centre, 2009).

During the period from the 1970s to the 1990s, Taipei experienced some of the worst air quality among large cities in the world (Edmonds, 1996). The pollution source inventory shows that emissions from motor vehicles represented an important source of several harmful pollutants. The inventory indicates that vehicles constituted 96% and 77% of the CO and NO_x emissions, respectively, while only 12% and 11% of the PM_{10} and SO_2 emissions, respectively (Chang and Lee, 2006). In response to the growing concerns about air pollution from the transportation sector, the Taiwanese equivalent of the EPA has imposed various regulations over the years. These include performance standards that impose limits on tailpipe emissions of CO and NO_x for newly manufactured vehicles and scooters. In compliance with the standards, manufactures have enhanced vehicle and scooter performance by introducing more efficient fuel injection, carburetors systems, or catalytic convertors. At the same time, reformulated gasoline (RFG) regulations have been introduced to reduce sulfur content in gasoline and diesel in 1992, 1995,

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[8] The current Taipei Metro system has expanded significantly beyond the first line we discuss here. The current Taipei Metro now consists 94.2 km of track on six routes (i.e., Danshui, Xindian, Zhonghe, Nangang/Banqiao, Muzha, and Neihu lines), with several extensions and a new route to the airport that are still under construction.

and 1997.[9] In addition, tax revenue from fuel consumption has been used to fund various programs related to air quality, including vehicle inspection and maintenance, subsides for retrofitting particulate filters, etc. (Taiwanese EPA, 2009a). One of the key challenges for the empirical analysis is to separate the effects of the Taipei Metro from these other environmental and transportation policy changes that also effect air pollution.

2.2 Empirical Approach

In this section we introduce the empirical approaches we use. We first describe a basic Ordinary Least Squares (OLS) approach to estimate the conditional correlation between transit ridership and air pollution in Taipei over time. The OLS models serve as a useful baseline for our main estimation strategy. They also provide a sense of what estimates of the correlation between ridership and air pollution would reveal without the event of the opening of a new metro system, though they are subject to the significant endogeneity concerns noted above. Our second approach is a Discontinuity Based Ordinary Least Squares (DB-OLS) model that addresses the key sources of bias likely present in the simple OLS models.

Basic Ordinary Least Squares. The most straightforward approach is to simply estimate the time series model by OLS,

$$y_t = \gamma_0 + \gamma_1 MetroRidership_t + \gamma_2 x_t + e_t, \tag{1}$$

where y_t is the log of air quality at time t, $MetroRidership_t$ is the number of Taipei Metro riders at time t, x_t includes indicator variables for gas content regulations being in place and weather variables including current and 1-hour lags of quartics in temperature, and wind speed, and e_t is the error term. The coefficient of interest is γ_1 which is the Metro ridership-air quality gradient.

We would expect that γ_1 would reflect a negative relationship between transit ridership and tailpipe emissions if people substitute away from high-emission automobile travel

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[9] The sulfur content regulations for both diesel and gasoline is set at 50 ppmw (parts per million by weight). See Auffhammer and Kellogg (2009) for evidence on the effects of RFG regulation on air pollution in the US.

towards low-emission Taipei Metro travel. As noted above there are at least two reasons why the simple approach in (1) is likely to yield an estimate of γ_1 that is biased upwards. First, the demand for rail transit travel is likely greatest when the demand for automobile travel is greatest, as the value of a trip varies over time due to work start time and other factors (Small, 1982; Small and Verhoef, 2007). Metro ridership is likely to be high when automobile travel is high, due to peak travel demand for the Taipei Metro and automobile travel happening at the same time. As peak travel times are likely to result in high levels of tailpipe emissions anyway, we would estimate a positive effect even if none were present. In addition, as the level and composition of the economic activity is likely to change over time, and be correlated with Taipei Metro ridership, omitted variable bias is an important concern.

A second reason why a simple time-series regression of Taipei Metro ridership on air pollution is unlikely to yield an estimate of γ_1 with a causal interpretation is that transportation choices are likely to be endogenously related to air quality. This is especially true in Taipei given the daily publication of air quality estimates and warnings. The avoidance behavior may lead optimizing individuals to substitute towards modes of transportation less exposed to ambient pollution that are also lower pollution intensity travel modes, such as the Taipei Metro.[10] Alternatively, individuals may substitute intertemporally to avoid air pollution, so that the number of Taipei Metro trips is lower when pollution is expected to be high. In either case, γ_1 in a simple OLS model will likely be upwards biased from the desire of optimizing individuals to avoid pollution exposure.

Discontinuity Based Ordinary Least Squares. To address concerns that Metro ridership might be endogenously related to unobservable determinants of air quality, we also estimate a Discontinuity Based specification. Our empirical strategy attempts to identify potentially exogenous sources of variation in expected Taipei Metro availability on a given day by taking advantage of the sharp discontinuity in Taipei Metro ridership that occurs on the opening day of the new transit system.[11]

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[10] Recent evidence from Taiwan indicates that Taipei Metro commuters have about half the exposure to particulate matter of motorcycle commuters, the dominant private vehicle transportation model in Taiwan. See Tsai, Wu, and Chan (2008).

[11] An alternative identification strategy would be to use pollution data from other cities to form a counterfactual for air pollution in Taipei without the Metro, and conduct a difference in difference analysis.

Specifically, we use ordinary least squares to estimate the following Discontinuity Based (DB-OLS) model:

$$y_t = \delta_0 + \delta_1 MetroOpen_t + \delta_2 x_t + \delta_3 P(t) + \delta_4 P(t) x MetroOpen_t + e_t, \tag{2}$$

where the coefficient of interest, δ_1, is the effect of Taipei Metro's opening on air pollution. The variable $MetroOpen_t$ is an indicator variable that takes a value of one for all hours after the Taipei Metro is operational and a value of zero before the Taipei Metro is operational. The vector of covariates, x_t, includes indicator variables for gas content regulations being in place and weather variables including current and 1-hour lags of quartics in temperature, wind speed, and humidity, in addition to, month, day of the week, hour fixed effects and the full set of interactions between hour and day of week fixed effects. The vector $P(t)$ contains a third-order polynomial time trend to flexibly control for time series variation in pollution that would have occurred in absence of the opening of the Taipei Metro. These controls are designed to pick up the smooth changes in the composition of economic activity in Taiwan in this time period. They will also pick up the smooth changes in air pollution due to changes in new vehicle emission standards and other policies that take effect slowly over time. We also include interactions between the $MetroOpen_t$ dummy variable and the polynomial time trend to allow the time trend in pollution to differ on either side of the opening date.[12] We include the gas content regulation events as separate controls as these are the one other policy change we are aware of that could have a discrete effect on air pollution.

The implementation of the DB-OLS strategy we focus on here uses a full year of data on either side of the Taipei Metro opening date, but controls the variation coming from days far from the opening day threshold using flexible controls for the time-series variation.[13] Assuming that the conditional expectation of the unobserved determinants

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We present results from a difference-in-difference analysis later in the paper, but focus on the discontinuity based specification to ease comparability with the prior work in Davis (2008).

[12] Our specification differs from Davis (2008) as we include an interaction between the metro open dummy and the time trend. This specification allows for a very flexible time trend and for the time trend to change after metro opening date. We thank an anonymous referee for suggesting this more flexible specification.

[13] An RD design can be estimated parametrically or non-parametrically, focusing on only dates very close to the Taipei Metro opening or the larger sample of a full year of data on either side of the opening date. We follow a parametric approach using two years of data because it allows straightforward

of y_t is continuous, we can approximate it by a polynomial of order g.

The intuition behind our identification strategy is straightforward. The key assumption is that the only reason for air pollution to discontinuously change on Taipei Metro's opening day is the opening of the Taipei Metro itself. By flexibly controlling for non-linearities in air pollution from other factors using the polynomial time trends, we are able to isolate the change in air pollution solely due to the operation of Taipei Metro. The DB-OLS approach will not be threatened if other unobservable variables affecting air pollution change smoothly in the neighborhood of the Taipei Metro opening date (Hahn, Todd, and Van der Klaauw, 2001). Our implementation of the DB-OLS approach based on a time-series discontinuity is similar to that used by Davis (2008).

Our coefficient of interest δ_1 will estimate the reduced form effect of the Taipei Metro's opening on air quality. The effect of rail transit on air quality depends crucially on the behavioral responses of automobile travelers.[14] If rail transit primarily attracts automobile travelers who would have travelled anyway, the *traffic diversion* effect will be large, and the overall effect of rail transit infrastructure on emissions may be meaningful. In contrast, if rail transit primarily draws discretionary travelers who would not have travelled at all, rail transit ridership will have little effect on total emissions as the *traffic creation* effect dominates. As the precise magnitude of these effects are unclear the magnitude of δ_1 remains an empirical question.

A few other estimation details are worth noting. First, as we are conducting our analysis with time-series data, the observations are unlikely to be independent.[15] To address this issue we cluster the standard errors at the 5-week level.[16] Second, we chose the

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hypothesis testing, and precise estimates. See Lee and Lemeuix (2008) for a detailed comparison of alternative approaches to estimating RD models.

[14] Of course, the size of the effect of rail transit infrastructure will also depend on the pollution intensity of automobile travel. While the pollution intensity of automobile technology in Taipei is likely different in other areas, it seems unlikely that differences in automobile technology alone will limit the portability of our results. As the pollution intensity of automobile travel is largely a function of the type of automobile (car, motorcycle, etc.) (Borken et al., 2007), adjusting of our estimates to account for differences in the compostition of automobile types across areas would likely account for differences in automobile technology.

[15] See Henderson (1996) for a detailed discussion of serial correlation in air pollution.

[16] We choose this lag length using the standard methods of estimating the models with multiple lags

third-order polynomial specification as our baseline model as additional orders of polynomials do not tend to increase the precision of our estimates and the work of Porter (2003) indicates that odd order polynomials tend to have better econometric properties. Third, we probe the validity and robustness of our estimates with a number of alternative specifications. We examine the robustness of our findings by considering alternative polynomial orders, sets of other controls, and samples. Lastly, as we lack detailed high frequency data on automobile or other travel we are unable to separately quantify the precise substitution responses underlying the reduced form effect we identify. For example, while we focus the discussion above on substitution responses of automobile travelers to rail transit infrastructure, it is possible that the substitution responses of bus travelers may be meaningful. As such, our estimates capture all of the responses of travelers to rail transit infrastructure that affect air pollution.[17]

Threats to Identification. Our identifying assumption is that absent the opening of the Metro, air quality would not have discontinuously changed in Taipei on that date. This assumption is reasonable since there is no reason to expect a large discontinuous change in economic or travel activity on the date that the Taipei Metro opened. Of course, days before and after the opening of the Metro may differ in ways that could affect levels of air pollution, such as seasonal variation in the demand for travel or atmospheric conditions. Any such differences that smoothly change near the Taipei Metro opening date will be captured by the flexible polynomial time trend, and will not contribute to identification. Only discontinuous changes in air quality on the Taipei Metro opening date driven by unobservables could pose a threat to our identification strategy. While it seems reasonable that our assumption is valid, it is instructive to consider cases where it might be violated.

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and choosing the model that minimized the AIC statistic. We choose the 5-week level as it reflects the level of persistence for the most persistent pollutant in our sample, CO, to be conservative and consistent. Other transportation based pollutants display less persistence NO_x and O_3 are persistent at the 3 and 1 week frequency, respectively. Davis (2008) also finds a similar 5-week persistence level in air pollutants for Mexico City.

[17] In an (unreported) analysis, we have examined the low frequency (monthly) data we have on bus travel responses to the opening of the Taipei Metro. This analysis reveals little relationship between bus travel and the opening of the Taipei Metro in either direction. Of course, the limited sample size implies that any test has low statistical power.

