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Climate change mitigation and co-benefits of feasible transport demand policies in Beijing

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ABSTRACT

Urban car transportation is a cause of climate change but is also associated with additional burdens such as traffic congestion and air pollution. Studies of external costs and potential impacts of travel demand management help to define policy instruments that mitigate the damaging impact of transportation. Here, we analyze different externalities of car transportation in Beijing and show that social costs induced by motorized transportation are equivalent to about 7.5–15.0% of Beijing's GDP. Congestion and air pollution contribute the most with climate change costs being the most uncertain. We show that a road charge could not only address congestion but also has environmental benefits. The paper investigates the role of demand elasticities and demonstrates that joint demand and supply-side policies provide considerable synergies.

1. Introduction

To avoid the possibility of irreversible catastrophic effects of climate change CO_2 concentration must be reduced from 385 ppm to at most 350 ppm (Hansen et al., 2008). This translates into rapid transformation of all economic sectors. In 2004, transport was responsible for 23% of world energy-related greenhouse gas emissions (GHG) and 74% of these were induced by road vehicle usage. Transport's emissions have increased at a faster rate than any other sector over the past decade (Kahn Ribeiro et al., 2007) and an 80% increase by 2030 is expected in the business-as-usual scenario (International Energy Agency, 2004). Although climate change mitigation is a major global concern, local environmental consequences and economic disbenefits of transportation are dominant at specific locations.

The situation in China is important for being the most populous country in the world and special for several reasons. In 2006, the transportation sector emitted only about 9% of the countries GHG emissions, well below the level of OECD countries (Wagner et al., 2006). However, the rapid growth rate in vehicle ownership – 570% from 1990 until 2006 (China Statistical Yearbook, 2007) – and air traffic demonstrates converging dynamics (Wagner et al., 2006). Beijing is a focal point: here, 1% of China's population drives 10% of China's vehicles (Beijing Statistical Yearbook, 2007).

China is rapidly urbanized; the urbanization rate increased from 17% in 1975 to 35% in 2000 (Chen et al., 2008). Chinese cities have relatively high population densities and traditionally have mixed-use, ease of non-motorized access to good and services. However, with low-density homocentric urban sprawl population density of cities is generally decreasing. Partially due to lack of integrated planning, settlement in the urban fringe heavily depend on the mother city, and, hence, transportation demand increases significantly. At the same time, urban sprawl puts additional pressure on China's land resources – already extremely scarce in comparison to world average (10% of available area for 21% of the world population,

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Chen et al., 2008). Rapid motorization, in combination with high population density in inner cities, entails massive environmental and economic problems. In Beijing, vehicles increased from 1.2 million in 2000 to 2.5 million in 2005 and 3.5 million in 2008. Air pollution has become one of the leading causes of deaths, outdoor air pollution alone leading to more than 400.000 premature deaths each year in China (Watts, 2005). In Tianjin, a municipality neighbouring Beijing, air pollution is associated with $1.1 billion, i.e. 3.7% of Tianjin's GDP, in terms of health costs in 2003 (Zhou and Tol, 2005). In Zhaozhuang, a city heavily dependent on coal, annual health costs accumulate to 10% of the GDP in 2000 (Wang and Mauzerall, 2006). As low-grade coal heating is successfully pushed back in Beijing and other cities, vehicle emissions become the main source of air pollution (Deng, 2006).

Urban vehicle traffic leads also to congestion. Costs of congestion manifest themselves economically in value-of-time: every additional car causes delay for other cars – time costs that are usually not accounted for by the individual car driver. Chinese cities are characterized by dense cities and rapid motorization, in this combination effectively resulting in massive congestion in inner cities that cannot be compensated even by immense road construction programmes. Congestion and road building not only affect car drivers but also cause delay for bus passengers and create barriers for pedestrians and cyclists.

Car noise is a major motivation for traffic management in Europe, but it is unclear how bothering traffic noise is in China. Traffic accidents are another major concern: China has the largest number of road deaths in the world, around 110.000 a year (Liren, 1996). So far, Beijing has invested in subway system extension and introduced vehicle restrictions based on the end number of the licence plate. However, absolute and significant emission reduction in the transportation sector can only be achieved by transportation demand management measures that include price signals (European Environmental Agency, 2008).

Some disbenefits like air pollution are external, others like congestion are internal to the transportation system. Demand management has been used to address disbenefits that are internal to the transportation system. Here, we compare environmental and economic disbenefits of urban car transportation in a single framework. We investigate if and how demand management can also be utilized to address environmental externalities. We furthermore explore how demand and supply-side instruments provide significant synergies.

2. Sources of external costs

In the following, we assume a conventional strict market-based perspective that aims to identify macro-economic inefficiencies. Environmental and social outcomes are projected into the economic dimension by means of value-of-time (VOT) and willingness-to-pay (WTP) functions. Such a methodology is subject to ethical considerations but allows the comparison of different disbenefits in one framework. If social cost values were not known for Beijing or China, values were adapted from European state-of-the-art values (Maibach et al., 2007), assuming the 2005 exchange rate of €1equals 10 RMB ($1 = 8.3 RMB). Uncertainties exist for most input values and calculations are partially assumption dependent; all input values are set out in Table 1. As the highest uncertainty is in how to translate social costs into monetary values, we have specified a plausible range of values for WTP-values by varying income elasticities and VOT-values. For climate change, the uncertainty is reflected in the price per tCO_2. For every disbenefit, we specify three different scenarios (low, medium, high) varying the corresponding social cost parameter. The lower estimates are specified in the following paragraphs. An overview on all scenarios is given in Table 2. The uncertainties can partially be attributed to the difficulty of converting social costs into monetary values. Distributional effects are crucial in the design of a city toll but would extend the scope of this paper.

