Available online at www.sciencedirect.com
ScienceDirect
Transportation Research Part D 13 (2008) 239–254
TRANSPORTATION RESEARCH PART D
www.elsevier.com/locate/trd

Air quality impacts of Tokyo's on-road diesel emission regulations

Daniel Rutherford [a,*], Leonard Ortolano [b]

[a] The International Council on Clean Transportation, 1 Hallidie Plaza Suite 503, San Francisco, CA 94012, United States
[b] Department of Civil and Environmental Engineering, Stanford University, United States

Abstract

In October 2003, the Tokyo Metropolitan Government began regulating emissions from diesel-powered trucks and buses under a local in-use particulate emission standard. This paper uses an empirically based emissions modeling approach to estimate the effect of Tokyo's regulations on emissions of particulate matter and nitrogen oxides. Results indicate that Tokyo's regulations cut exhaust particulate emissions from diesel-powered trucks and buses registered in Tokyo by 17% and 31% in 2003 and 2004 through the promotion of diesel particulate filters and oxidation catalysts and by accelerating fleet turnover. Modest emission reductions were also observed for nitrogen oxides. The model suggests that the bulk of emission reductions – 70% for particulate matter, and 30% for nitrogen oxides – after 2002 directly tied to environmental policies are attributable to Tokyo's local regulations rather than national emission control policies.

Keywords: Tokyo; Trucks; Diesel engines; Atmospheric pollution

1. Introduction

Since the mid-1980s, Japan has struggled with arguably the developed world's worst problem with pollution from on-road diesel vehicles due to the density of its cities, preferential pricing and taxation policies for diesel fuel adopted in the 1970s, and weak restrictions on emissions of particulate matter from new and in-use vehicles. Beginning around 1985, air quality began to decline in many Japanese cities as diesel trucks became more prevalent in goods movement, threatening progress the central government made in the 1970s controlling emissions from stationary sources and light-duty passenger vehicles. Bucking trends in much of the developed world, ambient concentrations of nitrogen oxides (NOx) and suspended particulate matter (SPM) worsened in urban areas during the 1980s, with the central government being forced to delay its targets for compliance with ambient air quality standards in 1985, 1988, and once again in 2000.

* Corresponding author. Tel.: +1 415 399 9019.
E-mail address: dan@theicct.org (D. Rutherford).

1361-9209/$ - see front matter
doi:10.1016/j.trd.2008.02.004

Japan's central government reacted in 1989 by adopting its first comprehensive diesel emissions policy, establishing emission standards for diesel particulates from new trucks and buses, requiring the sale of 500 parts per million (ppm) sulfur diesel fuel by 1997, and implementing regulations mandating the early retirement of older diesel trucks and buses in urban areas. While significant, those regulations failed to reverse the slide in air quality: by 1998, only 55% of the roadside monitoring stations in the extended Tokyo metropolitan region were in compliance with central ambient air quality standards for nitrogen dioxide (NO_2) originally targeted for 1976, with only 11% of stations complying with SPM standards (Environment Agency, 1999).

On August 27th, 1999, Japan's laissez faire policy toward diesel pollution came to an abrupt end when the Tokyo Metropolitan Government (TMG), led by controversial Governor Shintaro Ishihara, announced "Operation No Diesel", a local policy pushing for tougher regulation of on-road diesel emissions. The cornerstone of Tokyo's diesel policy was a local in-use particulate emission standard requiring the installation of either diesel particulate filters (DPF) or diesel oxidation catalysts (DOC) on all diesel-powered trucks, buses, and special purpose vehicles[1] in operation for more than seven years and used within city limits.

The implementation of Tokyo's in-use standard was correlated with significant improvements in local air quality. Roadside concentrations of SPM fell by over 20% between 2002 and 2004, with the percentage of stations complying with national ambient air quality standards jumping from 0% to 97% (Tokyo Bureau of Environment, 2005). Ueno et al. (2004) found that per kilometer emissions of primary particulate matter from diesel trucks and buses decreased by more than 40% from 2001 to 2003 in Tokyo.

This paper estimates the contribution of Tokyo's local in-use emission standard, in the form of reduced emissions of particulate matter and NOx from trucks, buses, and special purpose vehicles, to these air quality improvements. To do so, we introduce a simple emissions model capable of disaggregating the impact of local regulations from intervening variables such as central emission control policies and exogenous changes in transport demand.

2. Air quality improvements in Tokyo

Under "Operation No Diesel", TMG issued new diesel emission regulations that in October 2003 retroactively enforced the central government's particulate emission standards for model year 1998 vehicles on in-use medium and heavy-duty vehicles. Owners of affected vehicles could comply with Tokyo's regulations through one of three means: installing a TMG-certified DPF or DOC, replacing vehicles that had been in use for more than seven years with a newer diesel-powered vehicle, or purchasing a gasoline or alternative-fuel vehicle. When enforcement began, an estimated 200,000 diesel-powered trucks, buses, and special purpose vehicles registered in Tokyo needed to be either replaced or retrofit.

In response to pre-emptive TMG administrative guidance and targeted subsidies,[2] many diesel bus and truck owners began to bring their vehicles into compliance with Tokyo's requirements in the fall of 2002. From 2002 to 2004, significant improvements in air quality were observed in Tokyo. Four distinct changes suggest that Tokyo's regulations significantly impacted local diesel particulate emissions:

- A large increase in the number of roadside monitoring stations in compliance with central ambient air quality standards.
- A decrease in roadside SPM relative to other monitoring sites.
- Reductions in roadside SPM concentrations relative to other urban areas not adopting in-use emission standards.
- Reductions in the particulate emission factor of Tokyo's diesel vehicle fleet from 2001 to 2003.

[1] Special purpose vehicles include public vehicles (e.g. utility fleets, fire trucks and ambulances), as well as specialized trucks such as concrete mixers, tankers, and refrigerated vehicles.

[2] For information on the specific measures implemented by TMG to promote early compliance with its in-use emission standard, see Rutherford (2006).

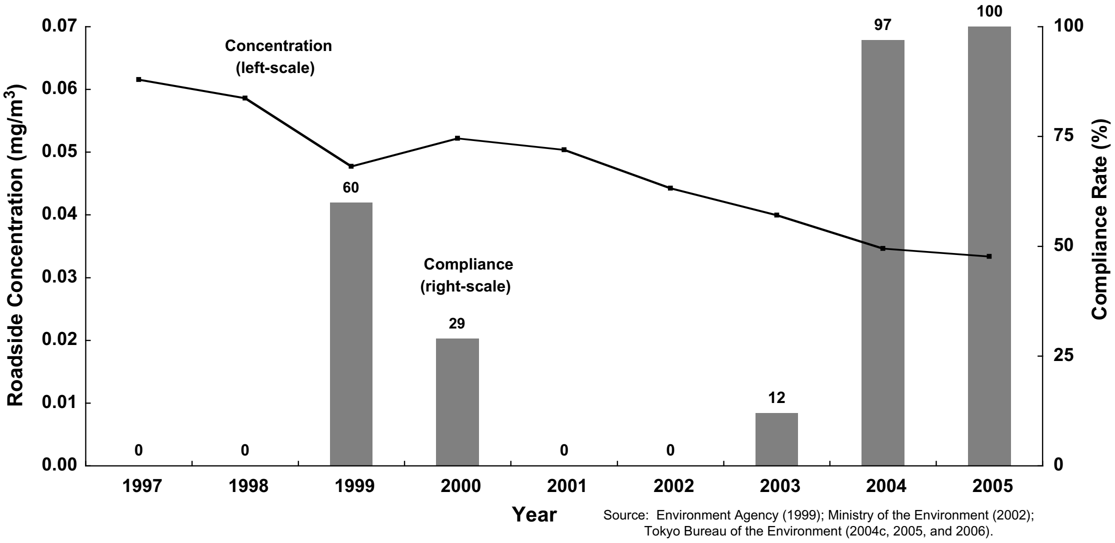

Fig. 1. Annual average roadside SPM concentrations and compliance with long-term air quality standards, 1997–2005.