First, it is useful to consider the implications for our estimates if Taipei Metro officials sought and were able to time the opening of the Taipei Metro with unobservable levels of travel demand. It is possible Taipei Metro officials strategically chose the opening date to maximize ridership (and good publicity) in the first few days. If officials opened the Taipei Metro on a day when the quantity of travel and pollution levels would be high regardless of Taipei Metro utilization, our strategy would yield a smaller estimate than the true causal effect. Conversely, Taipei Metro officials may have been concerned with the functionality of the new system, and any negative publicity that would occur if it did not perform as expected. In this case officials might well have preferred that the Taipei Metro opened on a low travel demand day so that they could see how it performed with lower levels of ridership, and address any problems that may have been revealed. In this case we would estimate a larger effect than the actual causal effect of Taipei Metro ridership. Each of these possibilities would be a concern for our empirical strategy. However, they seem unlikely given the numerous delays due to unsafe operating conditions and malfunctions that resulted in tight oversight of the opening timeline by government regulators.[18]

Second, it is possible that the building of, and operation of, the Taipei Metro affected the level of air pollution in Taipei independently of ridership. This could occur because the process of building the Taipei Metro generated substantial pollution, or the traffic congestion generated by the Taipei Metro construction increased the level of pollution. However, mean differences in Taipei Metro construction-induced air pollution before and after the opening of the Taipei Metro will not invalidate our research design. Only discontinuous changes in Taipei Metro construction induced pollution would bias our results. As any air pollution effects of Taipei Metro construction likely declined gradually in the months before the Taipei Metro actually opened, this is unlikely to be a serious concern in this context. For example, near the end of the construction cycle most activity is focused

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[18] Of course, we are not able to fully rule out manipulation of the opening date by Taipei Metro officials over long or short-time spans. However, our reading of the historical record is that in practice the scope for the manipulation of the opening date by metro officials was quite low over both long and short time periods. On one hand, officials faced mounting public pressure to open the system as the many more delays than anticipated had pushed the opening date more than four years behind schedule. On the other hand, the numerous malfunctions and safety problems had increased the level of government oversight over all aspects of the opening significantly limiting the ability of metro officials to chose any opening date that they preferred.

on installing equipment and fixtures, rather than actually constructing the metro system. In addition, as the Taipei Metro is based on electric power, changes in transportation source air pollution would not occur due to the operation of the Taipei Metro itself.[19]

However, as we are unable to test for discontinuous changes in confounding factors directly we also examine whether there is any evidence that the discontinuities we estimate also appear where they should not. Evidence of this sort would cast doubt on our assumption that the date the Taipei Metro became operational was unrelated to discontinuous changes in unobservable determinants of air quality. We do this in two ways. We first examine whether there is any evidence of discontinuous jumps in non-transportation source pollutants in Taipei on the date that the Taipei Metro opened. We then examine whether there are any discontinuous changes in transportation source pollutants in the two other main areas of Taiwan on the day that the Taipei Metro opened. As unobservable changes in national travel demand, regulatory enforcement, or other government policies will affect travel in these two areas we regard this last smoothness test as especially important.

In sum, while we cannot completely rule out the possibility that some of the effect reflects discontinuous changes in unobserved determinants of air pollution on the date that the Metro opened in Taipei, it appears that many sources of spurious correlation are accounted for by our discontinuity based analysis.

3 Data

Our empirical analysis requires high-frequency data on both air pollution and transit ridership. Fortunately, high quality data for both of these sets of variables are available for Taipei. Our data source for hourly air quality data is the Taiwanese EPA air quality monitoring network (Taiwanese EPA, 2009b). For regulatory purposes, the Taiwanese EPA maintains an air quality monitoring network that consists of 74 stations. It began as

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[19] In principle, the operation of the Taipei Metro system itself could affect the levels of pollution we observe as the Taipei Metro area as it is powered by electricity from a power plant located near to Taipei. However, as the air pollution from power plants is primarily SO_2, and not the transportation sources we focus on, these effects will not appear in our central analysis. In any case, we find little evidence of significant increases in SO_2 pollution due to the opening of the Taipei Metro.

a network of 19 stations that gradually expanded. These stations record the hourly data of the criteria pollutants (CO, NO_x, O_3, PM_{10}, SO_2) and other weather related variables (temperature, wind speed, and humidity).[20] We obtained these data for the Metro-Taipei area, Kaohsiung city, and the East Coast by selecting the stations within each city that were operating in 1995. The number of stations included in our sample is 10, 5 and 1, for Taipei, Kaohsiung and the East Coast, respectively. Several stations (marked by circles in Figure 2) in the Metro Taipei area that were subsequently added to the network by the Taiwanese EPA are not included in our sample because they were not in operation in 1995. The entries with zero concentration were treated as missing values in our analysis. The daily Taipei Metro ridership data were obtained from the Taipei Rapid Transit Company (Taipei Rapid Transit Company, 2009). For our main analysis we take the average accross monitoring stations in a city to obtain an hourly time-series of pollution.

We chose our sample period to be all observations within a two year window around the Taipei Metro opening date, one year before and one year after. As our central analysis is based on a Discontinuity Based OLS, using observations further from the Taipei Metro opening date is unlikely to add additional precision or validity of our method. In fact, as the conceptual basis of a Discontinuity Based estimate is local to the Taipei Metro opening threshold, choosing a sample containing observations as close as possible to the discontinuity is generally preferred. The tradeoff of using only observations very close to the discontinuity is a loss of precision as the sample size falls. As air quality has a significant degree of persistence (Henderson, 1996) the precision gains from using observations further from the window may be meaningful. We ultimately chose to use a two year window for our baseline specification as it seems to balance this tradeoff. Furthermore, as Davis (2008) notes, controlling for seasonal variation in air pollution becomes difficult with less than two years of data. However, as the conceptual basis of our estimation approach is local to the ridership discontinuity, we also present estimates using only observations from a two month window around the opening date as an important validity check.[21]

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[20] There are other stations reporting additional pollutants such as $PM_{2.5}$ and various species of VOC. However, these few stations are located in specific locations (e.g., a heavy-traffic intersection or an industrial complex) and so are not a representative sample.

[21] We thank an anonymous referee for pointing out the value of considering a narrower window to demonstrate the validity of our approach.

Table 1 summarizes the descriptive statistics for the air quality, weather, and ridership data. Results for the full sample are presented in the first column, and are decomposed into pre-Metro (the year before the Taipei Metro opened) and post-Metro (the year after the Taipei Metro opened) periods in columns (2) and (3), respectively. The sample size N refers to the number of hours with valid data. The results from a t-test based on the comparison between columns (2) and (3) are presented in column (4).

The first notable feature of these data revealed in Table 1 is pollution reporting is in general very complete. Data of this quality are not available for many cities in emerging economies. Most pollutants and weather variables have nearly as many reported observations as the maximum number of potential observations (17520). The variables with the least complete data are NO_x and humidity. To address any concerns about reporting we also estimate our models on only the sample of stations or hours with very high levels of reporting as a robustness check.[22]

A number of patterns emerge in Table 1. First, we see that the levels of concentrations of both carbon monoxide (CO) and nitrogen oxides (NO_x) are noticeably lower in the post-Metro period than in the pre-Metro period.[23] These reductions in pollution concentrations are also highly statistically significant, suggesting that the Taipei Metro opening led to large reductions in tailpipe emissions. However, as noted above there are many other factors that may account for the reductions in tailpipe emissions. The second finding to note is that ground level ozone (O_3) is also lower in the post-Metro period than in the pre-Metro period. However, the magnitude of the reduction in ground-level ozone is substantially smaller than for the tailpipe emissions. Third, the level of pollution

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[22] The missing values are largely due to the quality control protocol in Taiwanese EPA to calibrate the sampling instruments at 7 am every day. This calibration exercise leads to a few missing values, particularly for NO_x in hour 7 of our data. However, as shown in Table 1 the level of reporting for NO_x does not differ substantially between the pre- and post-Taipei Metro periods. In an (unreported) analysis of reporting we have found no evidence of differential reporting behavior around the Taipei Metro opening date.

[23] The baseline level of CO is far lower in Taipei than found in New Jersey by Currie, Neidell, and Schmieder (2009), or in Mexico City by Davis (2008). The difference in baseline levels of CO is likely due to CO monitors being placed many stories above the roadway in Taipei due to space limitations and security reasons, but much closer to the ground in other cities (C.-C. Chan, National Taiwan University, personal communication).

from non-transportation based pollutants also declines. Lastly, there are differences in the average levels of relevant weather conditions which likely also affect air pollution concentrations. Thus, a key challenge to quantifying the effect of rail transit infrastructure on air pollution is separating the effect of rail transit infrastructure from other unobservable determinants of air pollution.

The fact that there are differences in average non-transportation based air pollutants and weather conditions before and after the opening of the Taipei Metro raises two important issues. First, as the identification assumption underlying the discontinuity based method is that air pollution would have changed smoothly on the opening date if the Taipei Metro had not opened that day possible discontinuous changes on other observable determinants are important to note. We explore whether the mean differences in Table 1 reflect discontinuous changes in these observable variables and transportation based pollutants in other cities in the analysis that follows. As noted above, substantial evidence of discontinuous changes might suggest that metro officials sought and were able to manipulate the opening date of the Taipei Metro to occur on a particularly high or low pollution day. While the historic record suggests that officials were seeking to open the system as soon as possible but were delayed by difficult to predict accidents and government regulatory scrutiny rather than trying to open the metro to demonstrate any effect on air pollution, it is important to explore this possibility further.

A second issue is whether and what controls to include in the discontinuity model above. We first follow Davis (2008) and estimate the model with the relatively wide two year window around the opening date with an extensive set of controls for weather conditions. As atmospheric conditions have significant explanatory power for air pollution including these controls allows for relatively precise estimates of the metro opening effect.[24] These models also address a concern that the estimates are driven by unusual changes in weather conditions occurring on opening day. However, we also estimate models in a much shorter 30 day window around the metro opening date as our second main approach. We estimate these models both with and without the time series and weather controls. Lastly, we estimate difference-in-difference models where we use changes in air pollution in Kaohsiung (Taiwan's second largest city far from the Taipei airshed) in the

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[24] As noted by Lee and Lemeuix (2008) covariates are often included in a Regression Discontinuity specifications to enhance the precision of the treatment effect estimates.

30 day window around the Taipei Metro opening date to form the counterfactual. The difference-in-differences model is based on the quite different assumption that the before-after opening day differences in air pollution in Kaohsiung form the counterfactual for the before-after opening day differences in air pollution in Taipei. We view all three approaches as complementary as they place different assumptions on the data generating process.

4 Results

4.1 OLS Results

Table 2 presents the results from OLS estimates from fitting equation (1) above. Each column reports the results from one regression. Our sample for this analysis only includes post-Metro data, as this analysis seeks to estimate the time-series correlation between Metro ridership and pollution without use of the opening day discontinuity in transit ridership. As many cities with Metro systems did not begin to collect air quality data until long after their transit systems were operational, these types of correlations are similar to what would be estimable in other contexts.

The results in Table 2 indicate that Taipei Metro ridership is positively related to pollution levels, though the effect is not statistically significant from zero. The lack of a clear negative relationship between airborne pollutants and Metro ridership could reflect a number of possibilities. First, higher levels of Metro ridership could reflect the use of Metro travel to avoid high pollution or high traffic congestion days. Alternatively, the substitution response of automobile travel for rail travel could be very small. In this case observed Metro travel could reflect additional travel induced by rail transit availability. To shed some light on the source of the statistically insignificant correlations we next turn to our discontinuity based OLS analysis.

4.2 Main Results: Two Year Window Specification

We report the central estimates of this paper in Table 3. Each column reports the results from one regression using the discontinuity in Metro ridership that occurred on opening day to identify the effect. In columns (1), (2) and (3) we report the results from fitting equation (2).

Table 3 contains two central findings. First, the point estimates indicate that the opening of the Metro substantially reduced emissions from one automobile source, CO. The results in column (1) indicate that the opening of the Taipei Metro reduced CO pollution by more than 15 percent and this result is statistically significant at the 5% level. The point estimate in column (2) indicates that the opening of the Taipei Metro reduced NO_x pollution by 8 percent, but this point estimate is not statistically significant at the 5% level. Thus, the opening of the Taipei Metro has a statistically significant effect of reducing pollution from key transportation based pollutant, carbon monoxide.