2.1. Air pollution

Air pollution leads to adverse health costs, deterioration of buildings, and crop losses may have negative impacts on ecosystems (Maibach et al., 2007). Here, we only include adverse health effects – estimated to be the most important cost driver. Adverse health costs are caused by particulate matter (PM10 or PM2.5). The concentration of PM10 may be used as a proxy for health-affecting pollutants. Also needed is an estimate of the relative part of this concentration caused by motorized transport. The most important cost drivers are receptor density, for example population density, and emission standards of vehicles. Exposure-response functions relate PM10 levels to health effects such as premature death due to lung cancer, and chronic bronchitis and asthma. Health effects must then be converted to monetary values, e.g., by relying on willingness-to-pay studies.

Based on such a methodology Deng obtained a value of C_{AP2000} equal to $974 million of the health impact of air pollution (PM10) caused by motor vehicle emissions in Beijing in 2000 (Deng, 2006). This value must be adapted for the population growth of 12.8% and GDP growth of 88.4%. The latter implies a higher monetary value of life. Whereas unity is often used for the income elasticity with respective to health cost of air pollution in China may be up 1.4 (Wang and Mullahy, 2006). Furthermore, the number of motor vehicles rose from 1.24 million in 2000 to 2.46 million in 2005 (Beijing Statistical Yearbook, 2007). New vehicles are assumed to be produce 62.5% less PM10 then the existing fleet, corresponding to a transition from EURO II to EURO III norm (Maibach et al., 2007). This assumption is very optimistic, as EURO III was only introduced within 2005. The effect of the marginal change in speed on air pollution costs is of relatively minor

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Table 1
The Input values assumed.

Source of external cost	Variable	Value	Description	Source
Congestion	D	23.000	Average distance driven (km/car/a)	BJTRC 2007
	N	2.58 m	Number of vehicles	BJSYB 2007
	$Q = d*N$	59.3 10^9	Road usage (km/year)	derived
	F	0.72	Fraction of q inside city	BJTRC, internal model
	I_{fix}	0.44	RMB/km	BJTRC 2007
	Q_c	42.7 10^9	Road usage city (km/a)	Derived
	a	45	Speed free roads (km/h)	Estimation
	s	21.5	Speed (km/h)	BJTRC 2005
	n_p	1.13	Effective car occupation	BJTRC 2005
	VOT	[31.4 40.0 50.3]	Value-of-time (RMB/h)	BJTRC 2005
Bus speed	s_b	10	Speed (km/h)	CSTC, 2006
	a_b	18	Speed free roads (km/h)	CSTC, 2006
	Q_b	22.3 10^9	Road usage city (km/a)	Beijing Bus Group (2007)
	VOT_b	[5.8 8.2 10.6]	Value-of-time (RMB/h)	BJTRC 2005
Air pollution	C_{AP2000}	974 10^6	Cost of air pollution in 2000 in million $	Deng (2006)
	I_{adj}	1.56	(Income p. head 2005)/(income p. head 2000)	BJSYB 2007
	P_{adj}	1.128	(Population 2005)/(population 2000)	BJSYB 2007
	E_{rel}	3/8	Relative pollution efficiency of added veh.	Maibach et al. (2007)
	Car_{adj}	1.06	(# added veh. till 2005)/ (# veh. 2000)	BJSYB 2007
	ε	[1 1.2 1.4]	Income elasticity	Maibach et al., 2007; Wang and Mullahy, 2006
Climate change	$Q_c = Q$	42.7 10^9	Road usage inside city (km/year)	Derived
	E_{fuel}	210	Fuel efficiency (gCO2/km)	An and Sauer (2004)
	C_t	[15 70 280]	Cost in €/tCO_2	DLR (2006)
Accidents	N_f	1289	# fatalities	BJTRC 2007
	N_I	5536	# severe injuries	BJTRC 2007
	R_f	1.1	Underreporting fatalities	Jacobs et al., 2000, estimation
	R_I	1.5	Underreporting injuries	Maibach et al. (2007)
	C_f	1.500.000	Value of life (€)	Maibach et al. (2007)
	C_I	100.000	Value severe injury (€)	Maibach et al. (2007)
	ε	[1 1.2 1.4]	Income elasticity	As above
	κ	0.25	Fraction unsecured	Maibach et al. (2007)
Noise	L	69	Noise level in dB (A)	BJTRC 2007
	P	9.77	Population	BJSYB 2007
	p_{aff}	0.4	Affected proportion	Own estimation
	C_N	167	Costs of noise/cap. (€/a)	Maibach et al. (2007)
	ε	[1 1.2 1.4]	Income elasticity	As above

Table 2
The basic scenarios used.