Table 1
Ambient concentrations of suspended particulate matter in Tokyo, Osaka, and Aichi Prefectures, 2000–2005

Prefecture	Roadside concentration (mg/m^3)					
	2000	2001	2002	2003	2004	2005
Tokyo	0.052	0.050	0.044	0.040	0.035	0.033
Osaka	0.044	0.040	0.037	0.035	0.033	0.033
Aichi	0.041	0.040	0.038	0.038	0.035	0.037

Concentrations of roadside suspended particulate matter fell substantially in Tokyo from 2002 to 2004. Fig. 1 displays average annual roadside SPM concentrations (line, left-scale) with compliance rates for daily average SPM ambient air quality standards[3] (bar, right-scale) from 1997 to 2005. As the graph demonstrates, with the exception of a substantial outlier during 1999 attributable to an unusual typhoon season, compliance rates with SPM standards at roadside monitoring stations in Tokyo were steady at zero for most years prior to "Operation No Diesel". In contrast, roadside stations reached near-universal compliance in 2004, the first full year of implementation of TMG's local in-use emission standard.

The large decreases in roadside ambient SPM relative to monitoring stations located away from major roadways during that period is likewise consistent with the contention that Tokyo's in-use standard improved air quality. In 2002, average annual ambient concentrations of SPM at roadside monitoring stations in continuous operation since 1995 in Tokyo were 30% higher than concentrations at monitoring stations located further from major roadways (0.044 mg/m^3 and 0.034 mg/m^3, respectively.) By 2005, roadside concentrations fell to 0.033 g/m^3, a drop of 25%. In contrast, SPM concentrations at latter stations dropped more modestly, to 0.029 mg/m^3, a reduction of only 15% (Japanese Ministry of the Environment, 2002; Tokyo Metropolitan Government, 2004c, 2005 and 2006).

Improvements in Tokyo's air quality were also disproportionately large relative to areas not adopting local diesel regulations. Table 1 compares average annual concentrations of roadside suspended particulate matter in Tokyo with Osaka and Aichi, two other urban prefectures not implementing local in-use standards. In 2000, roadside concentrations of SPM in Tokyo were 29% higher than in Aichi, and 20% above that of Osaka.

[3] Japan's daily average SPM standard is set at a maximum of 0.10 mg/m^3.

In contrast, Tokyo's roadside SPM levels dropped noticeably in 2002 as vehicle owners began complying with TMG's regulations – by 2005, roadside concentrations in Tokyo matched those of Osaka and were 0.004 mg/m^3 lower than in Aichi.

Finally, this period also shows significant reductions in the mass of particulate matter emitted per kilometer traveled by diesel vehicles in Tokyo. Ueno et al. (2004) estimates that per kilometer emissions of elemental carbon from diesel-powered vehicles fell by 44% from 2001 to 2003. The reduction in the elemental carbon emission factor, which is commonly used as a proxy for diesel exhaust particulates (DEP), provides compelling evidence that recent reductions in ambient SPM were driven by lower diesel emissions resulting from tougher regulations.

Taken in sum, these developments strongly suggest that Tokyo's in-use emission standard improved local air quality. It is still necessary, however, to isolate the impact of those standards from other intervening variables, notably central emission control regulations being implemented at the same time. The next section introduces key features of the set of central and local regulations influencing on-road diesel emissions in Tokyo during this time frame.

3. Japan's diesel emissions regulations

Three primary motor vehicle emission regulations – two central, and one local – likely contributed to the substantial improvement in Tokyo's air quality from 2002 to 2004. The first were tighter emission standards for NOx and particulate matter adopted in December 1989 by Japan's Environment Agency. These requirements were introduced in two phases: "short-term" (*tanki*) standards enforced in 1994 for heavy-duty vehicles, and "long-range" (*chouki*) standards introduced in 1998 (Japanese Ministry of Land, Infrastructure, and Transport, 2005).[4]

The central government's decision to introduce tighter emission standards for new diesel vehicles in 1994 was correlated with significant reductions in DEP and NOx emission factors for new vehicles. Fig. 2 shows diesel exhaust particulate emission factors for direct-injection diesel trucks, of gross vehicle weight (GVW) between 2.5 and 5 tons, for various model years at different operating speeds.

Both DEP and NOx emission factors fell over time in tandem with tougher emission standards for new diesel vehicles, with especially large reductions after 1994. This strong, negative correlation between model year and emissions means that vehicle turnover, whether through natural attrition or due to policy measures promoting early retirement and replacement, significantly reduces emissions.

The second key regulation influencing diesel emissions over the past decade is the 1992 *Law Concerning Special Measures to Reduce the Total Amount of Nitrogen Oxides Emitted From Motor Vehicles in Specified Areas*, generally referred to simply as the "NOx law" (updated in 2001 as the "NOx/PM law"). The NOx law restricted the registration of older diesel-powered vehicles in designated metropolitan areas by retroactively applying 1988 and 1989 new vehicle emission standards for nitrogen oxides on in-use diesel trucks, buses, and special-purpose vehicles.[5] Vehicles failing to meet the standard[6] were to be retired, replaced, or registered outside of heavily polluted urban areas.

The final regulatory instrument that likely contributed to recent improvements in Tokyo's air quality was the TMG's local in-use particulate emission standard, set at the central government's "next most stringent"

[4] Central emissions standards for diesel vehicles in Japan are generally phased in over a three-year period depending upon gross vehicle weight. For example, the "long-range" standards were implemented in 1997 for vehicles with a GVW of less than 3.5 tons, 1998 for vehicles weighing between 3.5 and 12 tons, and in 1999 for vehicles weighing more than 12 tons. For simplicity, in this paper we refer to standards based upon their enforcement date for heavy-duty (i.e. GVW of 3.5–12 tons) vehicles.

[5] The law also included weaker policy measures, including requirements that governors draft and submit NOx emission reduction plans for central approval. See Nishikawa (1993) for further details.

[6] In reality, the NOx law's employment of the term "in-use emission standard" is somewhat misleading, given that the lack of systematic NOx testing under Japan's registration system for diesel vehicles. In lieu of individual vehicle testing, the central government assumes that a vehicle manufactured under a given new emission standard continued to meet that standard throughout its entire operating lifetime. As enforced, the NOx law determined that any diesel-powered truck, bus, or special purpose vehicle registered before 1988 or 1989 (depending upon vehicle class) failed to meet the emission standard and was ineligible for registration in designated areas following the expiration of a grace period.

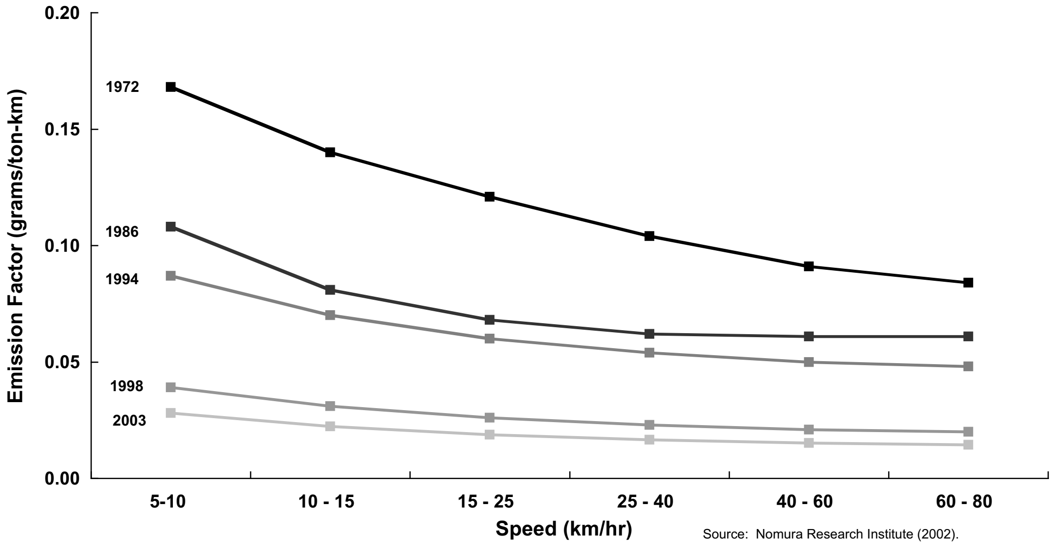

Fig. 2. DEP emission factor by model year and operating speed (direct injection diesel trucks, GVW 2.5–5 tons).