Second, Taipei Metro's opening had little effect on air pollution from O_3. The point estimate in column (3) does indicate that the opening of the Taipei Metro reduced O_3, but the results are not statistically significant at any conventional level of statistical significance. As the health consequences of ground level ozone exposure are quite significant, this lack of effect on ozone pollution is notable.

We next consider graphical evidence of the effect of Taipei Metro opening on air quality using the full two year window of data. A visually prominent break in the outcome at the discontinuity is often seen as providing support for the identification assumption. In the case of air pollution data the ocular method is challenging as air pollution has significant variance and seasonal cycles. The challenge of using graphical methods alone to detect the effect of the metro opening is borne out in Figures 3A and 3B.

We present the time series air pollution data visually in Figure 3A and 3B. We first present graphs of the weekly averages of the pollution variables without any trend line superimposed.[25] We then present graphs of the data with the third-order trend line

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[25] Of course the seasonal components of air pollution could be taken out by plotting the residuals from a regression of seasonal dummy and weather variables on the air pollution outcome. We have chosen not

and break at the Taipei Metro opening date superimposed. Displaying graphs with and without the trend line provides the opportunity to examine whether the breaks in pollution levels on Taipei Metro opening date that the econometric model estimates are visually prominent in the raw data. In Figure 3A we see that a prominent trend break occurring at the opening date of the Taipei Metro is difficult to detect by ocular methods. When we add the trend line in Figure 3B we are able to see the break that the econometric models estimate. These figures may simply point to the difficulty detecting a break in air quality by ocular methods alone. Of course, they also raise a concern that our results above are driven by the specification we use to estimate the model rather then the opening of the Taipei method itself. We next conduct a number of alternative specifications, smoothness tests, and alternative estimation approaches to rule out this second possibility.

4.3 Identifying Assumption Validity and Robustness Checks: Two Year Window Specification

This section reports our analysis examining evidence for the validity of identifying assumption, and the robustness of our main results. We first probe the validity of our identifying assumption by testing for discontinuities where we would not expect them. The results for other pollutants and other cities are reported in Table 4. We also report the results of testing for discontinuous changes in weather conditions on Taipei Metro opening day in Table 5. Finally, we present estimates of model (2) that also add controls for lags of the pollution outcome variables in Table 6.

A central potential concern for our identifying assumption is that the opening date of the Taipei Metro was not chosen randomly. As noted above, if officials wished to open the Taipei Metro on either a high or low travel day, were able to do so, and were able to accurately predict the level of travel on a given day, our identifying assumption may be threatened. Alternatively, if the opening of the Taipei Metro was bundled with another unmeasured policy (or enforcement) activity that also affects automobile pollution our interpretation of the results would be unwarranted. While we cannot test the identifying

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to follow this approach and instead followed Lee and Lemeuix (2008) in presenting unadjusted data for visual evidence.

assumption directly, we can implement two sets of tests to probe its validity. First, if officials sought, and were able, to open the Taipei Metro on a day with unobservably different pollution levels than the days just prior, we should observe that observable measures of transportation demand jump on the Taipei Metro opening date also. To examine this possibility we estimate our discontinuity based OLS models on the data from the full two year window with air pollution from non-transportation sources as outcomes.Second, if officials strategically manipulated the Taipei Metro opening day based on unobservable (to the researcher) measures of national travel demand, we should observe a discontinuous change in transportation source pollutants in other cities in Taiwan on the same day.[26] To examine this possibility we estimate equation (2) using hourly pollution data from other air sheds in Taiwan - Kaohsiung and the East Coast.[27]

Table 4 reports the results of our tests for discontinuities in observable measures of travel demand in Taipei on Taipei Metro opening day in column (1). Comfortingly, we find little evidence of discontinuities on Taipei Metro opening day in Taipei for either primarily industry source pollutants. Columns (2) and (3) of Table 4 report the results from the tests of fitting equation (2) to data on air pollution on the East Coast and in Kaohsiung (Taiwan's second largest city). East Coast cities and Kaohsiung are located far from the Metro Taipei area, and so air quality is not expected to be affected by the Taipei Metro opening directly, but will be affected by any national changes in unobserved determinants of pollution due to changes in regulatory enforcement or economic activity, for example. Overall, we find little evidence for a large discontinuity in pollution on Taipei

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[26] While the results from other cities do not provide any evidence of manipulation of opening day, we are unable to completely rule out manipulation that could happen on a shorter time scale. We thank an anonymous referee for pointing this out.

[27] Kaohsiung is the second largest city in Taiwan located in southwestern Taiwan, facing the Taiwan Strait on the west. It has a population around 2.5 million with a population density of 2400 per square mile, an order of magnitude lower than Taipei. Kaohsiung serves as a center for manufacturing, refining, shipbuilding, and other light and heavy industries, with a major port. The east coast is located on the east side Taiwan, is mostly occupied by mountains, and consists of two major cities – Tatung and Hyaline with a population density of less than 300 per square mile. The main income sources are tourism, agriculture, and fishing. We report the differences in baseline air pollution levels across the three cities in Table A2. The table reveals that the cities do differ in terms of pre-Taipei Metro air pollution levels. Of course, as they are all located in Taiwan they are all subject to the same national policy, economic, or environmental enforcement regimes, they represent the best comparison cities available.

Metro opening date in other cities. These findings lends further credence to the validity of our identifying assumption, however concerns about whether our results are driven by unusual weather conditions remain.

Table 5 reports the results of smoothness tests for the weather variables we use as controls on the opening date of the Taipei metro. We estimate version of equation (2) with the indicated weather variable as the outcome and all weather controls dropped from the specification. We report estimates of the models for Taipei, Kaohsiung, and the East Coast. The results in Table 5 show that wind speed and temperature change smoothly on the Taipei Metro opening date in all three cities. Humidity however does not change smoothly on Taipei Metro opening day in any of the cities. Ideally all the weather controls would change smoothly at the discontinuity, however we feel the discontinuous change in humidity is not a major problem in this context for two reasons. First, wind speed and temperature have more explanatory power for air pollution than humidity. Second, the CO results in the last row of appendix table A1 of model (2) without humidity covariates are very similar with a slightly smaller to those above in magnitude, but at 10 percent comfortably within the range we note above, and remain statistically significant at the 10% level. However, as Table 5 reveals that not all of the control variables are smooth on opening day we present further estimates that use only the 30 day window around opening day without any weather control variables to further address this potential concern in the subsection 4.4.

One additional issue to examine in a time-series discontinuity based approach is how persistence in air pollution affects the magnitude of the metro opening effect.[28] While clustering the standard errors at the 5 week level addresses for the effects of persistence on inference, it is well worth examining whether controlling for shorter-term lags substantially affects the point estimate results. As Henderson (1996) notes ozone concentrations in the US persist for 4 hours. Thus, we estimate (2) with controls for 1,2,3, and 4 hour lags of the pollution outcome added. The results of these estimates are presented in Table 6. Table 6 demonstrates that adding lagged pollution measures has little effect on the sign or statistical significance of the metro opening effect, as both the CO and NO_x results demonstrate. The magnitude of the point estimates are indeed smaller than in Table 3,

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[28] We thank an anonymous referee for this suggestion.

as would be expected. The models in Table 3 reflect the total effect of the metro opening between the pre-TM pollution and post-TM pollution levels, whereas the point estimate in the Table 6 reflect only the very short term effect. To make the estimates comparable we solve for the total effect of the metro opening by iteratively substituting into the lagged version of equation (2) and present the results in the last column of Table 6.[29] The total Taipei Metro opening effect estimates in the last row of Table 6 are very close to those reported above indicating that persistence in air pollution does little to alter the magnitude of the air effects in this context.

We also examine in the supplementary appendix the robustness of our results along three dimensions: reporting, polynomial order specification, and covariate choice. These results reported in Table A1 show that our CO results from the two year window discontinuity based OLS specification are highly robust in general, while the estimates for O3 and NO_X pollution outcome are more sensitive to specification choices.[30]

4.4 Main Results: 30 Day Window Specification

In this subsection we consider two further specifications that use only the observations within 30 days of the Taipei Metro opening date.[31] First, in Table 7 we report the results of estimating equation (2) without any weather, regulation, or time trend controls. Second, we report estimates from a simple difference-in-differences model that compares the change in air pollution before and after the Taipei metro opening in Taipei where the

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[29] We express the lagged version of equation (2) as:

$$y_t = \delta_0 + \delta_1 MetroOpen_t + \delta_2 x_t + \delta_3 P(t) + \delta_4 P(t) x MetroOpen_t + \beta_1 y_{t-1} + \beta_2 y_{t-2} + \beta_3 y_{t-3} + \beta_4 y_{t-4} + e_t.$$

Following Henderson (1996), we stack the equations for y_t to y_{t-4} and recursively substitute for the lagged outcomes to obtain the total effect of the metro opening, δ_1^{TE}. We obtain the expression $\delta_1^{TE} = [1 + \beta_1 + \beta_1^2 + \beta_1^3 + \beta_1^4 + 3(\beta_1^2\beta_2) + 2(\beta_1\beta_2) + 2(\beta_1\beta_3) + \beta_2 + \beta_2^2 + \beta_3 + \beta_4] x \delta_1 = \gamma x \delta_1$. We refer to γ as the multiplier for the total effect. Based on the estimates of β_1, β_2, β_3, and β_4 for each pollutant in Table 6 we obtain $\gamma CO = 4.03$, $\gamma NO_x = 3.75$, and $\gamma O_3 = 3.42$. With these multipliers in hand the total effect of the metro opening (reported in the last row of Table 6) are obtained by multiplying the relevant γ multiplier times the relevant δ_1 estimate.

[30] The supplementary appendix is available at: faculty.ucmerced.edu/awhalley/.

[31] We thank an anonymous referee for suggesting this alternative narrow window specification.

metro opens to Kaohsiung where there is no change in transportation infrastructure in Table 8.

The results in Table 7 indicate that the opening of the Taipei Metro led to a statistically significant reduction in CO and NO_x pollution. The point estimates of -0.13 and -0.14 are quite similar to those reported in Table 3. The fact that the unconditional differences right in the neighborhood of the Taipei Metro opening show a statistically significant negative effect that is quite comparable to those in Table 3 is comforting.

Examining data only in a narrow window around the opening date also eases concerns noted above with using the ocular method to detect a visually prominent metro opening effect as season changes in this narrow range are minimal. We present a simple scatter plot of the daily average of air pollution around the Taipei Metro opening date in Figure 4. In this case, the ocular method faces less challenges in detecting a drop in the average level of CO pollution in Figure 4A following the opening of the Taipei Metro as the distribution of air pollution appears to shift downwards. While air pollution continues to display substantial variance around the trend line it is certainly much easier to see a discontinuous break in air pollution in Figure 4A than in Figure 3A. The graphs for NO_x and O_3 in Figures 4C and 4E also allow for break detection by the ocular method on the opening date of the Taipei Metro. Thus, the visual depiction of the data in the narrow range of the Taipei Metro opening date allows for the detection of a discontinuous break in air pollution by ocular methods alone.

In our last set of specifications we consider an alternative approach to forming the counterfactual of what would have happened to air pollution in Taipei if the metro had not opened. Here we use the trend in air pollution in Kaohsiung, the second largest city in Taiwan, to form the counterfactual in a simple difference in difference specification.[32] The model RD-OLS model we estimate is given by,

$$(3) \qquad y_t = \delta_0 + \delta_1 MetroOpen_t + \delta_2 x_t + \delta_3 Taipei + \delta_4 TaipeixMetroOpen_t + e_t,$$

where the coefficient of interest, δ_4, is the effect of Taipei Metro's opening on air pollution.

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[32] We chose Kaohsiung as the control city for two reasons. First, it is a completely different airshed from Taipei and so air pollution there will not be directly affect by the opening of the Taipei Metro itself. Second, as the results in Table A2 demonstrate Kaohsiung is more comparable to Taipei in terms of baseline pollution levels than the East Coast (though many baseline levels are remain far from identical).