	Low	Median	Upper
Air pollution	**19.8**	23.8	27.8
Climate Change	**1.4**	6.6	26.3
Noise	**0.9**	1.0	1.2
Congestion	**22.8**	29.7	36.6
Bus speed	**5.8**	8.1	10.5
Accidents	**1.0**	1.2	1.4
Total	**51.7**	70.4	103.8

Note: All values are in billion RMB. Gray background denotes environmental externalities. White background denotes user externalities internal to the transportation system.

(Maveres et al., 1996); the 24 billion RMB effect corresponds to 3.5% of GDP in line with Zhang et al. (2007) who calculate that air pollution, also including coal combustion, dust and other sources, caused health costs of about 7% of the GDP in 2004.

2.2. Climate change

The climate change mitigation cost is estimated via the fuel consumption (mileage inside Beijing divided by fuel efficiency in km per litre). This estimate represents the global costs of GHG emissions from Beijing car transportation and is different to the climate change costs that will be experienced by the Beijing population. The estimate of the fuel efficiency is

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taken to be E_{fuel} = 210 g CO_2/km relying on An and Sauer (2004). The cost of greenhouse gas (GHG) emissions per ton of CO_2 can be estimated by either stating avoidance costs, i.e., the cost of not emitting a certain amount of GHG given a certain reduction scenario, or by estimated damage costs. Here we are interested in evaluating external costs. Hence, we focus on damage costs of GHG emissions. Uncertainty of damage cost is high as, first, climate change impact can only be predicted with limited accuracy and, second, valuation of social cost is uncertain and socially contingent. Potential catastrophic events are not included in many studies. Here, we rely on the most recent study that estimates a range of damage cost of €15 to 280/tCO_2 with €70/tCO_2 as recommended value (Deutsches Zentrum für Luft- und Raumfahrt, 2006). The social costs of climate change amount to 1.4 billion RMB/a for €15/tCO_2 – a very low estimate.

2.3. Noise

The average noise level induced by car traffic is around 69 dB(A) both in inner and outer districts (Beijing Transportation Research Center, 2007). Car density in inner districts is 4–5 times higher than in outer districts, whereas speed is higher in outer districts. The health costs at these noise levels is estimated to be around €167 per year per affected person (Maibach et al., 2007). The population of the eight districts inside the 6th ring is 9.77 million inhabitants. We assume that only 40% of this population is affected by these noise levels. The health or stress cost per person is adapted for GDP values with income elasticities between 1 and 1.4, resulting in social costs of noise caused by this yields a costs of noise are around 0.9 billion RMB/a. It should be noted that this social cost needs most additional research as noise measurements are scarce and willingness-to-pay for noise reduction has not been investigated in China.

2.4. Congestion

Congestion is internal to the transportation system and is not an environmental disbenefit. However, congestion constitutes an important motivation for integrated transportation demand management and, hence, is part of this analysis. The social costs of congestion in value-of-time are 22.8 billion RMB/a for car drivers. Additionally, the value-of-time lost in bus transportation due to car congestion amounts to 5.8 billion RMB/a. Assumptions and calculations are detailed in Appendix A.

2.5. Traffic accidents

In 2005, 1289 people died as a consequence of car accidents and 5536 were severely injured (Beijing Transportation Research Center, 2007). The rates of underreporting were estimated to be 1.02 and 1.5 in the European Union (Maibach et al., 2007), but the rates for fatalities in East Asia is known to be much higher, 1.25 being a lower estimate (Jacobs et al., 2000) and 1.4 has been suggested for China (Liren, 1996). As we assume relatively high standards of monitoring in Beijing, the rate of underreporting for fatalities is assumed to be 1.1 and 1.5 for severe injuries. The values of life and severe injuries in Europe are €1.5 million and €0.1 million, respectively (Maibach et al., 2007). Furthermore, we conservatively assume that 75% of accident costs are covered by insurances with 25% external. The social costs of accidents thus amount to 1 billion RMB/a.

2.6. Total external costs

The external costs of motorized transport in Beijing are summarized in Table 2. Three different scenarios are distinguished: a low, a medium and an upper estimate of social costs. For the three different scenarios, we varied the parameter of each social cost dimension that we considered to have the largest uncertainty, in most cases related to the translation of social costs into monetary values (willingness-to-pay, value-of-travel-time). Highest uncertainty is in the external costs of climate change, reflecting both the uncertainty in predicting climate change and uncertainty in estimation of social cost (Deutsches Zentrum für Luft- und Raumfahrt, 2006).

In the low-estimate, congestion and air pollution both cause social costs of approximately the same magnitude ($\sim$20 billion RMB/a). The other externalities (traffic accidents, noise, climate change) contribute relatively little to social costs. However, in the upper estimate, climate change contributes as much as congestion and air pollution. In total, external costs of motorized traffic in Beijing were between 52 and 104 billion RMB in 2005, corresponding to between 7.5 and 15.0% of GDP. In the following, we mainly focus on the conservative low-estimate.