Table 2
"Next most stringent" particulate emission standard

Standard	Value (g/kWh)	Year effective (central, new vehicles)	Year effective (TMG, in-use vehicles)
Short-term	0.7	1994	–
Long-range	0.25	1998	2003
New short-term	0.18	2003	2006
New long-range	0.023	2005	–

Note: Heavy-duty vehicles (GVW > 3.5 tons), average values.
Source: Tokyo Bureau of Environment (2003).

particulate standard for new vehicles (Table 2). Beginning in October 2003, when the central government enforced the "new short-term" particulate standards on new diesel vehicles, Tokyo began requiring in-use vehicles to meet the previous, "long-range" standards. After the central government began imposing its tougher "new long-range" standards on new vehicles, Tokyo retroactively enforced the "new short-term" targets on all vehicles operating within city limits.

Older vehicles not meeting Tokyo's in-use standard could be brought into compliance through replacement, either with a newer diesel vehicle or a gasoline or alternative-fuel powered alternative, or by retrofit with a TMG-approved particulate control device (i.e. DOC or DPF). Vehicle registration data, along with enforcement surveys carried about by TMG staff, show that both vehicle replacement and retrofit proved to be important compliance strategies.

Figs. 3 and 4 display new registrations and retirements, respectively, of heavy commercial vehicles[7] in various prefectures in Japan from 1999, when Tokyo announced "Operation No Diesel", to 2004, the year after TMG began enforcing its in-use emission standard.[8] New vehicle registrations increased substan-

[7] Because the vast majority of heavy commercial vehicles are powered by diesel fuel (in 2000, 97% in Tokyo), they serve as a useful proxy for diesel-powered vehicles where statistics are not disaggregated by fuel type.

[8] For Figs. 9 and 10, monthly statistics have been aggregated to semiannual data to smooth over seasonal trends in vehicle registration and retirements over the fiscal year. "Unregulated national" statistics were generated by subtracting retirements and registrations in the four prefectures mentioned above, along with the data for Chiba and Saitama Prefectures, which implemented the same regulations as Tokyo and Kanagawa Prefectures.

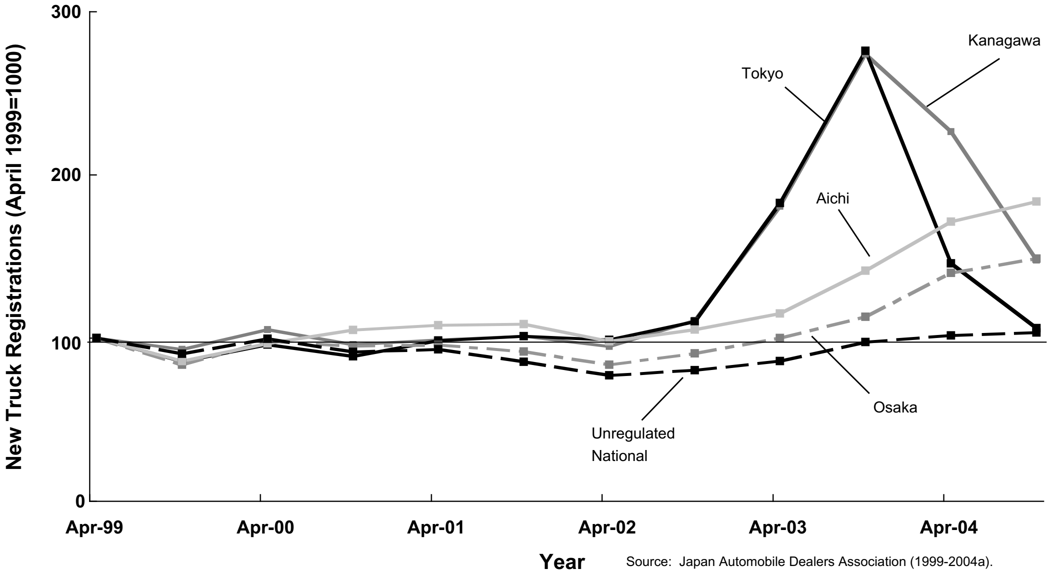

Fig. 3. Relative truck new registrations by jurisdiction, 1999–2004. (See above-mentioned references for further information.)

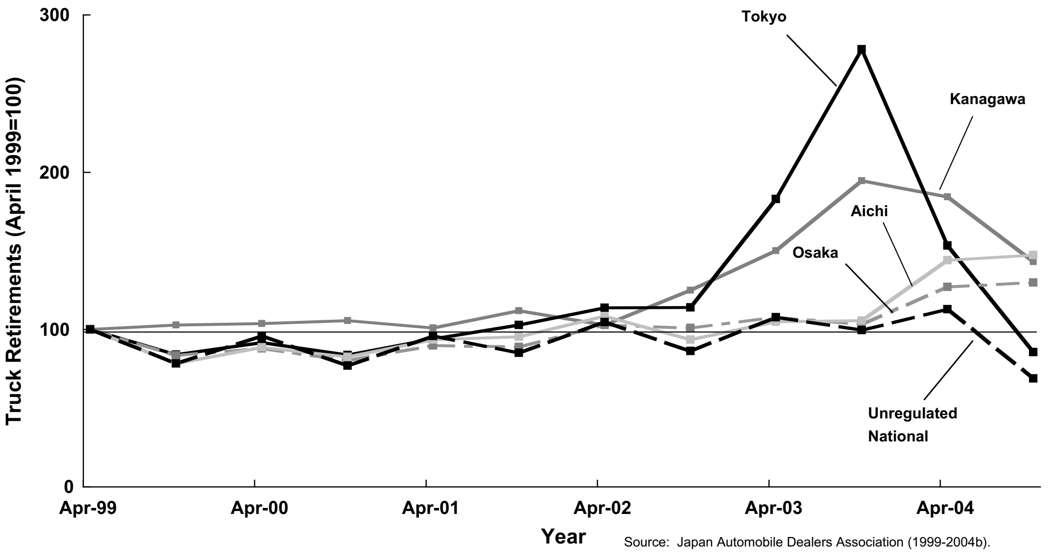

Fig. 4. Relative truck retirements by jurisdiction, 1999–2004. (See above-mentioned references for further information.)

tially between October 2002 and March 2004 in both Tokyo and neighboring Kanagawa Prefecture as they jointly implemented their local in-use standard, peaking in late 2003 at more than 170% above 1999 levels. Vehicle retirements also increased significantly in the second half of 2003: 170% in Tokyo, and 95% in Kanagawa. New registrations in these two prefectures clearly exceeded Aichi and Osaka, which increased only gradually after 2002 in response to the NOx law. For all other prefectures in Japan not covered by the NOx law (labeled ‘‘Unregulated National’’), new truck registrations and retirements were largely unchanged.

Tokyo’s regulations likewise promoted DPF and DOC retrofits.[9] TMG’s Bureau of Environment estimates that 105,000 diesel trucks, buses, and special purpose vehicles registered in Tokyo were retrofit by 2004 – of these, 85% with equipped with oxidation catalysts (Tokyo Bureau of Environment, 2004a). This corresponds to approximately 30% of all diesel-powered trucks, buses, and special purpose vehicles in Tokyo. Based upon on-road and on-site inspections of commercial trucking firms from September 2003 to August 2004, the TMG estimates a compliance rate of 97%: 98% of vehicles registered in Tokyo and 96% of trucks and buses driving into the city from unregulated areas (Tokyo Bureau of Environment, 2004b). Correcting for vehicles complying with the emission standard by model year, this corresponds to approximately 90% of vehicles registered in Tokyo and requiring retrofits having them.