Again, the variable $MetroOpen_t$ is an indicator variable that takes a value of one for all hours after the Taipei Metro is operational and a value of zero before the Taipei Metro is operational. The vector of covariates, x_t, includes indicator variables for gas content regulations being in place and weather variables including current and 1-hour lags of quartics in temperature, wind speed, and humidity, in addition to, month, day of the week, hour fixed effects, a third order time trend, and the full set of interactions between hour and day of week fixed effects. The variable $Taipei$ is a dummy variable that takes a value of one for air pollution monitoring station in Taipei and zero otherwise.[33]

The results for the difference-in-difference model are presented in Table 8. We first present results for specifications without any weather and time series controls in Panel A. We then present results of models that include controls for city weather conditions and time trends in Panel B to account for differences in weather conditions between the two cities. The broad pattern of results is very similar to those reported in Table 3 above. The point estimates indicate that the opening of the Taipei Metro reduced air pollution from CO and NO_x, and increased air pollution from O_3.[34] The magnitude of the point estimates do differ somewhat from those above. Compared to the results above the absolute value of the point estimates in Table 8 are smaller for CO, larger for NO_x, and larger for O_3. We take the results of difference-in-difference specification to form the lower bound of the range of estimates noted in the introduction. The majority of estimates are statistically significant at the 5% level, with the exception of the CO estimate in panel A that illustrates the precision gain from including the weather controls. Thus, the results in Table 8 indicate that the effect of Taipei Metro opening on CO pollution is robust

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[33] We continue to collapse the monitoring station data to one observation per city in an hour by taking the average level of pollution across all monitoring stations in that city. We thus have two observations per hour, one for Taipei and one for Kaohsiung.

[34] A positive estimate for Ozone is expected because Taipei has a VOC-limited climate leading to a negative relationship between NO_x emissions and O_3 concentrations. Ozone is produced by a series of chemical reactions that involve nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight and heat. The formation involves highly nonlinear and complicated processes, depending on the relative forcing of various chemical species and local meteorological conditions that could vary over space and time (Seinfeld and Pandis 1998). Overall in urban areas, such as Taipei, which O_3 formation is VOC-limited, implying that a reduction in NO_x emissions would increase O_3 concentrations. On the other hand in the VOC-limited climate, O_3 concentrations will decrease if NO_x emissions increase.

alternative formulations of the counterfactual, even though they indicate the effect is smaller then those reported above.

4.5 Estimate Magnitudes

Implied Behavioral Responses. Are CO effects of the magnitudes we find plausible? One way to think about the answer is to compute the implied traffic diversion ratio away from automobile travel towards rail transit. As the emissions inventory indicates that virtually all CO emissions are transportation based, our estimates can be interpreted as an approximation of the percentage change in automobile vehicle miles travelled from the opening of the Taipei Metro. To compute the traffic diversion ratio, we then need to compute the ratio of the daily number of Taipei Metro trips in Table 1 of 40,000 to the number of total automobile commuting trips in Taipei before the Taipei Metro. Unfortunately, this simple calculation proves difficult as detailed transportation mode utilization data are unavailable for Taipei before the Taipei Metro opened. However, we can infer the number of automobile trips before the Taipei Metro by using 2001 mode share data in concert with an estimate of the total number of commuters before the Taipei Metro opened. Doing so we obtain an estimate of 375,000 automobile trips per day in Taipei before the Taipei Metro opened.[35] The daily Taipei Metro ridership is just over 10% of the automobile trips. Our estimated effect strikes us as quite plausible as our estimated CO effects ranging from a 5% to 15% reduction in CO pollution contains this back of the envelope calculation of the percentage change of total automobile commute trips Taipei Metro ridership represents.

A second exercise is to calculate what the expected magnitude of a CO pollution response would be if Taipei had the same traffic diversion ratio as used in Parry and Small (2009) for Washington DC. Conducting this calculation allows us to see whether

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[35] According to a large sample survey of Taipei commuters in 1988 there were 250,000 people commuting daily in and out of Taipei city for a total of 500,000 trips per day (Chen, 1992). We do not have access to mode share data before the Taipei Metro, however, Jou et al. (2010) report that in 2001 in Taipei 75 percent of commuters used a car or motorbike as the primary travel modes. Together these estimates suggest that a rough estimate of the daily number automobile trips before the Taipei Metro opened of about 375,000.

our estimates are plausible based on the available estimates of the behavioral responses of automobile travelers to mass urban transit. Parry and Small (2009) use a traffic diversion ratios of 0.70 (peak) and 0.60 (off-peak) for Washington, DC. Multiplying these estimates by the observed number of daily trips on the Taipei Metro from Table 1 (40,000) we obtain estimates of the number of automobile trips diverted to the metro of 28,000 (peak) and 24,000 (off-peak). As virtually all of CO emissions are due to automobile trips we can estimate the expected CO effect by simply dividing the number of diverted trips by the total number of trips. Based on these calculations we would expect the Taipei Metro opening to reduce CO pollution by 7% (peak) to 6% (off-peak). Thus, these calculations lead to estimates that are smaller but close to our DB-OLS estimates and larger than our difference-in-difference estimates. Again, as the range of our CO estimates contain an estimate derived from existing estimates of the behavioral response of automobile travel this calculation provides further reassurance that the magnitudes of estimated pollution effects are plausible.

Economic Significance. It is also interesting to ask, how large are air quality benefits we estimate in economic terms? One way to assess the size of the benefit of our estimates is to first calculate the effects of the reduction in CO pollution due to Taipei Metro ridership focusing on the well documented health effects.[36] To make this comparison we proceed in two steps. We first calculate the magnitude of the health effects that our CO estimates imply. We then scale the health effect benefits by the Metro ridership per mile so that a comparison to the estimates in Smalll and Parry (2009) is possible.[37]

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[36] While the epidemiological literature has carefully estimated relationships between air pollution and a range of health outcomes, the avoidance behavior of optimizing individuals is typically not accounted for (Dockery et al. 1993; Samet et al. 2000; Bell et al. 2004). As the economics literature has demonstrated that accounting for avoidance behavior is important, estimates that account for avoidance are preferred to understand the magnitude of the health effects of air pollution (Neidell, 2004, 2009, and Moretti and Neidell, 2008). We thus focus on using estimates that account for avoidance behavior in estimating the welfare consequences of Taipei Metro ridership.

[37] An implicit assumption with our calculation of the health effects implied by the air quality benefits is that the majority of the pollution in Taipei is from sources in Taipei itself. Certainly, the air pollution from the neighboring areas is likely to affect the air quality in Taipei. However, as Taipei has a basin-type topology (similar to Los Angeles) it is an independent airshed, so that the effect of non-local activity on air pollution is relatively minor compared to the local source activity (Chang and Chung, 2006). We thank an anonymous referee for pointing out this implicit assumption in our calculation.

We first use the recent estimates of the health effects of air pollution to calculate the implied health benefits of the Taipei Metro opening. Recent work by Currie, Neidell, and Schmieder (2009) finds that a one ppm reduction in CO reduced infant mortality by 2.5 percent in proportion to the baseline risk, accounting for avoidance behavior.[38] Focusing very narrowly on infant mortality health effects only we obtain estimates of 1.7 lives saved valued at \$8.7 Million USD in the first year of Taipei Metro operation using our baseline estimates.[39] More broadly, and perhaps speculatively, if we apply the infant mortality estimate to the elderly population who are also at risk of mortality from air pollution exposure we obtain an estimate of 58 elderly lives saved, leading to a total value of all lives saved of around \$85.2 Million USD in the first year of Taipei Metro operation.[40]

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[38] We are unaware of studies of other health effects of CO exposure that account for avoidance behavior. However, one recent study of the effects of CO exposure of asthma incidence suggests that non-mortality effects are likely to be small. For example, the estimates in Clark et al. (2010) allow us to get a sense of how large the reductions in asthma would be. To calculate incremental risk associated with 1ppm of CO, we assume that asthma is rare so that the odds ratio is a good approximation of the relative risk. Given that we do not have access to data on the baseline incidence of asthma, we used prevalence of (4.5%) as a surrogate (Lee et al. 2007). Under these assumptions, our calculation shows that the Taipei Metro reduced lifetime asthma by 234 cases per year $(=(1-\frac{1}{e^{0.834ppm\times0.7745\times0.157}})\times0.045\times77209)$. As the annual health cost of a patient with asthma in Taiwan is estimated to be \$260 (Sun et al. 2007) higher than that of a patient without asthma, the economic benefit of these avoided asthma related health care costs is estimated to be roughly \$57,000 per year.

[39] In 1996 there were 77,029 infants (children less than one year) with a mortality rate of 6.66 per 1000 infants in the Taipei Metro area according to census data. Thus, our baseline estimates of the reduction in CO caused by Taipei Metro ridership of 15.6 percent, yields an estimated reduction in infant deaths in Taipei of about 1.7 $(=0.834\text{ppm}\times0.156\times0.025\times0.00666\times77029)$ in the first year of operation. We apply the value of \$4.87 million per life used in Small and Kazimi (1995) for comparison purposes as this estimate is utilized in total benefit of mass transit calculations in Small and Perry (2009) enabling comparisons to be made on an equal footing. It is important to note however that this value of a statistical life is significantly larger than that estimated for Taiwan. Liu and Hammitt (1999) estimate the statistical value life for Taiwan as being \$1.2 million.

[40] To calculate the number of elderly lives saved we use the mortality rate, excluding accidents, for elder population of roughly 4,275 per 100,000, and the number of elders is 422,995 in the Metropolitan Taipei area according to census data. With these numbers in hand our estimate of the reduction in CO caused by the Taipei Metro ridership yields an estimated reduction in elder deaths of 58.8 cases $(=0.834\text{ppm}\times0.156\times0.025\times0.04275\times422995)$ As those older than 65 have a much shorter life remaining we apply the adjustment for life expectancy formula in Aldy and Viscusi (2007) (p.8) with their suggested value of a year of life of \$300,000, a remaining life for the over 65 in Taiwan of 5 years, and a discount rate of 5%. Doing so yields a statistical value of remaining life for this population of \$1.3 Million, and a

To complete the comparison, we next express the air pollution benefit of rail transit infrastructure in terms of cents per passenger mile. Doing so yields an implied local air pollution benefit of between 6.4 and 62.7 cents per passenger mile.[41] This is significantly larger than what prior work would imply. The calculations in Parry and Small (2009) are based on an external costs of automobile travel from local pollution of 2.0 cents per mile (Parry and Small (2009), App-13, and Small and Kazimi (1995)). Dividing the per mile vehicle local air pollution cost by the average modal diversion rate for Washington DC (Parry and Small (2009), Table 2) of 0.65 leads to an implied air pollution benefit of 3 cents per passenger mile of rail transit, less than half of what we find for our infant only calculation.

In addition, the air quality effects we measure here represent a sizable component of the total benefits of rail transit infrastructure calculated by Parry and Small (2009). Again for the Washington DC Metro, Parry and Small (2009) report overall social values of 19.8 (peak) and 13.9 (off-peak) cents per passenger mile. Our estimates of 5.4 cents per passenger mile imply that the air quality effects account for between 31 and over 400 percent of the social value of rail transit they compute. Indeed, our (more speculative) upper bound calculations suggest that the air quality effects of rail transit may be an order of magnitude larger than the total social value of rail transit computed in prior work. Regardless of the precise method used to interpret the magnitude of the air quality benefits, our estimated effects are significantly larger than those in prior work, and indicate that the air quality effects of rail transit infrastructure are economically substantial.

Of course our calculation is subject to many limitations. In one sense, our calculation is likely to represent a lower bound estimate of the full benefit of enhanced air quality as it does not include the full range of potential health effects or include the social costs of avoidance behavior. It is also possible that the effects of CO on health in Taipei could differ from those in the US where the data underlying the health effect estimates we employ are based. Furthermore, the long-run substitution response towards the metro could well be larger than the short run response underlying the estimates here.

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total value of the reduction in mortality of \$76.4 Million for the over-65 population.