3. Demand management by road pricing

External costs of road traffic can be internalized by road pricing.[1] The optimal charge or toll depends on which external costs are considered. Conventionally, a congestion charge is raised to reduce slow moving traffic conditions (Fig. 1, cg = congestion). Neglecting effects on other externalities, an congestion charge of about 1 RMB/km would reduce social costs of congestion by 11 billion RMB a year while constituting opportunity costs for car drivers of around 4 billion RMB (Appendix A).

[1] For methodological see Appendix B.

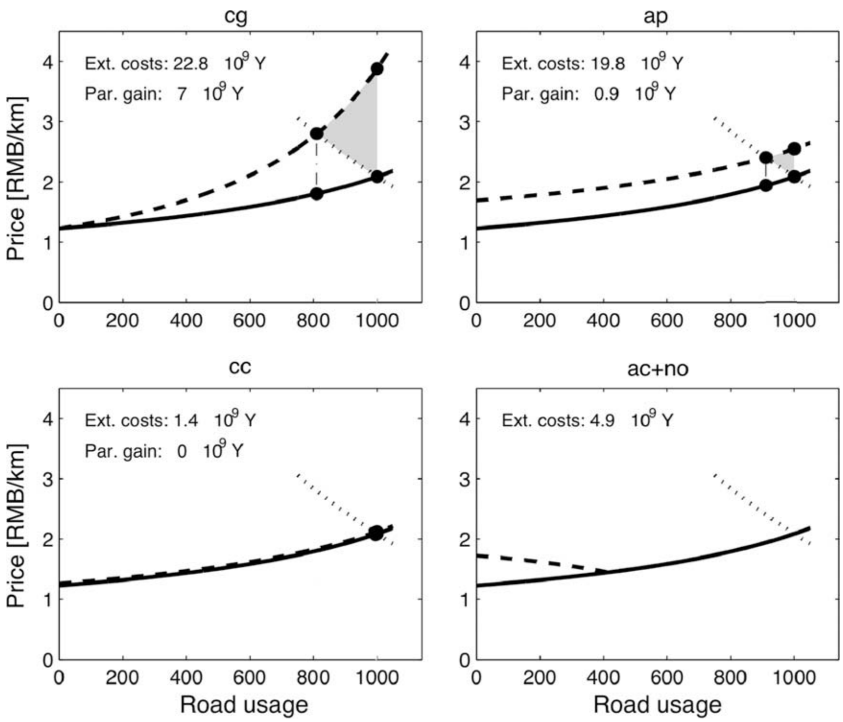

Fig. 1. Welfare gain for different social costs given that a road charge is charged to internalize these specific costs.

Hence, the welfare gain amounts to 7 billion RMB a year. Though air pollution (ap) causes as much social costs as congestion, a charge would internalize only a much smaller proportion (Fig. 1, ap). This is intuitive as we assume that air pollution is not dependent on traffic density and is evoked by every km travelled. This is a conservative assumption with respect to internalization capabilities as traffic usually produces more air pollution and has higher fuel consumption in congested situations. The same is true for climate change (cc) effects: relative value and equal distribution of external costs with respect to road usage make a charging scheme unreasonable to achieve climate change mitigation, at least in the low-estimate scenario (Fig. 1). Noise (no) decreases with less traffic on the road but increases with vehicle speed. Hence, it is unclear and situation dependent whether a reduction of road usage causes a reduction of noise levels. Here, we judge conservatively that all reduction of external costs of traffic noise emerges when traffic levels are reduced to values where congestion has already disappeared. Traffic accidents (ac) change similarly: a small number of cars leads to fewer accidents, but higher speed causes more fatalities. Hence, accidents may only be reduced significantly when congestion falls. This statement is more conservative than Smeed's law (Smeed, 1964) but justified as fatality rates in Beijing have stayed constant since 2000 while the car population has increased (Beijing Transportation Research Center, 2007). Internalization of both dimensions is represented by a filling-up of the social cost curve of congestion (Fig. 1, ac + no). We conclude that user charges that address environmental externalities only have little effect.

Congestion relief provides not only benefits for the remaining car drivers but also for bus passengers by reduced travel time, allowing an additional welfare gain of 1.2 billion RMB/a (Fig. 2, cg/cb). Jointly charging for the external cost of overall congestion (including bus speed) and air pollution increases welfare gain significantly to 12.8 billion RMB/a, while also increasing the average charge from 37 to 47 RMB/day (Fig. 2, cg/cb/ap). Adding climate change costs adds a small margin to benefit (Fig. 2, cg/cb/ap/cc). Including accidents and noise does not change welfare gain (Fig. 2, all). The consequences of optimal congestion charging for different scenarios are summarized in Table 3.

4. Variation of demand elasticity

Demand elasticity is a measure that shows how transportation demand and behavior changes with increased price. A high elasticity value corresponds to a high effectiveness of pricing instruments. A review by Graham and Glaister (2004) concludes that the long-term elasticity of vehicle-km with respect to price is 0.3 but most studies examined focused on fuel prices and not urban congestion charges. Fuel prices and congestion charges are different:

- Fuel prices are paid only when refueling whereas congestion charges are paid with higher frequency, e.g., with every trip into the city.