4. Emissions modeling procedure

Each of these policy instruments likely contributed to the recently observed air quality improvements in Tokyo. For this study, we have adapted a model previously used by Japan’s Environment Agency to construct national motor vehicle emissions inventories (Nomura Research Institute, 1998) to estimate the specific contribution of Tokyo’s in-use emission standard.

The model estimates a fleet average annual emission factor (EF) for four vehicle types – light and heavy commercial vehicles, buses, and special purpose vehicles – by weighting empirically determined emission factors disaggregated by GVW, model year, engine and fuel type, and operating speed. That EF is then subsequently combined with prefectural-level vehicle registration and transport demand data (vehicle kilometers traveled, or VKT) to estimate particulate and nitrogen oxide emissions from trucks, buses, and special purpose vehicles registered in Tokyo over a given year.

Table 3 summarizes variables and data sources for the model, which is described in full detail in Appendix B of Rutherford (2006).

This model has several key advantages that make it suitable for estimating the impact of Tokyo’s regulations. Since the key input data are compiled annually and at the prefectural level, the model can estimate emissions at useful temporal and geographic scales. As described below, our analysis takes advantage of the fact that two of the three key regulatory instruments impacting emissions in Tokyo –the NOx law and Tokyo’s local in-use standard – were implemented at different times and in different jurisdictions throughout Japan. This, along with several simplifying assumptions, provides a means of isolating the impact of each regulatory instrument on diesel emissions in Tokyo.

Figs. 5 and 6 depict modeled emissions of particulate matter and NOx, respectively, from diesel-powered trucks, buses, and special purpose vehicles registered in Tokyo from 1996 to 2004. As shown in Fig. 5, modeled annual particulate emissions in Tokyo fell by an estimated two-thirds from 1996 to 2004, from approximately 2800 to 940 metric tons, as a result of tighter central and local emission regulations, reductions in VKT, and the decreased use of diesel engines in light commercial vehicles. Diesel particulate emissions fell particularly quickly after 2002, when Tokyo began on-site inspections for compliance with its regulations: in total, particulate emissions dropped by about one-half from 2002 to 2004. NOx emissions also decreased significantly, falling by approximately 20% over the same period (Fig. 6).

Modeled emissions are well correlated with annual average ambient concentrations of SPM (Fig. 7; R^2 values of 0.90 and 0.91) and NOx (Fig. 8; R^2 values of 0.97 and 0.88) both roadside and at general monitoring stations not located near major roadways. The model estimates a 35% reduction of per kilometer diesel particulate emissions, which is broadly comparable to Ueno et al.’s (2004) empirical estimate of 44% and 39%

[9] Retrofits represented the favored means of compliance with TMG regulations for at least two classes of vehicles: expensive vehicles, such as buses and large special purpose vehicles, manufactured before the 1994 ‘‘short-term’’ emission standards and with relatively long-operating lifetimes; and light and heavy commercial vehicles manufactured between 1994 and 2003 with significant years left in operation.

Table 3
Model variables and data sources

Variable	Dimensions	Scale	Frequency	Source
Model year EF	GVW Engine type Operating speed	National	Once	Nomura Research Institute (2002)
Model year	Vehicle class	Prefectural	Annual	Automobile Inspection and Registration Association (1996–2005a)
Diesel engine share	Vehicle class Freight capacity	Prefectural	Annual	Automobile Inspection and Registration Association (1996–2005b)
GVW	Vehicle Class Registration Type	Prefectural	Annual	Automobile Inspection and Registration Association (1996–2005b)
Vehicle freight capacity	Vehicle class Registration type	Prefectural	Annual	Automobile Inspection and Registration Association (1996–2005b)
Average vehicle loading	Freight capacity	Tokyo	Once	Nomura Research Institute (2002)
Average vehicle weight	Vehicle class Vehicle weight class Registration type	Prefectural	Annual	Estimated from other variables
VKT	Vehicle class Registration type	Prefectural	Annual	Japanese Ministry of Transport (1996–2000) Japanese Ministry of Land, Infrastructure, and Transport (2001–2005)
Fleet freight capacity	Vehicle class Registration type	Prefectural	Annual	Japanese Ministry of Transport (1996–2000) Japanese Ministry of Land, Infrastructure, and Transport (2001–2005)
Road speed distribution	Road type	Urban area	1994, 1997, 1999	Transport Engineering Research Group (1994, 1997, 2001)
VKT share	Vehicle class Vehicle weight class Registration type	Prefectural	Annual	Estimated from other variables
Engine type	Vehicle weight class	National	Once	Japan Clean Air Program (2000)
Retrofit percentage	–	Tokyo	Annual	Tokyo Metropolitan Government (2004b)

reductions in the elemental carbon and SPM[10] emission factors for diesel vehicles in Tokyo over a similar time period.[11]

5. Estimating emission reductions attributable to Tokyo's in-use standard

The emission reductions seen in Figs. 5 and 6 are driven by three major trends – a reduction in particulate and NOx emission factors for new vehicles over time, a decrease in the mean vehicle age due to accelerated fleet turnover, and the spread of DPF and DOC retrofits since 2002 – along with two less important changes: reductions in vehicle kilometers traveled by light and heavy commercial vehicles, and the falling incidence of diesel engines in light and medium-duty trucks.

The first three trends are a direct result of emission control policies: central emission standards make newer vehicles cleaner over time; fleet turnover has accelerated in response to the NOx law and Tokyo's in-use emission standard; and particulate aftertreatment technologies were actively promoted by TMG policy.

[10] The SPM emission factor includes both the non-elemental carbon fraction of DEP (organic carbon and inorganic matter) as well as particulates associated with mechanical forces (e.g. resuspension of road dust and emissions from braking). The Ueno study did not include special purpose vehicles, and the model emission factors presented have been adjusted to provide a fair comparison.

[11] The modeling approach is expected to be conservative for two reasons. First, according to TMG staff, most owners of non-compliant vehicles, faced with the need to meet different in-use emission standards for PM in 2003 and 2006, chose to retrofit their vehicles to meet the later, more stringent standard. Second, the model assumes that vehicle owners installed retrofits at a constant rate from April 2003 to March 2004, rather than what was observed, namely, high compliance rates well before enforcement began in October 2003. If we assume that all retrofits for the 2003 fiscal year were made by October 2003 and were able to meet the 2006 standard, the 2003 estimated PM emission factor would be 102 mg/km, a 39% reduction from 2001 values.

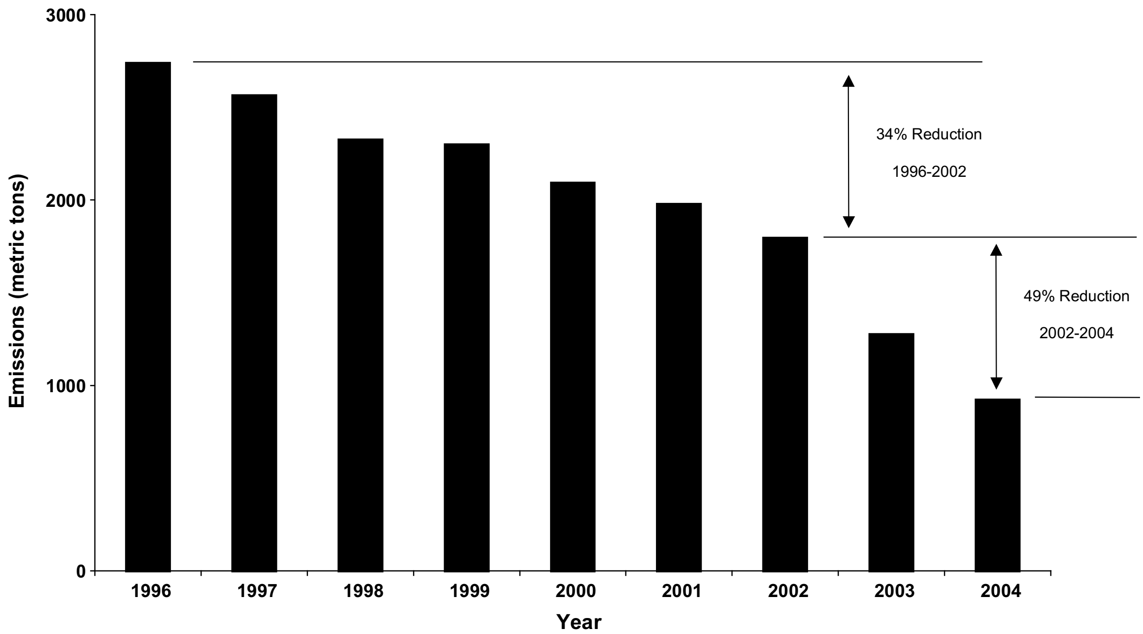

Fig. 5. Estimated on-road diesel particulate emissions in Tokyo, 1996–2004.