[41] The exact calculation of the air quality benefit in cents per passenger mile = $\frac{totalbenefit}{[trips/day]\times[days/year]\times[milesoftrack]}$. The infant health effect= $\frac{8.6M}{40{,}000\times365\times9.3} = 0.063$. The infant and elderly effect is = $\frac{85.2M}{40{,}000\times365\times9.3} = 0.627$

However, our calculation may represent an upper bound to the long term health effects of a metro system. This would be the case if the substitution away from non-travel activities toward travel caused by the metro opening took substantial time. For example, as the metro system leads to substitution away from automobile travel congestion on the roads is reduced. If potential travelers learn of the congestion reduction over time and respond by driving more total traffic levels may fall less in the long term than the short term. To the extent that the effects of rail transit on travel time are expected, our estimates will incorporate the short run adjustment responses of workers and firms, such as changes in work schedules. However, as some of the adjustments to rail transit infrastructure may take time (such as changes in land use), longer term traffic creation responses may well be larger than the shorter term traffic creation responses in our estimates. As the best available estimates of traffic creation (i.e. that account for the endogenous location of highway capacity) indicate that the majority of traffic creation occurs in the short term our estimates likely capture much of the traffic creation effect. These estimates indicate that the short term traffic creation elasticity (0.54) is about two thirds of the longer term traffic creation elasticity (0.78-0.84), and that the long-run elasticity is less than one (Cervevo, 2002).

While we regard our results as being informative about the effects urban rail transit in air quality over more than the very short term, it is important to be clear about the limitations in applying our estimates over a much longer time period. One central limitation is that our estimates do not capture any sorting responses to local public good provision (i.e. Seig, Smith, Banzhaf, and Walsh, 2004). These sorting responses have been shown to be important for large scale urban transit projects in particular. As Kahn (2007) and Glaeser, Kahn, and Rappaport (2008) demonstrate that urban transit infrastructure projects tend to tend to attract a lower income population who do not own vehicles. The effects of these types of sorting responses on air quality are not entirely clear. On one hand, a lower income population might travel more by public transit and less by private vehicles so that the sorting responses lead to further negative impacts on local air pollution. On the other hand, population density is likely to increase with the reduction in average income which could lead to additional private vehicle travel in the area. In any case, we are able to say little about population sorting responses in the analysis here and leave the question of whether sorting attenuates or amplifies the air quality effects of urban rail transit we document for future research.

4.6 Heterogeneous Effects

The results thus far have demonstrated an important effect of the Metro's opening on average level of tailpipe air pollution in Taipei. In the next subsection we examine whether there is any evidence of heterogeneous effects of the Taipei Metro opening. We first examine whether there are any distributional effects of the metro opening by examining whether neighborhoods with a larger number of households in poverty experience especially large or small metro opening effects. To do so, we classify each pollution monitoring station as being above or below median poverty level and interact the high poverty indicator variable with the metro opening dummy.[42] The results of this exercise are useful for understanding whether there are 'environmental justice' implications of the results and are particularly worth examining as public transportation plays an important role in the location decisions of the low income population (Kahn, Glaeser, and Rappaport, 2008).

We also examine whether there is any evidence for a substantial traffic creation effect of the Metro opening based on heterogeneous responses to the Metro opening. The idea is that discretionary automobile trips are likely to occur where or when levels of traffic congestion and travel times are lower. Thus, if the opening of the Taipei Metro led to significant traffic creation effect, we would expect smaller decreases in air pollution during off-peak hours or locations far from the central business district. Of course, if adjusting the time or location of travel time is quite costly for automobile travelers then we would expect to see little adjustments made by optimizing travelers. To shed some light on these issues we study whether travel patterns adapt to the availability of rail transit by examining whether there are heterogeneous responses to the Taipei Metro.

To conduct our analysis we simply add interactions to our baseline RD model above.

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[42] Unfortunately, after numerous attempts we were unable to obtain data on the characteristics of the population by neighborhood before the Taipei Metro opened. The reported results are based on the earliest year of neighborhood poverty data we were able to obtain, from 2006. Thus, the estimates may partially reflect sorting response to the metro opening in addition to the distributional effects of interest.

Specifically, we fit the following model,

$$(4) \quad y_t = \delta_0 + \delta_1 MetroOpen_t + \delta_2 C_{t,i} + \delta_3 MetroOpen_t \times C_{t,i} + \delta_2 x_t + \delta_3 P(t) + e_t,$$

with the variables $MetroOpen_t$,x_t, $P(t)$ defined as above. In this model we also include the dummy variable $C_{t,i}$ that measures either time specific characteristics (rush hour) or location specific characteristics (above median poverty level or above median monitoring station distance to the Taipei Metro track). The coefficient estimate δ_3 measures whether there are differential effects of Taipei Metro opening by the relevant time or location.[43]

We present evidence for heterogeneous responses of tailpipe pollutants to Taipei Metro opening by monitoring station distance to the Taipei Metro, and time of day in Table 9.[44] Again, each entry in each panel of the table presents the coefficient estimates with the outcome variable given in the column heading and the sample in the row heading.

In the first panel of Table 9 we present the estimates with the interactions between high poverty level and Taipei Metro opening. We see very large differences in the level of tailpipe pollution by poverty level. Those stations with higher levels of poverty in the population experience much higher levels of air pollution. However, the interactions reveal little differences in the effect of Taipei Metro opening by poverty level. This finding indicates that the air quality effects of the opening of the Taipei Metro do not differentially affect the lower income population.

In the second panel of Table 9 we present the estimates with the interactions between above median monitoring station distance from the Taipei Metro track and Taipei Metro opening. We see very large differences in the level of tailpipe pollution by distance to the Taipei Metro track. As expected, those stations located near the Taipei Metro track in the

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[43] For the analysis of the differential impacts by hour we make one further change to the set of controls included in the regression. We do not include the hour times day of week interactions. This allows for more straightforward interpretation of the main time effect variable as the difference in mean pollution at rush hour versus other time periods.

[44] To measure the differences in the effect of Taipei Metro opening by station distance to the Taipei Metro we first divide the sample of monitoring stations into two subsamples, those with above and below median distance to Taipei Metro. We then create an hourly time series of all pollution measures for each sub sample by taking the average across all stations in the subsample, so that the resulting data set has two observations per hour.

central business district experience much larger levels of air pollution. Most importantly, the interactions reveal little differences in the effect of Taipei Metro opening by distance to the Taipei Metro. This finding suggests that automobile travelers did not significantly alter their route of travel in response to the opening of the Taipei Metro.

In the third panel of Table 9 we examine whether the response of air quality to Taipei Metro opening differs during peak travel hours. Again, we see very large differences in the level of tailpipe pollution between peak and non-peak travel hours. Perhaps surprisingly, peak travel hours experience lower levels of tailpipe air pollution than other hours of the day, though this fact is likely due to the persistence in air pollution noted above. We again see little evidence of a travel pattern response. The interaction effects are very small and statistically indistinguishable from zero at conventional statistical significance levels. Thus, it does not appear that automobile travelers significantly altered their time of travel in response to the opening of the Taipei Metro.

It is important to note an important limitation with using high frequency air pollution data to measure high frequency travel behavior. As air pollution displays some persistence in the atmosphere, high frequency changes in air pollution may well understate high frequency changes in travel behavior. As such we regard the evidence reported in Table 9 on the heterogeneous effects as more suggestive than our main results above. Taking the results in Table 9 at face value the fact that we find little evidence of changes in automobile time or route of travel in response to the opening of the Metro could be due to two possibilities. First, it could be the case that because the opening and route of the Taipei Metro were known years in advance of opening day individuals already made adjustments to these travel patterns in advance of opening day. It could also be the case that adjustments in time or route of travel are costly. For example, if the costs of finding a new job with different work hours are meaningful, they may outweigh the benefits from adjustment in terms of reduced travel time. Of course, without additional evidence it is difficult to untangle the precise reason for the lack of adjustment in the time or route of travel.

5 Conclusion

The transportation sector is a major source of air pollution worldwide. Recent evidence has indicated that automobile pollution poses significantly larger adverse health impacts than previously realized. Despite the importance of the transportation sector for air pollution, little work has examined the air pollution effects of transportation infrastructure directly. This paper seeks to fill the gap by examining the effects of one major type of transportation infrastructure – urban rail transit – on air quality.

Our analysis of the effects of the opening of a completely new Metro system in Taipei reveals three findings. First, we find that the opening of the Taipei Metro reduced air pollution from one tailpipe pollutant, carbon monoxide, by 5 to 15 percent. Our second set of findings shows little evidence that ground level ozone pollution is affected by the opening of the Taipei Metro however. Lastly, our results show little evidence of sizable travel pattern adjustments by automobile travelers in response to rail transit infrastructure. Importantly, the air quality effects we identify here for a large fraction of the total social value of rail transit infrastructure estimated in prior work. Thus, the air quality effects we measure here are important components of the benefits of rail transit infrastructure. Our results demonstrate that environmental effects can be important components of the social value of public infrastructure.

While this paper has reported new evidence on the environmental effects of rail transit infrastructure, it is natural to ask whether our results will carry over to other cities. Of course, the precise effects of rail transit infrastructure depend on many factors, which may differ across areas. While it seems likely the differences in automobile technology can be accounted for relatively easily the portability of our estimates to other areas also depends on behavioral responses of travelers. A more definitive answer awaits compelling evidence for other areas.

There are several worthwhile directions for future research. First, applying a similar discontinuity approach to evaluate the air quality effects of other types of transport infrastructure would be fruitful. For example, the air quality effects of high speed rail or an airport infrastructure could be measured by using the opening of project that was subject to hard to predict construction delays. As a number of anecdotal accounts suggest that high-speed rail ridership has come in below expectations, the air quality effects of high speed rail might well be smaller than those documented here. Secondly, measuring the effects of transportation infrastructure on health outcomes directly would be very interesting, as the responsiveness of individual travel behavior to transportation infrastructure availability may depend partly on their underlying health conditions.

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TABLE 1: Descriptive Statistics, Taipei

	Full Sample (1)	Pre-Taipei Metro (2)	Post-Taipei Metro (3)	(2) – (3) t-stat (4)
A. Primarily Transportation Source Pollutants				
Carbon Monoxide (CO)	0.802	0.834	0.770	-10.03
	[0.422]	[0.440]	[0.400]	(0.000)
	N=17495	N=8735	N=8760	
Nitrogen Oxides (NO_x)	0.033	0.035	0.031	-9.65
	[0.021]	[0.021]	[0.020]	(0.000)
	N=16872	N=8437	N=8435	
B. Indirect Transportation Source Pollutants				
Ground-Level Ozone (O_3)	0.023	0.023	0.022	-4.43
	[0.015]	[0.015]	[0.014]	(0.000)
	N=17489	N=8731	N=8758	
C. Primarily Non-Transportation Source Pollutants				
Particulate Matter (PM10)	46.961	48.868	45.055	-9.15
	[27.612]	[27.898]	[27.193]	(0.000)
	N=17470	N=8734	N=8736	
Sulfur Dioxide (SO_2)	0.005	0.006	0.004	-32.48
	[0.004]	[0.005]	[0.003]	(0.000)
	N=17494	N=8735	N=8759	
D. Weather				
Wind Speed	2.25	2.23	2.27	1.86
	[1.19]	[1.16]	[1.21]	(0.063)
	N=17496	N=8736	N=8760	
Temperature	21.83	21.68	21.98	3.33
	[6.01]	[6.12]	[5.90]	(0.001)
	N=17495	N=8735	N=8760	
Humidity	73.86	73.21	74.47	10.39
	[7.86]	[8.22]	[7.44]	(0.000)
	N=17120	N=8373	N=8747	
E. Transportation				
Taipei Metro Ridership (daily)	--	--	40410	--
			[9153]	

N=365

Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network and TM data. The unit of observation is hour for all variables in panels A-D. The unit of observation is day in panel E. All pollutants are expressed in parts per million, wind speed is expressed in meters per second, temperature is expressed in degrees Celsius, and humidity is expressed in percentage terms. The main entries in columns (1), (2) and (3) report the mean level of the variable indicated in the row heading and the sample indicated in the column heading. The entries in square brackets in columns (1), (2) and (3) report the standard deviation of the variable indicated in the row heading and the sample indicated in the column heading. The t-statistic and the p-value in square brackets for the hypothesis test that the variable indicated in the row heading does not differ between columns (2) and (3) is reported in column (4).