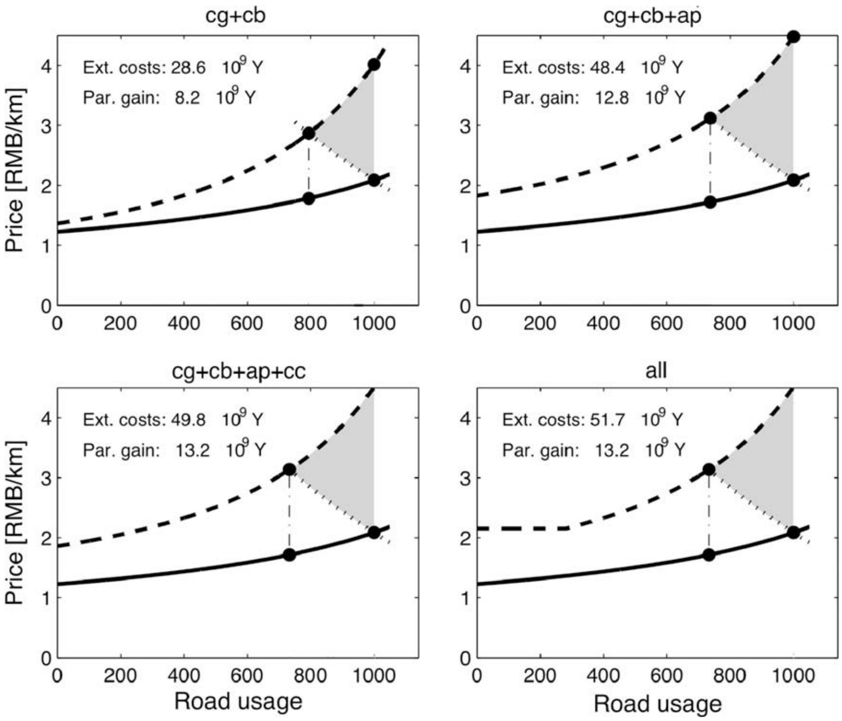

Fig. 2. Welfare gains for road charges internalizing combinations of social costs.

Table 3
Assumed optimal congestion levels.

	cg	ap	cc	cg/cb	cg/cb/ap	cg/cb/ap/cc	All
External costs	22.8	19.8	1.4	28.6	48.4	49.8	51.7
Pareto gain	7.0	0.9	0.0	8.2	12.8	13.2	13.2
(A) Total gain	11.0	1.8	0.0	12.9	20.6	21.2	21.2
1. Congestion	11.0	6.0	0.5	11.7	13.8	14.0	14.0
2. Bus speed	1.1	0.5	0.0	1.2	1.5	1.5	1.5
3. Air pollution	3.8	1.8	0.1	4.1	5.2	5.3	5.3
4. Climate change	0.3	0.1	0.0	0.3	0.4	0.4	0.4
(B) Opport. costs cars	4.0	0.9	0.0	4.7	7.8	8.0	8.0
Annual revenue	34.5	18.1	1.4	36.8	44.0	44.5	44.5
Charge/day in Y	36.6	19.2	1.5	39.1	46.7	47.3	47.3
Cars perceived costs	38.5	18.9	1.4	41.5	51.8	52.5	52.5
Traffic reduction in%	19.0	8.9	0.6	20.6	26.3	26.7	26.7
New speed in km/h	26.0	23.6	21.7	26.4	27.7	27.8	27.8

If not specified otherwise, values are in billion RMB.

- Higher fuel prices can be compensated by the purchase of a more fuel-efficient car.
- Fuel prices affect both rural and urban population, congestion charges mostly urban population. Alternative modes are usually available for urban populations offering options for car drivers.

Altogether, price elasticity for congestion charges seem to vary between 0.5 and 0.7, although London's experience suggests that it may exceed 0.8 (Prud'homme and Bocajero, 2005). However, London had already a dense subway network and unsuitable roads. In the very rich city of London, cars count little as status symbols. All of this is different in Beijing, where subway network is still relatively sparse in comparison, the road networks aggressively developed, and cars have high prestige value. Hence, we expect elasticity for Beijing to be 0.6, as used in the previous section.

The effect of different elasticities (0.3, 0.6 and 1.0) on the three social cost estimates is seen in Fig. 3. A higher elasticity value shifts the Pareto optimum, where $D(q) = S(q)$, to the left. This increases overall welfare gain, reduces external costs by an additional margin, and reduces the charges and, by this, the costs for car drivers. The benefits to different social cost dimensions and welfare gain when varying the elasticity values are illustrated in Fig. 4. Congestion relief constitutes the