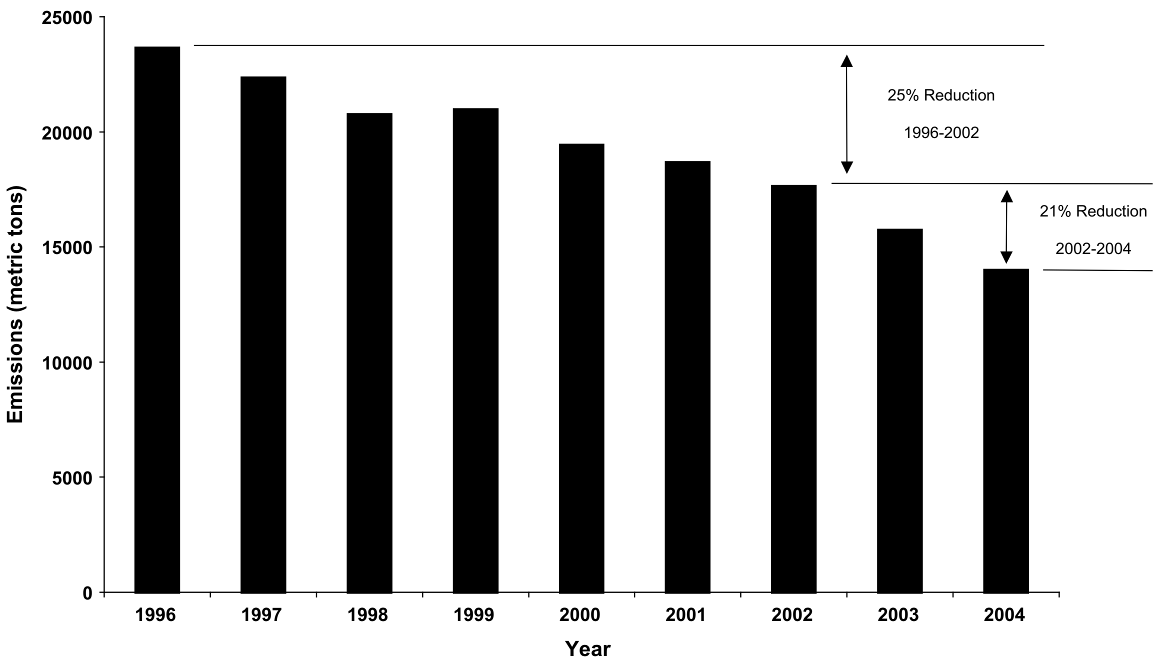

Fig. 6. Estimated on-road diesel NOx emissions in Tokyo, 1996–2004.

In contrast, the relationship between individual emission control regulations and changes in VKT and the diesel engine share is complicated by a variety of intervening variables. For this reason, we assume that the reg-

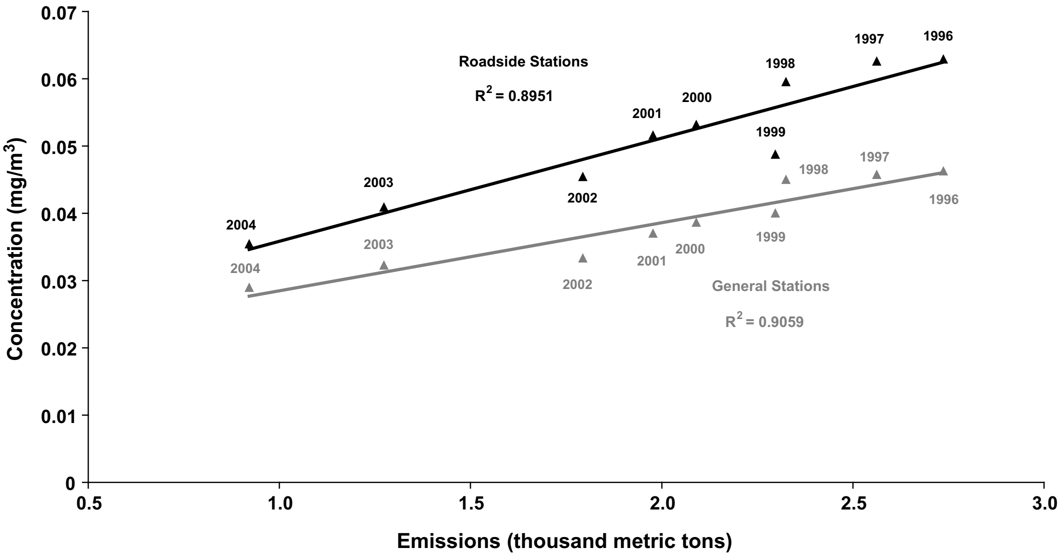

Fig. 7. On-road diesel particulate emissions and SPM concentrations in Tokyo, 1996–2004.

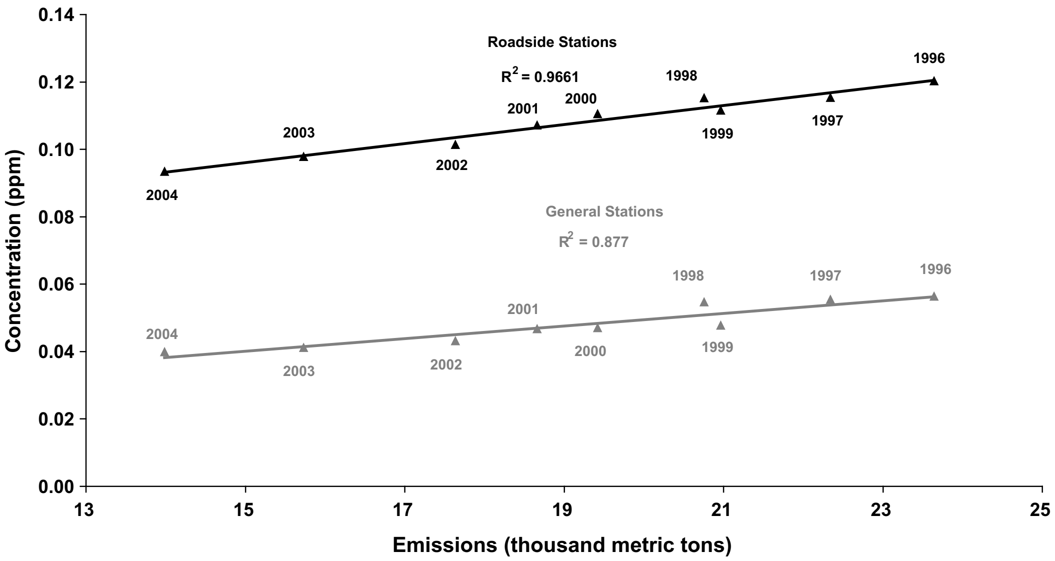

Fig. 8. On-road diesel NOx emissions and ambient NOx concentrations in Tokyo, 1996–2004.

ulations analyzed in this paper influence neither transport demand nor the incidence of diesel engines in commercial vehicles.[12]

This assumption – that central and local emission control policies do not impact emissions by reducing VKT or the use of diesel engines – should lead to an underestimation of the impact of Tokyo's in-use emission

[12] See Rutherford (2006) for a more detailed justification for the exclusion of VKT and diesel engine share from this analysis.

standard. Since the enforcement of that standard imposes substantial costs on the use of diesel vehicles, to the extent it influence transport demand and the share of diesel engines used in commercial vehicles, we expect it would do so in a negative manner. Neglecting changes in these variables, by holding them constant in the emissions model, should thus provide a conservative estimate of the regulations' overall effects.