TABLE 2: The Effect of Metro Ridership on Transportation Source Pollutants: Basic OLS Estimates

Dependent Variable:	Log(CO)	Log(NO_x)	Log(O_3)
Model:	OLS (1)	OLS (2)	OLS (3)
Taipei Metro Ridership (‘000)	0.006 (0.013)	0.021 (0.017)	0.017 (0.021)
Sample	Post-Metro	Post-Metro	Post-Metro
N	8745	8421	8743

Notes: Source: Authors’ Calculations from Taiwanese EPA air quality monitoring network and TM data. Each column reports the result from one regression. The unit of observation is hour. The sample is for one full year after the TM opens. The main entries in columns (1)-(3) report the coefficient estimate from fitting model (1) in the text by ordinary least squares, with standard errors clustered at the 5-week level reported in brackets. The models fit equation (1) in the text by ordinary least squares and also contain controls for gas content regulation events, quartics in wind speed, temperature, and humidity, as well as, one hour lags of these variables as controls, with standard errors clustered at the 5-week level reported in brackets. *** indicates significantly different from zero at the 1% level. ** indicates significantly different from zero at the 5% level. * indicates significantly different from zero at the 10% level.

TABLE 3: The Effect of Metro Opening on Transportation Source Pollutants: Ridership Discontinuity Based OLS

Dependent Variable:	Log(CO)	Log(NO_x)	Log(O_3)
Model:	DB-OLS (1)	DB-OLS (2)	DB-OLS (3)
Taipei Metro Open	-0.156** (0.059)	-0.083 (0.052)	-0.037 (0.063)
N	17076	16466	17070

Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network and TM data. Each column reports the result from one regression with controls for a third-order polynomial time trend, gas content regulation events, quartics in wind speed, temperature, and humidity, as well as, one hour lags of these variables. The unit of observation is hour. The sample for all regressions is one full year before and one full year after the TM opening date. The main entries in columns (1), (2) and (3) report the coefficient estimate from fitting model (2) in the text by ordinary least squares, with standard errors clustered at the 5-week level reported in brackets. *** indicates significantly different from zero at the 1% level. ** indicates significantly different from zero at the 5% level. * indicates significantly different from zero at the 10% level.

TABLE 4: Taipei Non-Transportation Pollutants and Non-Taipei Transportation Pollution Smoothness Tests: Ridership Discontinuity Based OLS

City:	Taipei	East Coast	Kaohsiung
Model:	DB-OLS	DB-OLS	DB-OLS
	(1)	(2)	(3)
Dependent Variable=			
Log(PM10)	0.041		
	(0.141)		
Log(SO_2)	-0.249		
	(0.199)		
Log(CO)		0.088	-0.037
		(0.096)	(0.052)
Log(NO_x)		0.062	-0.085
		(0.058)	(0.057)
Log(O_3)		0.165	0.056
		(0.225)	(0.221)

Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network and TM data. Each cell reports the result from one regression with controls for a third-order polynomial time trend, gas content regulation events, quartics in wind speed, temperature, and humidity, as well as, one hour lags of these variables. The dependant variable for each regression is listed in the first column and the sample is listed in the column header. The unit of observation is hour. The sample is all for one full year before and after the TM opening date for Taipei in column (1), for the east coast in column (2) and for Kaohsiung in column (3). The main entries in the columns report the coefficient estimate from fitting model (2) in the text by ordinary least squares for the dependent variable and sample indicated, with the standard errors clustered at the 5-week level reported in brackets. *** indicates significantly different from zero at the 1% level. ** indicates significantly different from zero at the 5% level. * indicates significantly different from zero at the 10% level.

TABLE 5: Taipei and Non-Taipei Weather Control Smoothness Tests: Ridership Discontinuity Based OLS

Dependent Variable:	Wind Speed	Temperature	Humidity
Model:	DB-OLS (1)	DB-OLS (2)	DB-OLS (3)
Panel A: Taipei			
Taipei Metro Open	-0.140	-2.132	10.732***
	(0.376)	(2.020)	(2.728)
N	17496	17495	17121
Panel B: East Coast			
Taipei Metro Open	-0.234	-0.768	9.016**
	(0.171)	(1.615)	(4.480)
N	17356	17265	17008
Panel C: Kaohsiung			
Taipei Metro Open	-0.349	-1.143	10.652***
	(0.404)	(1.020)	(2.794)
N	17495	17495	17115

Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network and TM data. Each column reports the result from one regression with controls for a third-order polynomial time trend, gas content regulation events, quartics in wind speed, temperature, and humidity, as well as, one hour lags of these variables. The unit of observation is hour. The sample for all regressions is one full year before and one full year after the TM opening date. The main entries in columns (1), (2) and (3) report the coefficient estimate from fitting model (2) in the text by ordinary least squares, with standard errors clustered at the 5-week level reported in brackets. *** indicates significantly different from zero at the 1% level. ** indicates significantly different from zero at the 5% level. * indicates significantly different from zero at the 10% level.

TABLE 6: The Effect of Metro Opening on Transportation Source Pollutants: Ridership Discontinuity Based OLS, Lagged Outcome Controls

Dependent Variable:	Log(CO)	Log(NO_x)	Log(O_3)
Model:	DB-OLS (1)	DB-OLS (2)	DB-OLS (3)
Taipei Metro Open	-0.035**	-0.028*	-0.001
	(0.015)	(0.014)	(0.016)
First Lag	1.092***	0.922***	0.686***
	(0.020)	(0.031)	(0.039)
Second Lag	-0.332***	-0.092*	0.220***
	(0.026)	(0.032)	(0.021)
Third Lag	0.052**	-0.007	-0.027*
	(0.015)	(0.013)	(0.016)
Fourth Lag	-0.005	-0.020**	-0.096***
	(0.006)	(0.007)	(0.007)
N	17072	14027	17042
Cumulative Effect of Taipei Metro Open	-0.141	-0.105	-0.003

Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network and TM data. Each column reports the result from one regression with controls for a third-order polynomial time trend, gas content regulation events, quartics in wind speed, temperature, and humidity, as well as, one hour lags of these variables. The unit of observation is hour. The sample for all regressions is one full year before and one full year after the TM opening date. The main entries in columns (1), (2) and (3) report the coefficient estimate from fitting model (2) in the text by ordinary least squares, with standard errors clustered at the 5-week level reported in brackets. *** indicates significantly different from zero at the 1% level. ** indicates significantly different from zero at the 5% level. * indicates significantly different from zero at the 10% level.

TABLE 7: Effects of Metro Opening on Transportation Source Pollutants: Ridership Discontinuity Based OLS, 30 Day Window Specification

Dependent Variable:	Log(CO)	Log(NO_x)	Log(O_3)
Model:	DB-OLS (1)	DB-OLS (2)	DB-OLS (3)
Taipei Metro Open	-0.132***	-0.146***	0.197
	(0.026)	(0.045)	(0.110)
N	1416	1409	1415

Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network and TM data. Each column reports the result from one regression without additional controls. The unit of observation is hour. The sample for all regressions is 30 days before and 30 days after the TM opening date. The main entries in columns (1), (2) and (3) report the coefficient estimate from fitting model (2) in the text by ordinary least squares, with standard errors clustered at the 5-week level reported in brackets. *** indicates significantly different from zero at the 1% level. ** indicates significantly different from zero at the 5% level. * indicates significantly different from zero at the 10% level.

TABLE 8: The Effect of Metro Opening on Transportation Source Pollutants: Difference-in-Difference Estimates, 30 Day Window Specification

Dependent Variable:	Log(CO)	Log(NO_x)	Log(O_3)
Model:	DD-OLS (1)	DD-OLS (2)	DD-OLS (3)
	Panel A: No Controls		
Taipei Metro Open X Taipei	-0.079* (0.042)	-0.139*** (0.049)	0.253*** (0.093)
N	2832	2767	2830
	Panel B: Including Weather and Time Controls		
Taipei Metro Open X Taipei	-0.056*** (0.020)	-0.101*** (0.024)	0.232*** (0.022)
N	2832	2767	2830

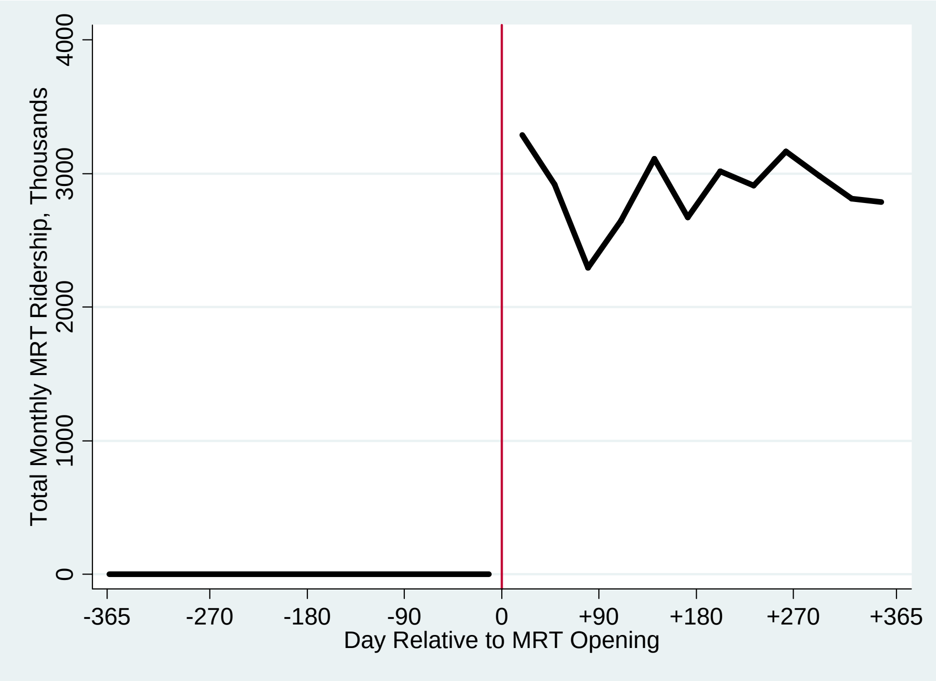
Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network and TM data. Each column reports the result from one regression with controls for a third-order polynomial time trend, gas content regulation events, quartics in wind speed, temperature, and humidity, as well as, one hour lags of these variables. The unit of observation is hour. The sample for all regressions is one full year before and one full year after the TM opening date. The main entries in columns (1), (2) and (3) report the coefficient estimate from fitting model (2) in the text by ordinary least squares, with standard errors clustered at the 5-week level reported in brackets. *** indicates significantly different from zero at the 1% level. ** indicates significantly different from zero at the 5% level. * indicates significantly different from zero at the 10% level.