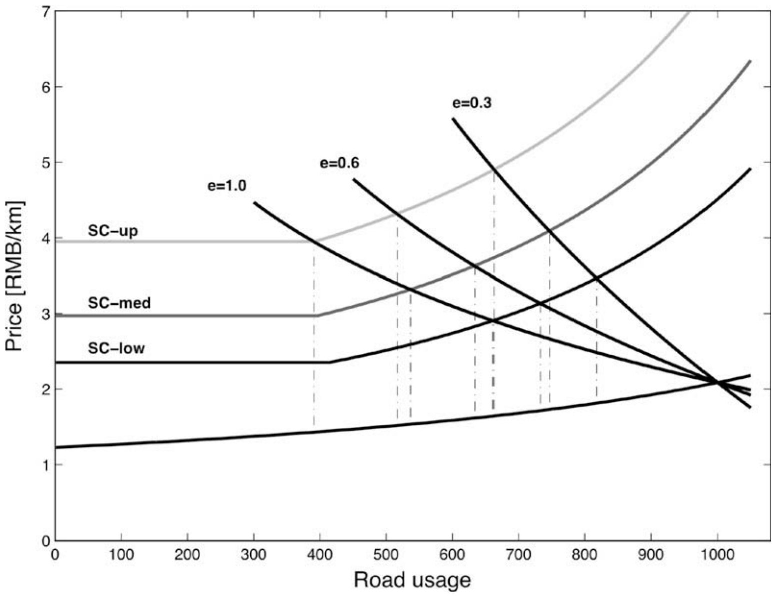

Fig. 3. Total social costs for three different assumptions on willingness-to-pay.

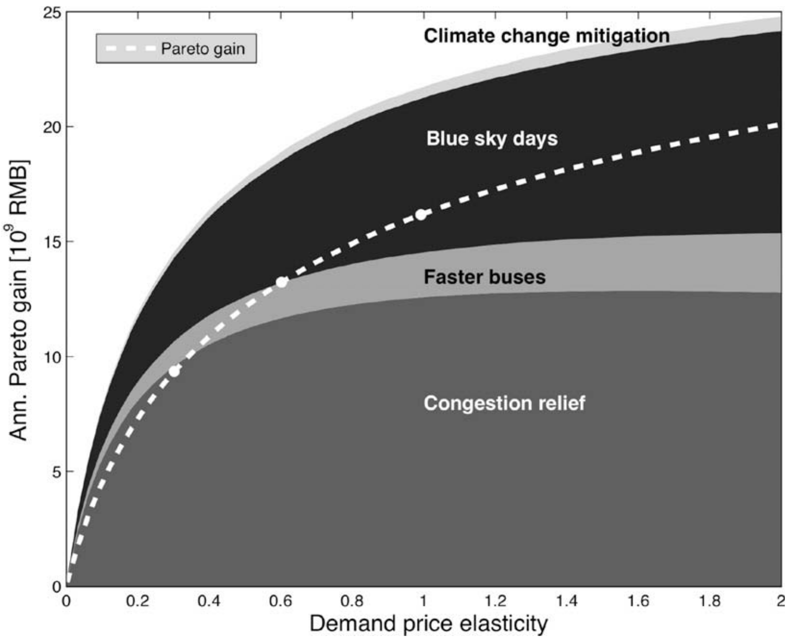

Fig. 4. Annual welfare gain due to optimal road charging for different social cost dimensions as a function of demand elasticity.

main contribution to welfare gain. The marginal welfare gain decreases with increasing elasticity as congestion relief becomes less significant. A high elasticity is not essential to free the roads.

However, the relative contribution of social gain in mitigating environmental social costs, air pollution, and climate change mitigation, increases with higher elasticity; higher values translate more into significant environmental gains as well as congestion relief. For example, increasing the elasticity from 0.6 to 1.0, translates into reduced air pollution worth 1.4 billion RMB whereas congestion relief is only worth 0.9 billion RMB. Particularly, for this change in elasticity, the relative gain of air pollution reduction, climate change mitigation and bus speed increase is about 26% whereas congestion relief is only 8%.

From a political perspective, a city toll cannot be discussed without understanding the impact on car drivers. The effect on car drivers' costs are displayed in Fig. 5. Higher elasticity translates into lower congestion charges needed to reduce traffic

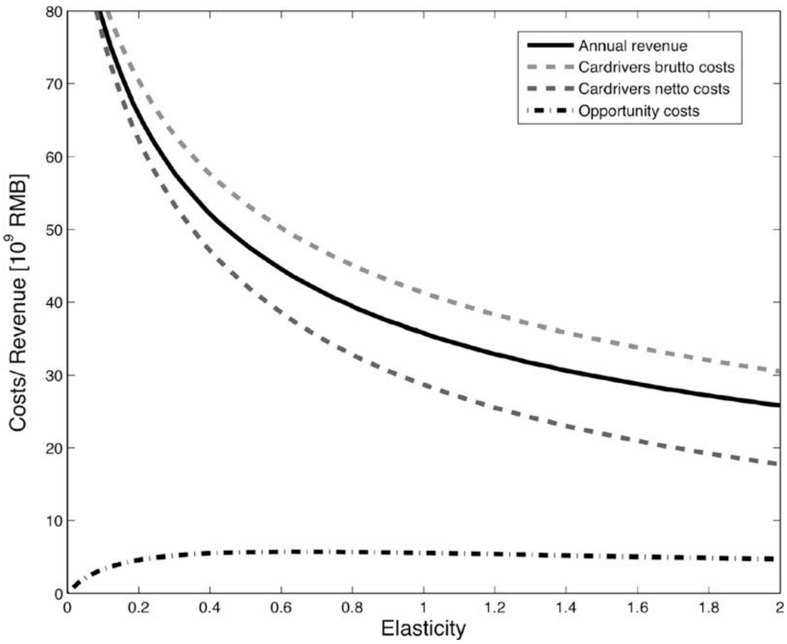

Fig. 5. Annual revenue, opportunity costs, gross costs for car drivers and net costs for car drivers as a function of demand elasticity.