Estimating the impact of DPF and DOC retrofits under TMG policy is relatively straightforward owing to the fact that Tokyo's in-use emission standard was enforced through model year restrictions: in October 2003, vehicles manufactured after 1996 could no longer being registered or operated in Tokyo without aftertreament retrofits. We therefore assume that vehicles manufactured after those dates and still registered in Tokyo in 2003 and 2004 are retrofit in proportion to TMG compliance estimates and emit particulate matter at levels required for DPF and DOC certification (i.e. in 2003, on average at the levels of the central government's "long-term" emission standard of 0.25 g/kWh).

Estimating emissions reductions due to vehicle turnover is more challenging, since the three regulatory instruments introduced above all impact pollution through vehicle replacement: central emission standards as natural turnover makes vehicles cleaner over time, and the NOx law and Tokyo's in-use standard by promoting turnover in excess of natural levels. Our model, by leveraging temporal and geographic variations in the implementation of local and national diesel emission regulations, provides a means to apportion the relative emissions benefits of vehicle turnover to individual policy instruments.

Table 4 summarizes when each of these three policy instruments were enforced in four urban prefectures – Tokyo, Kanagawa, Osaka, and Aichi – as well as at the national level. (Fig. 9 also identifies the relative location of each jurisdiction within Japan.) As that table indicates, national vehicle emission standards were implemented simultaneously across all jurisdictions, while the NOx law and Tokyo's local in-use emission standards were implemented differently in different jurisdictions.

Rates of vehicle turnover in these five jurisdictions are strongly correlated with the set of policy instruments in effect in each area. Between 1993 and 2001, Tokyo, Kanagawa, and Osaka, each regulated under both central emission regulations and the NOx law, experience very similar (and accelerated) rates of vehicle turnover, leading to fleets noticeably newer than those registered in areas not falling under the NOx law. After 2002, vehicle turnover in Aichi accelerated as it was added to the revised NOx law, with average fleet age converging with that of Osaka. The same year, the large increases in vehicle retirement and replacement in Tokyo and Kanagawa shown in Figs. 3 and 4 led mean vehicle age, and consequently, fleet average emission factors for PM and NOx, to fall rapidly in those two prefectures.

This relationship is shown in detail in Figs. 10 and 11. Fig. 10 illustrates model estimates for particulate emission factors for diesel trucks, buses, and special purpose vehicles registered in Tokyo using fleet turnover rates from the five jurisdictions shown in Table 4. The lowest black line corresponds to Tokyo's actual modeled emission factor without retrofits, with the other four lines corresponding to the particulate emission factors of Tokyo's fleet after assigning it the fleet age distribution of Kanagawa, Osaka, and Aichi Prefectures, and the national average, respectively. Fig. 11 shows the same treatment for NOx.

In both Figs. 10 and 11 the lines labeled Tokyo and Kanagawa are practically identical, as expected given the understanding that both prefectures faced the same national and local regulations. The line for Osaka tracked the line for Tokyo until 2002, after which time truck and bus owners in Tokyo began to bring their vehicles into compliance with TMG's regulations. Furthermore, the line for Aichi tracked the Unregulated National line until 2001, diverging in 2002 only when Aichi was brought under the NOx law. The line for Aichi converged with that for Osaka in 2004, at which time the two prefectures shared a common set of central regulations (and no local regulations). Figs. 10 and 11, which also show key dates of regulatory implementation,

Table 4
Regulation implementation timing by jurisdiction

Policy	Year of initial implementation				
	Tokyo	Kanagawa	Osaka	Aichi	National
Central emission standards	1994	1994	1994	1994	1994
NOx law	1993	1993	1993	2002	–
Local in-use standard	2003	2003	–	–	–

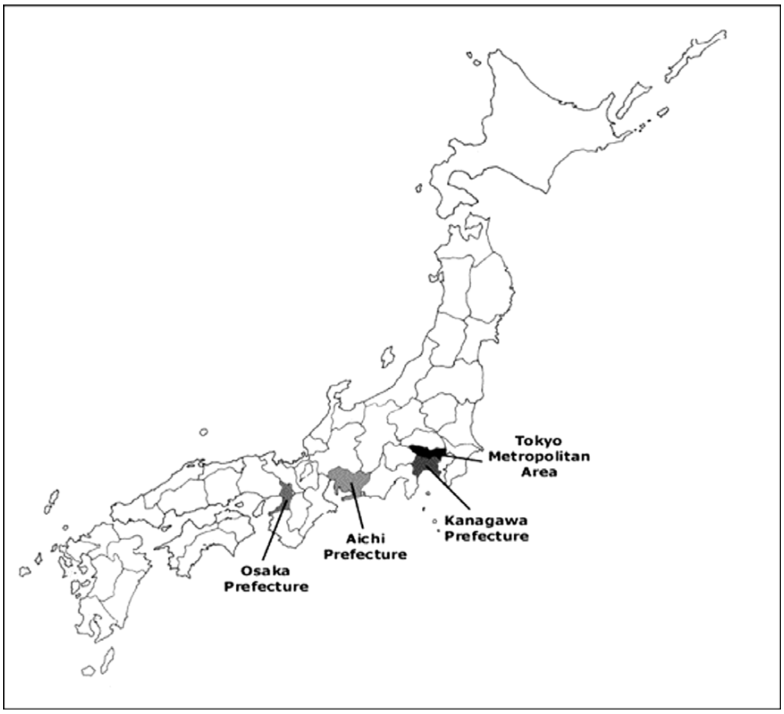

Fig. 9. Location of regulated areas.

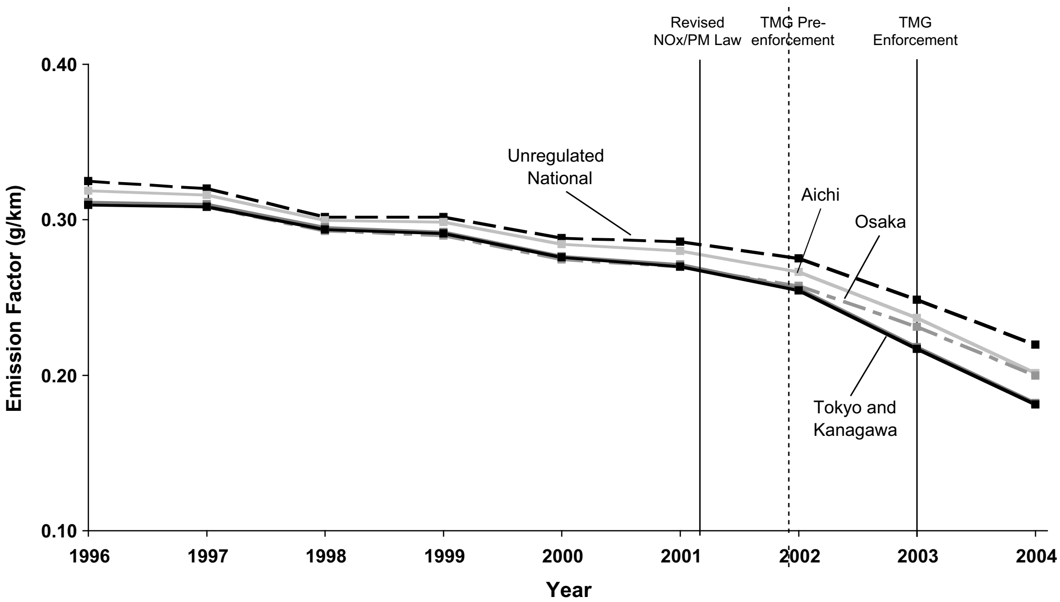

Fig. 10. Calculated particulate emission factor by jurisdiction, 1996–2004.