TABLE 9: The Effect of Metro Opening on Primarily Transportation Source Pollutants, Heterogeneous Effects: Ridership Discontinuity Based OLS

Dependent Variable:	Log(CO)	Log(NO_x)
Model:	DB-OLS	DB-OLS
	(1)	(2)
Panel A: Poverty Level		
Metro Open	-0.086**	0.034
	(0.039)	(0.100)
High Poverty Monitoring Station	-0.085***	-0.471**
	(0.016)	(0.044)
Metro Open	0.019	0.004
X High Poverty Monitoring Station	(0.020)	(0.073)
Panel B: Station Location		
Metro Open	-0.129**	-0.004
	(0.046)	(0.115)
Monitoring Station Close to Metro	0.426***	0.636***
	(0.013)	(0.043)
Metro Open	0.040	0.013
X Monitoring Station Close to Metro	(0.035)	(0.073)
Panel C: Time Of Day		
Metro Open	-0.078**	0.035
	(0.040)	(0.119)
Rush Hour	-0.144***	-0.140*
	(0.049)	(0.073)
Metro Open	0.006	0.034
X Rush Hour	(0.032)	(0.049)

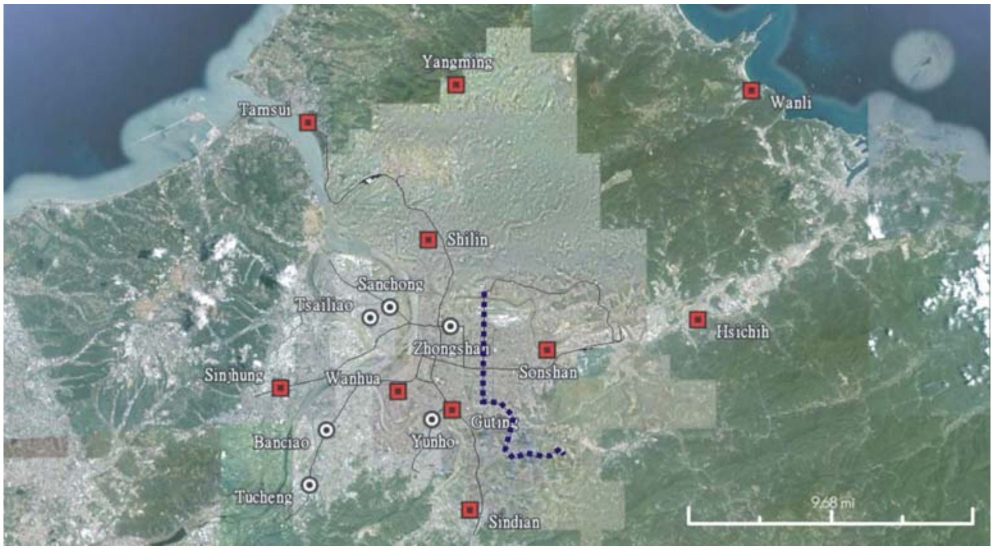
Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network and TM data. Each cell reports the result from one regression with controls for a third-order polynomial time trend, gas content regulation events, quartics in wind speed, temperature, and humidity, as well as, one hour lags of these variables. The unit of observation is hour. The sample is all observations for one full year before and after the TM opening date. The main entries in columns (1) and (2) report the coefficient estimate from fitting model (4) in the text by ordinary least squares, with the standard errors clustered at the 5-week level reported in brackets. *** indicates significantly different from zero at the 1% level. ** indicates significantly different from zero at the 5% level. * indicates significantly different from zero at the 10% level.

FIGURE 1: Ridership on the Taipei Metro



Notes: Source: Authors' Calculations from monthly TM data.

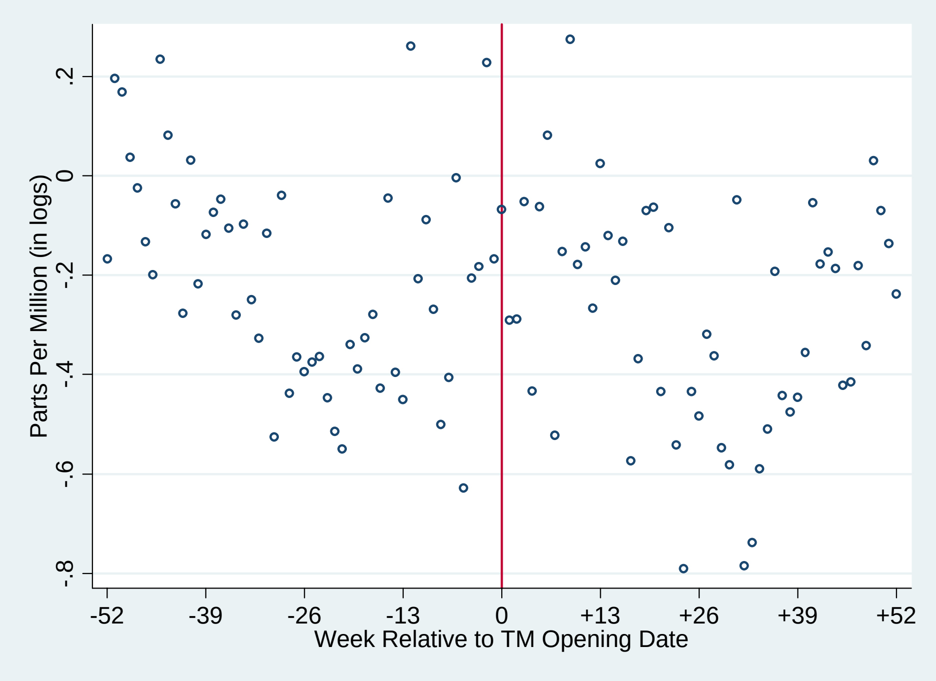
FIGURE 2: Map of the Taipei Metro System and Air Quality Monitoring Stations in Taipei



Notes: The TM system route is indicated by the dotted line. The monitoring stations in operation during our sample period are indicated by the red squares, the monitoring stations not operating for our full sample period are indicated by white circles.

FIGURE 3: Mean Weekly Pollution Level in Taipei, Two Year Window

A. CO - Without Time Trend

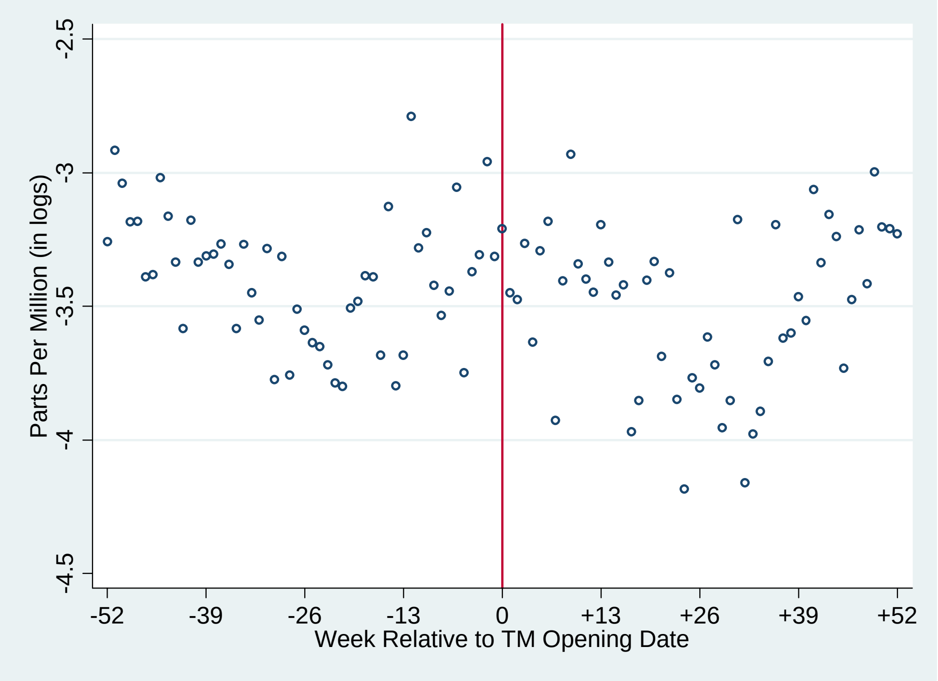


Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network data.

B. CO - With Time Trend

Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network data.

C. NOx - Without Time Trend

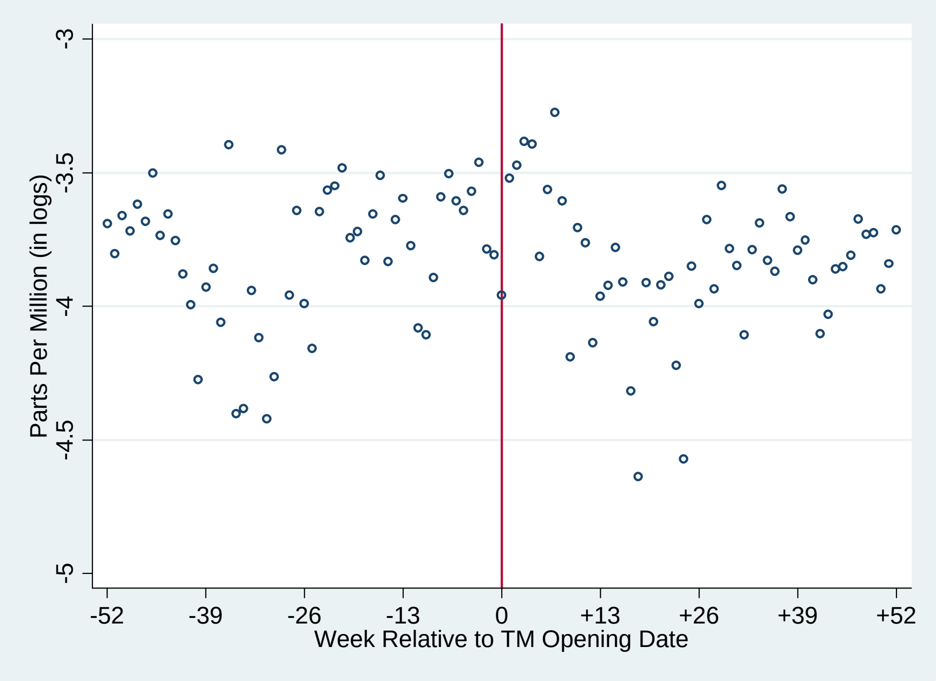


Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network data.

D. NOx - With Time Trend

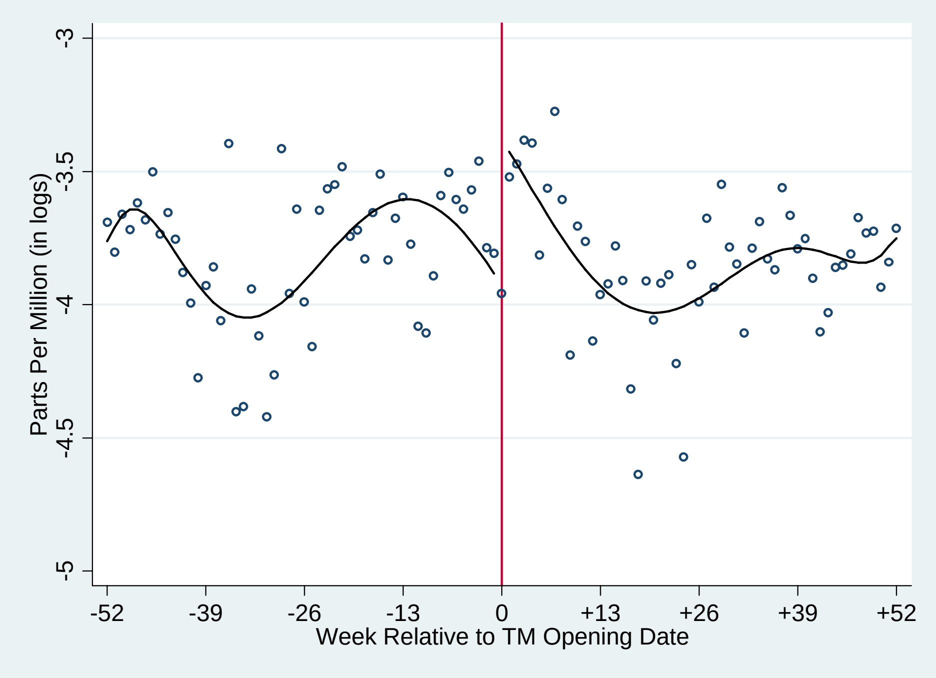
Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network data.

E. O_3 - Without Time Trend



Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network and TM data.