Table 4
The impact of three different elasticities.

	SC-low			SC-med			SC-up		
	e = 0.3	*e* = 0.6	*e* = 1.0	*e* = 0.3	*e* = 0.6	*e* = 1.0	*e* = 0.3	*e* = 0.6	*e* = 1.0
External costs	51.7	51.7	51.7	70.4	70.4	70.4	103.8	103.8	103.8
Pareto gain	9.3	13.2	16.2	19.7	27.4	33.3	37.4	51.5	62.4
(A) Total gain	15.6	21.2	25.3	32.1	42.6	50.5	59.9	78.7	92.9
1. Congestion	10.7	14.0	16.1	22.3	28.5	32.6	38.0	47.4	53.5
2. Bus speed	1.1	1.5	2.0	2.1	3.0	3.8	3.6	5.1	6.4
3. Air pollution	3.6	5.3	6.7	6.0	8.7	11.0	9.4	13.4	16.9
4. Climate change	0.3	0.4	0.5	1.7	2.4	3.1	8.9	12.7	16.1
(B) Opport. costs cars	6.3	8.0	9.1	12.4	15.2	17.2	22.5	27.2	30.5
Annual revenue	57.8	44.5	35.7	75.4	54.5	41.0	92.3	61.9	42.1
Charge/day in Y	61.4	47.3	37.9	80.1	57.9	43.5	98.0	65.7	44.7
Cars perceived costs	64.1	52.5	44.8	87.8	69.8	58.1	114.8	89.1	72.6
Traffic reduction in%	18.2	26.7	33.9	25.3	36.6	46.3	33.7	48.3	60.9
New speed in km/h	25.8	27.8	29.5	27.5	30.1	32.4	29.4	32.9	35.8

burden. For example the annual revenue is reduced from 58 billion RMB/a for elasticity 0.3–45 billion RMB/a or 36 billion RMB/a, respectively for elasticity 0.6 or 1.0. The cardrivers' gross costs, i.e. the sum of annual revenue and opportunity costs and the cardrivers' net costs, i.e. the gross costs minus the gain from congestion relief decrease accordingly with higher demand elasticity (Fig. 5). The change of net costs for car drivers for varying demand elasticity is significant (from 53 to 29 billion RMB/a when increasing elasticity from 0.3 to 1.0). Furthermore, with higher elasticity values beyond 0.5 the opportunity costs for motorists decrease, e.g., due to the availability of public transportation.

How is the average travel speed and traffic reduction affected by elasticity? Increasing the elasticity value from 0.3 to 1.0 reduces traffic by 33.9% instead of 18.2% and increases the speed in average from 25.8 to 29.5 km/h. In Table 4, the impact of three different elasticities (0.3; 0.6; 1.0) for the three different external cost scenarios is summarized.

5. Road pricing and supply-side policies in Beijing

Beijing currently has five ring roads – ring road 2 to 6 – and eight radial roads intersecting the 3rd or 4th ring road comprising the urban expressway system. Further, three vertical and six horizontal arterie pass through the area within the 2nd ring. Some expressways such as the Badaling and the airport expressway are tolled. The 5th ring road, constructed in 2003, was initially tolled 0.5 RMB/km. But as 4th ring road was completed, it was avoided and tolls were abolished in 2004.

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The design of road pricing depends on the objective. If the aim is only congestion, a charge according to traffic density is appropriate. For example, in Singapore the charge is changed every three months so that 85% of the traffic moves at least 45 km/h on expressways, and varies according to route and time of the day. This leads to smoother traffic flow but has limited effects on traffic as drivers may opt to drive at different times or on different routes. However, for some routes in Beijing peak hour already extends throughout the day. A city toll tackling congestion could charge from the 4th ring inwards, increasing the fee from about 1 RMB/km to 3 RMB/km inside the 2nd ring.

If the objective is to tackle most or all known externalities the strategy may differ. Emissions appear also in uncongested situations, noise is most stressful at night and fatalities are more likely in less congested situations. This perspective calls for an absolute reduction in car transportation. Hence, every km driven inside the 6th ring (the area under consideration of this study) would be charged 1 RMB/km. However, it may still be appropriate to charge more inside the 3rd ring as receptor density is higher here. The price may also vary according to fuel efficiency, weight of the car or emission standard. Such an environmental city toll would not be the first one: The Ecopass of Milan was explicitly introduced to address air pollution. In Milan, cars are charged according to emission class and PM10 values were reduced by about 20% in the first six months after the introduction of the Ecopass (Masi, 2008).

Beijing municipality has already considered the introduction of a congestion charge inside the 2nd ring road. A main obstacle is the perceived social dimension of a city toll as many people would be limited in their mobility. The main part of the road pricing revenue could be distributed in equal parts as mobility lump sum to all Beijing inhabitants – including the very significant number of migrant worker. This lump sum could be loaded onto the so-called Yikatong cards, the store-value contactless smart card currently used for public transportation. Yikatong cards could then also be used for payment of road charges. An introduction of the lump sum would also increase political acceptance of road pricing measures. A large proportion of vehicles are government or company cars. According to the current perception of privileges for government officials, car drivers would not pay the charges themselves and have no incentives to reduce motorized transport. The municipality decided against further pursuing congestion charging. Hence, it may be a prerequisite for road pricing in Beijing to change mobility subsidies for government and business employees: they should receive a mobility cash-out on their Yikatong card instead of car subsidies.