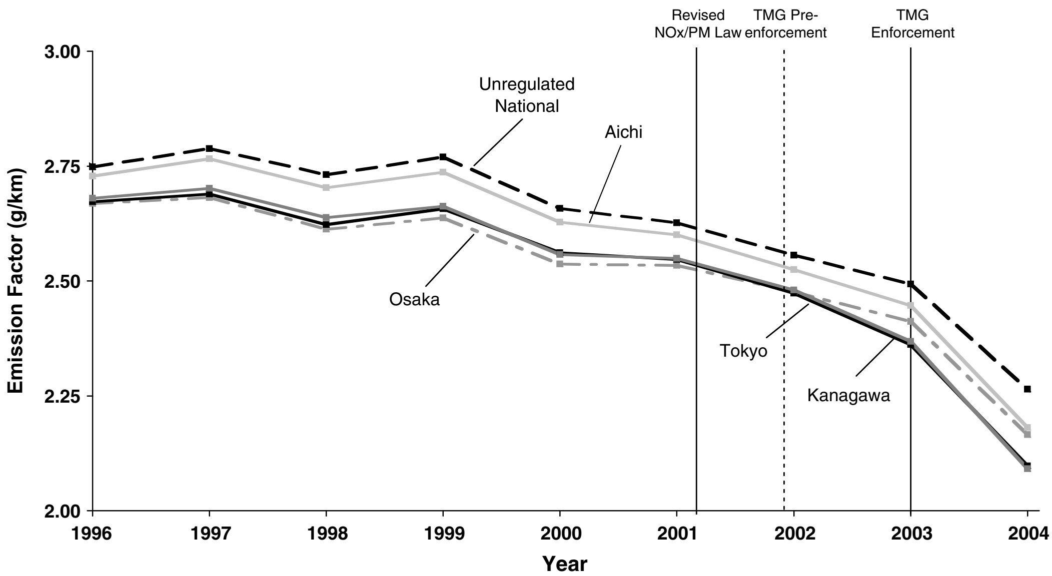

Fig. 11. Calculated NOx emission factor by jurisdiction, 1996–2004.

suggests that a strong correlation exists between emission factors and the particular set of applicable central and local regulations.[13]

To apportion policy-driven emission reductions to either central emission standards, the NOx law, or Tokyo's local diesel regulations, we have adopted the following assumptions:

- Without Tokyo's in-use standard, fleet age in Tokyo would approximate the Osaka average, where vehicles were regulated under the NOx law and central emission standards for new vehicles.
- Absent both Tokyo's in-use standard and the NOx law, fleet age in Tokyo would approximate the national average.
- New vehicles manufactured after 1994 would continue to emit at the rate of model year 1993 vehicles absent tougher central emission standards.

These assumptions allow us to estimate policy-related reductions by modeling emission levels in Tokyo under a variety of hypothetical alternate regulatory regimes. Fig. 12 shows estimated particulate emission factors in Tokyo from 1996 to 2004 after replacing the prefectural labels on Fig. 10 with labels representing alternative regulatory regimes in accordance with the three assumptions above. Two additional lines have also been added: a line labeled "TMG regulations" representing Tokyo's actual emission factor after accounting for DPF and DOC retrofits, and a line labeled "No 1994 Standards" derived by holding model year emission factor constant at 1993 levels.[14]

The four numbers on the far right-hand side of Fig. 12 demonstrate how we estimated the individual contributions of these three regulations to recent air quality improvements in Tokyo – in essence, by subtracting one policy instrument at a time and calculating the resulting increase in the average emission factor. Multiply-

[13] There is a reasonable level of divergence between Aichi's NOx emission factor and that of the national level prior to 2002 using Tokyo's set of static and exogenous variables. If anything, this should lead to an overestimation of the impact of the NOx law on NOx emissions in Tokyo.

[14] The discontinuities in the "No 1994 Standards" line result from year-to-year variations in other model variables, notably VKT and diesel engine share.

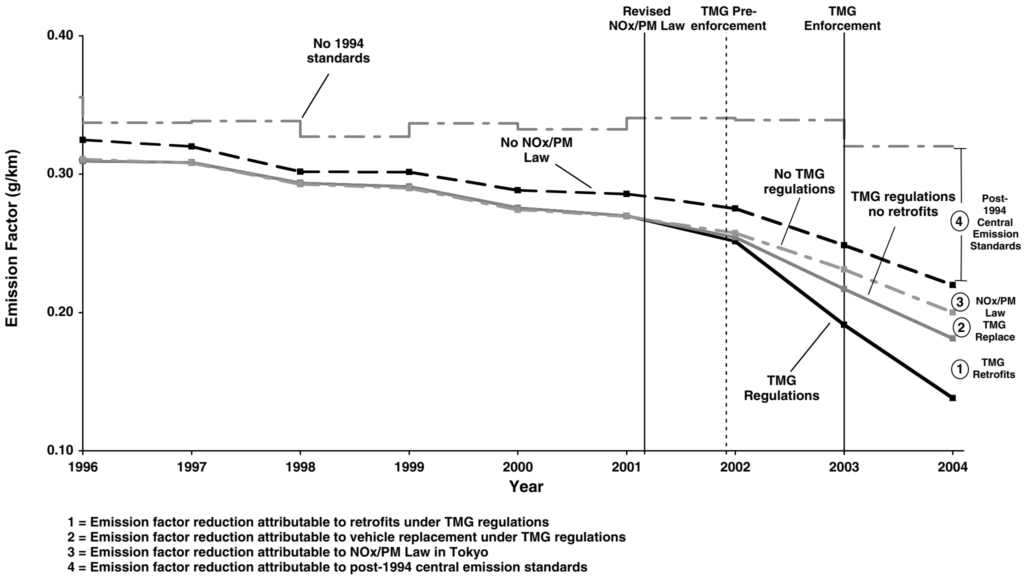

Fig. 12. Effect on particulate matter emission factor in Tokyo by regulation, 1996–2004.

ing this increase by Tokyo's VKT yields the corresponding emission reduction benefit of each policy in a given year.

The impact of retrofits under TMG regulations is estimated by subtracting emissions under TMG regulations with retrofits from emissions without retrofits, the distance marked with a circled 1. The impact of vehicle replacement under TMG regulations can likewise be estimated by comparing emissions without retrofits to emissions without Tokyo regulations entirely; this calculation is represented by the distance designated with a circled 2. Similar estimations may be made in conjunction with distances represented by circles 3 and 4, corresponding to the impacts of the NOx law and tighter new vehicle emission standards after 1994, respectively.

6. Interpretation of model results

Tables 5 and 6 illustrate the air quality impact of Tokyo's in-use particulate standard by showing emission reductions attributable to each local and central regulatory instrument from 2001 to 2004. To facilitate comparison, all emission reductions are calculated relative to a hypothetical "no-regulation" case corresponding to emission levels in the absence of local and central emission regulations after 1993.