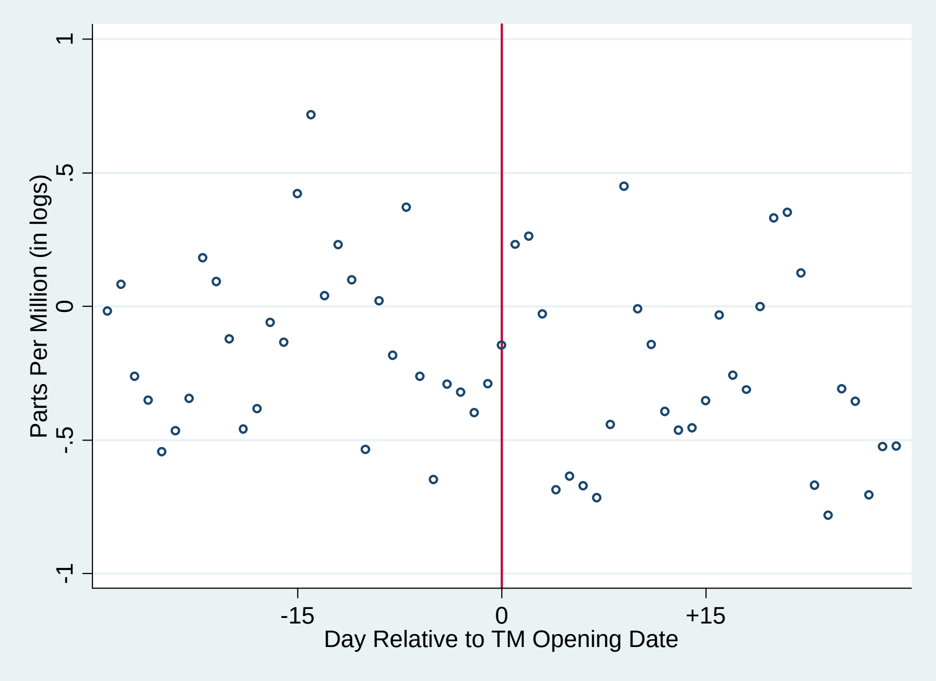
F. O_3 - With Time Trend



Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network data.

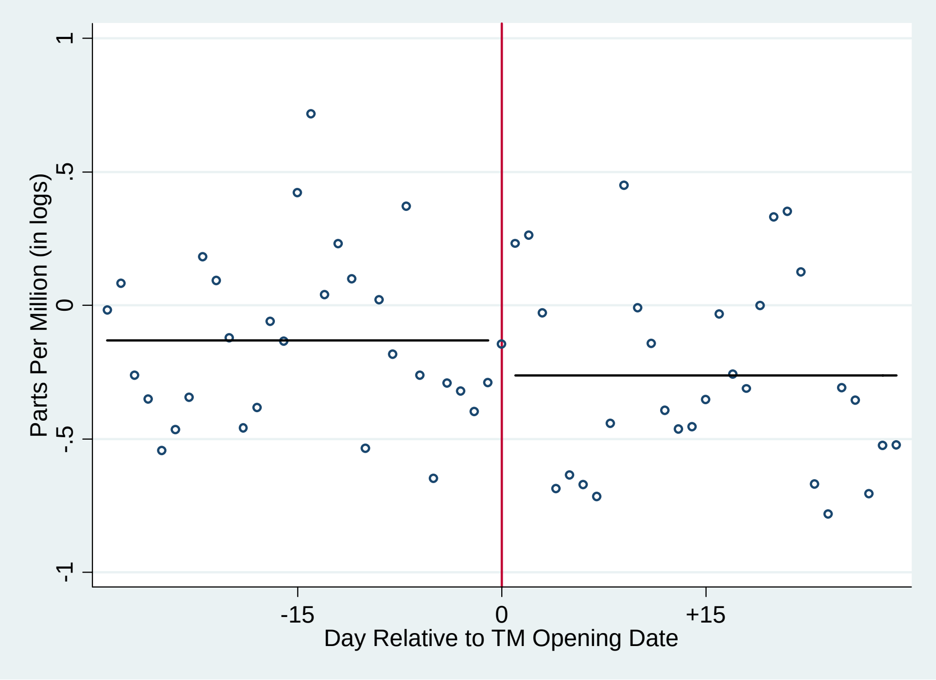
FIGURE 4: Mean Daily Pollution Level in Taipei, 30 Day Window

A. CO - Without Time Trend



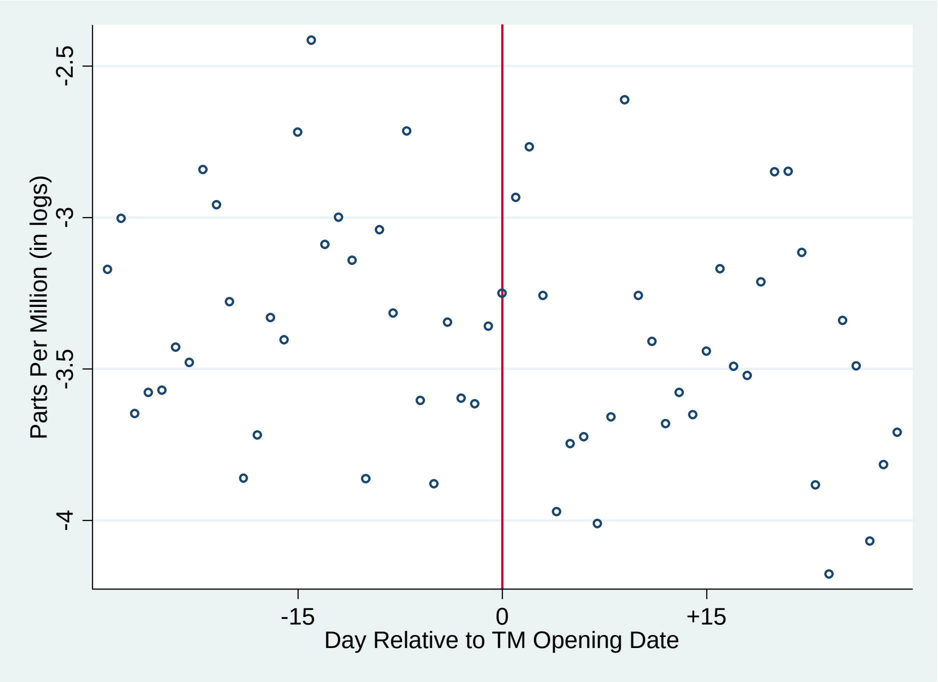
Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network data.

B. CO- With Time Trend



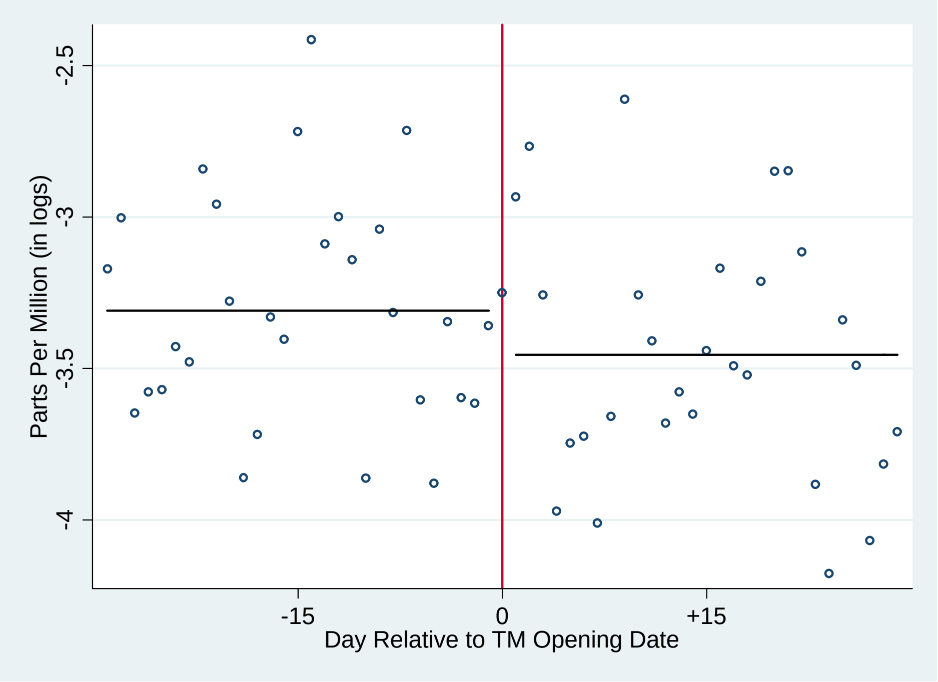
Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network data.

C. NOx - Without Time Trend



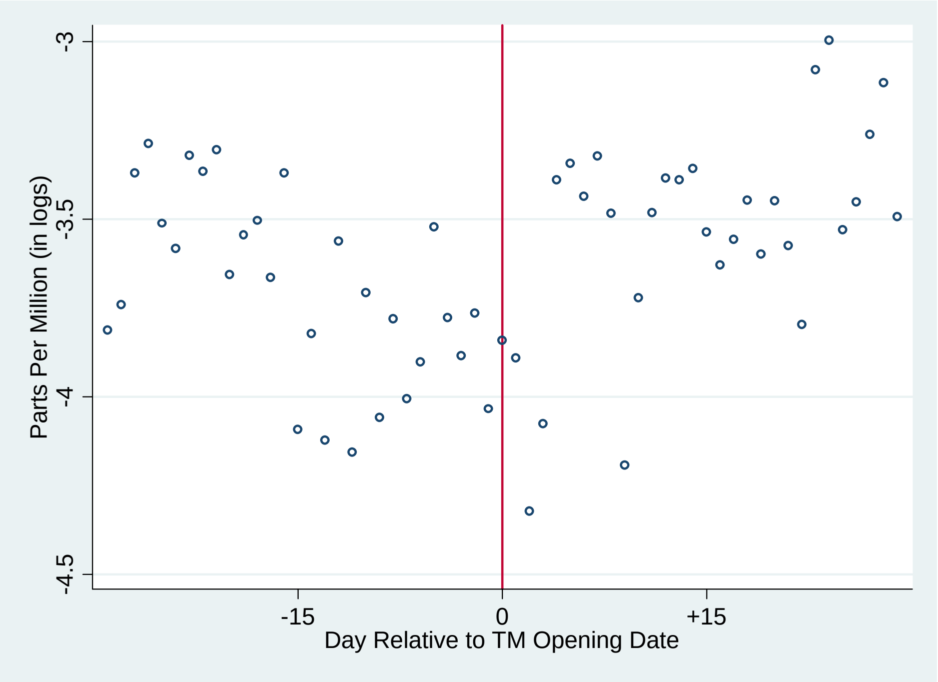
Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network data.

D. NOx - With Time Trend



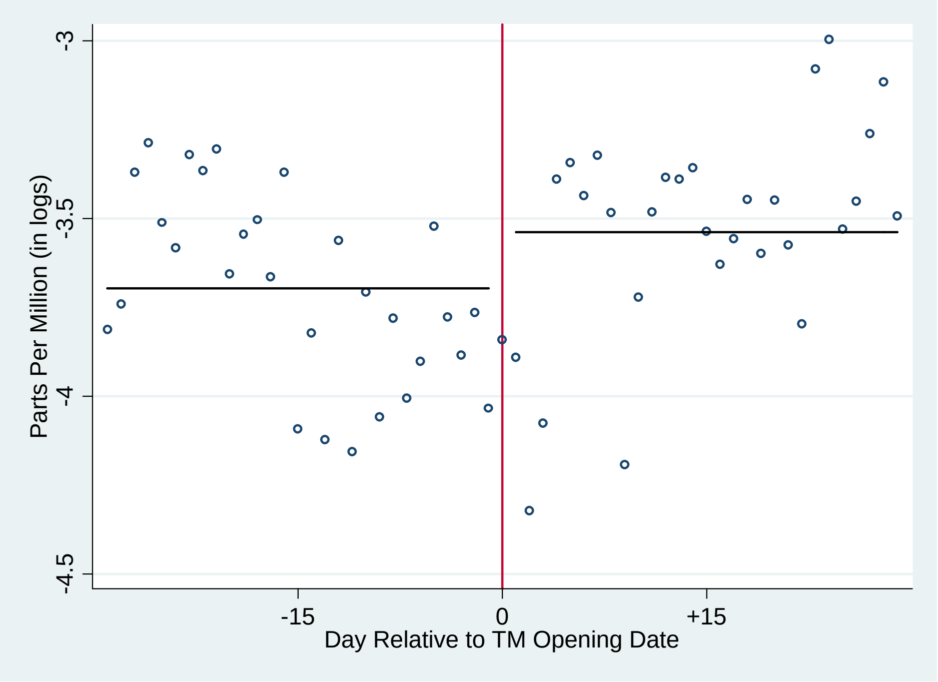
Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network data.

E. O_3 - Without Time Trend



Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network data.

F. O_3 - With Time Trend



Notes: Source: Authors' Calculations from Taiwanese EPA air quality monitoring network data.