Absent central and local regulations, the model predicts that particulate emissions in Tokyo in 2004, the first full fiscal year in which Tokyo's local regulations were enforced, would have been approximately 2000 tons. New vehicle emission standards alone reduced emissions to around 1500 tons, a 26% decrease. The

Table 5
Unregulated DEP emissions and emission reductions by policy instrument, 2001–2004

Year	Unregulated emissions (tons)	% reductions from				
		New vehicle standards	NOx law	Tokyo Metropolitan Government Regulations		
				Replacement	Retrofit	Total
2001	2500	16	5	0	0	0
2002	2400	19	5	1	1	2
2003	2100	22	5	4	8	12
2004	2000	26	7	6	15	21

Table 6
Unregulated NOx emissions and emission reductions by policy instrument, 2001–2004

Year	Unregulated emissions (tons)	% reductions from				
		New vehicle standards	NOx law	Tokyo Metropolitan Government Regulations		
				Replacement	Retrofit	Total
2001	21,000	9	3	0	0	0
2002	20,200	10	3	0	0	0
2003	18,800	11	3	2	0	2
2004	17,500	14	4	3	0	3

NOx law caused an additional reduction of 7%, to 1330 tons. The combined effect of vehicle replacement and retrofit under TMG regulations cut emissions to approximately 920 tons, or an additional 21% from unregulated levels. Results for NOx are also shown in Table 6. Tokyo's diesel regulations, which formally covered only particulate emissions, also had a modest impact on NOx emissions by accelerating vehicle replacement.

The results in Tables 5 and 6 allow us to draw three conclusions regarding the relative contribution of individual regulations to improved air quality in Tokyo. First, TMG deserves significant credit for recent improvements. TMG's in-use standard reduced primary particulate emissions from diesel-powered trucks, buses, and special purpose vehicles registered within Tokyo by 270 metric tons in 2003, and by 410 tons in 2004, the first full year of implementation. This represents a 17% and 31% reduction from emissions levels without local regulations in 2003 and 2004, respectively.[15] The modeling approach suggests that the bulk of emissions reductions in Tokyo after 2002 directly attributable to environmental regulations – 70% for particulate matter, and 30% for NOx – were caused by TMG's local regulations.

Second, results in the two tables suggest that, in terms of emission reductions, Tokyo's in-use standard compares favorably to central regulations, particularly when considering the period of time over which each was implemented. By the second full year of implementation, Tokyo's retrofit regulations had reduced diesel particulate emissions by amounts comparable to those achieved by the national emission standards for PM (21% for TMG's local retrofit regulations, versus 26% for central emission standards), and cut NOx emissions by about as much as the NOx law (3% versus 4%, respectively), despite both of these central regulations having been implemented more than ten years prior.

Finally, our modeling suggests that pollution control retrofits represent a viable policy alternative to vehicle replacement in controlling in-use emissions. In total, the model suggests that incremental emission reductions attributable to particulate control retrofits were substantially larger than reductions from natural and accelerated vehicle replacement (270 tons versus 180 tons, respectively) from 2002 to 2004.[16] The finding that TMG's promotion of DPF and DOC retrofits for in-use vehicles was effective in reducing local particulate emissions should be of great interest to the growing numbers of governments worldwide considering similar retrofit programs.

Acknowledgements

The authors would like to thank the staff of the Tokyo Bureau of Environment, in particular Teruyuki Ohno, Masa Ohara, Yuko Nishida, and Toshiko Chiba, for their aid in collecting the data necessary for this paper. Thanks goes as well to Duc Wong for her help in preparing this manuscript. This research was conducted with the generous financial support of the Japan US Educational Commission, the Japan Fund, the Stanford Center for East Asian Studies, the UPS Foundation, and the Shorenstein Asia Pacific Research Center.

[15] Reductions would have been somewhat higher if particulate emission reductions associated with the introduction of low-sulfur fuel in 2003, which Rutherford (2006) shows to be a direct result of "Operation No Diesel," had been included in these estimates.

[16] In 2004, vehicle replacement under Tokyo's retrofits reduced particulate emissions by approximately 100 tons more than in 2002, while incremental reductions due to central emission standards and the NOx/PM Law totalled 70 and 10 tons, respectively.

References

Automobile Inspection and Registration Association, 1996–2005a. Jidousha hoyuu sharyousuu, hatsu tourokunen betsu (Motor vehicle ownership by year of first registration), Tokyo.
Automobile Inspection and Registration Association, 1996–2005b. Jidousha hoyuu sharyousuu, shobunbetsu (Motor vehicle ownership by category), Tokyo.
Environment Agency, 1999. Heisei 10 nendo ippan kankyou taiki sokutei kyoku sokutei kekka (Monitoring results for general air pollution monitoring stations, 1998), Tokyo.
Japan Automobile Dealers Association, 1999–2004a. Jidousha touroku toukei jouhou, shinshahen (Motor vehicle registration statistical information: new car edition), Tokyo.
Japan Automobile Dealers Association, 1999–2004b. Jidousha touroku toukei jouhou, chuukohen (Motor vehicle registration statistical information: used car edition), Tokyo.
Japan Clean Air Program, 2000. Dhiizeru kihaisha taisaku no taikishitsu he no eikyou hyouka houkokusho (Air quality impact assessment of countermeasures against in-use diesel vehicles), Tokyo.
Japanese Ministry of Land, Infrastructure, and Transport, 2001–2005. Jidousha unsou toukei chousa nenpyou (Annual survey of motor vehicle transport statistics), Tokyo.
Japanese Ministry of Land, Infrastructure, and Transport, 2005. Rikuun toukei youran (Survey of land transport statistics), Tokyo.
Japanese Ministry of the Environment, 2002. Heisei 13 nendo ippan kankyou taiki sokutei kyoku sokutei kekka (Monitoring results for general air pollution monitoring stations, 2001), Tokyo.
Japanese Ministry of Transport, 1996–2000. Jidousha unsou toukei chousa nenpyou (Annual survey of motor vehicle transport statistics), Tokyo.
Nishikawa, N., 1993. NOx kisei ni tsuite (Regarding the NOx regulations). Kankyou to Kougai (Environment and Pollution) 23, 58–63.
Nomura Research Institute, 1998. Jidousha haishutsu gasu gentani oyobi souryou ni kan suru chousa (Survey of motor vehicle emission factors and aggregate emissions), Tokyo.
Nomura Research Institute, 2002. Jidousha haishutsu gasu gentani oyobi souryou ni kan suru chousa (Survey of motor vehicle emission factors and aggregate emissions), Tokyo.
Rutherford, D., 2006. Policy Change in Japan: The Tokyo Metropolitan Government's Regulation of Diesel Emissions. Stanford University.
Tokyo Bureau of Environment, 2003. Toukyouto no dhiizeru taisaku: kuni no taiman to to no seika (The Tokyo metropolitan government's diesel policy: national neglect, local solutions), Tokyo.
Tokyo Bureau of Environment, 2004a. Mitsui bussan (kabu) ni yoru DPF souchi shitei mousei ni atatte no kyogi deeta no shiyou ni tsuite (Regarding the use of false data in DPF certification applications by Mitsui and Co.), Tokyo.
Tokyo Bureau of Environment, 2004b. Kisei kaishi 1 nen no ihan dhiizerusha torishimari kekka nit suite (Regarding the results of the first year of controlling non-compliant diesel vehicles).
Tokyo Bureau of Environment, 2004c. Heisei 15 nendo taiki osen jyoukyou no sokutei kekka ni tsuite (Regarding the 2003 air pollution monitoring survey), Tokyo.
Tokyo Bureau of Environment, 2005. Heisei 16 nendo taiki osen jyoukyou no sokutei kekka ni tsuite (Regarding the 2004 air pollution monitoring survey), Tokyo.
Tokyo Bureau of Environment, 2006. Heisei 17 nendo taiki osen jyoukyou no sokutei kekka ni tsuite (Regarding the 2005 air pollution monitoring survey), Tokyo.
Transport Engineering Research Group, 1996. Heisei 6-nendo douro koutsuu sensasu (Road transport census 1994), Tokyo.
Transport Engineering Research Group, 1999. Heisei 9-nendo douro koutsuu sensasu (Road transport census 1997), Tokyo.
Transport Engineering Research Group, 2001. Heisei 11-nendo douro koutsuu sensasu (Road transport census 1999), Tokyo.
Ueno, H., Ishii, K., Hoshi, J., Kurita, K., Amano, S., Mitsuya, R., Kinoshita, T., Nakagawa, T., Ihara, M., 2004. Evaluation of the diesel emissions control regulation by a road tunnel study. In: Tokyo Research Institute for Environmental Protection. Annual Report 2004, Tokyo.