A summary of supply-side policies is given in Goodwin (2008). We focus on suitable measures for Beijing. Time-savings often motivate for car use and may be more important than monetary operational costs. Faster public transportation can induce significant modal shift: in Seoul, a 10% increase in speed of public transportation induces 5% of car drivers to switch to bus and subway (Lee et al., 2003). For the Olympic Games, Beijing added 56 km of subway tracks (200 km in total) and plans to extend the subway system to 560 km by 2015.[2]

In 2005, the number of bus trips was 4.2 times larger than the number of subway trips. In contrast to subways, the bus system directly interacts with motor vehicles: dense traffic causes slowing down of bus transportation that, in turn, causes people to switch to car transportation thus causing more congestion. In Beijing, bus transportation is plagued with extraordinary low speed, mostly due to congestion. A comprehensive bus rapid transit (BRT) system could double operational speed from 10 to 20 km/h. This measure effectively doubles capacity, potentially adding eight million passengers a day, without requiring an increase in the number of vehicles. A bus rapid transit system is very cost-effective. The London experience indicates that congestion charging channeled modal transitions to buses not to subway (Transport for London, 2007). If an extended subway system and BRT decrease departure-arrival time by 45%, demand elasticity can increase significantly.

Other important measures include:

- Fare reductions have a long-term elasticity value of 0.6–0.9 with cross-elasticity (from car to public transportation) probably around 0.3 (Litman, 2004). This measure has been successfully exploited by introducing a flat fare of 2 RMB/trip in 2007, attracting additional ridership (see above). This measure is sometimes criticized for inducing additional demand.
- The parking price elasticity is estimated by a number of studies to be a around -0.20 to -0.32 while variation is high (Feeney, 1989). Case studies suggest that parking pricing strategies are most effective in areas where transit is already available. Beijing has already introduced parking management with varying prices according to location, while explicitly aiming to reduce traffic jams.
- Transfer times at stations are often perceived as rather annoying. Some Beijing subway stations are not conveniently accessible. For example, transfer time between line 13 and line 2 at Xizhimen takes up to 15 min during rush hour. Better design can remedy these unwanted effects, attracting more people from car to subway.
- Cycling is an important mode for Chinese cities, in 2005 still being the dominant mode in terms of number of trips in Beijing, losing this status only in 2006 to car transportation. Safety (too much car traffic) is a major concern for cyclist to switch from bicycle to public transit or private car. Additional separated bike lines along some roads where they do not yet exist may improve this situation at low costs. Cycling is the mode of choice to access subway stations.
- From a broader perspective, urban planning, forced relocation in inner city inhabitants and habitation for migrant workers must be part of integrated transportation planning in Beijing.

[2] The introduction of line 5 and reductions in fares to 2 RMB per trip in 2007 caused a ridership to increase from 1.9 million passengers a day in 2005 to 3.4 million in 2008. The planned network would triple overall capacity and add 10 million passengers a day.

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6. Conclusion

Climate change mitigation is a pressing issue in OECD countries but also for other nations. Of particular importance is China due to its size and economic drive. Rapid motorization there makes urban transportation a target for climate change mitigation measures. Here we show that Beijing suffers from high local external costs due to motor vehicle use that, together with global climate change externalities are equivalent to between 7.5 and 15.0% of Beijing's GDP, the range depending on assumptions how social costs are translated into economic costs. The uncertainty about social costs of climate change is large but if long-term costs and risks are internalized, the magnitude of climate change externalities may be similar to congestion costs and air pollution. Some externalities, such those related to land use and time delays for pedestrians and cyclists, are not included.

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Appendix A. Costs of congestion

Free access to public roads leads to misallocation of resources (Pigou, 1920). The reason is that each car trip on the road forces others to slow down. These are external costs that are not paid by the individual road user. To illustrate, each driver pays a constant amount for each km reflecting fuel and other operating costs I_{fix}. Furthermore, each car driver values the time spent on the road. With increased road usage q, the speed $s(q)$ decreases and the trip takes more time, reflected in the individual cost function:

$$I(q) = I_{\text{fix}} + n_p \text{VOT}/s(q). \tag{A1}$$

See also Fig. A1. VOT denotes the value of travel time in RMB/h and n_p denotes the average number of passengers per car. Road usage q is a density measure and can be interpreted as cars per road capacity. The speed is assumed to be a linear function of road usage:

$$s(q) = \alpha - \beta q. \tag{A2}$$

Crucially, with higher q each additional driver slows down more car drivers by a higher margin, increasing social costs (marginal costs) by q times marginal cost of slowing down:

$$\begin{aligned} S(q) &= I(q) + q\, dI(q)/dq \\ &= I(q) + q\beta n_p \text{VOT}(1/s(q))^2 \end{aligned} \tag{A3}$$

In Fig. A1, the area between the social and individual costs corresponds to the external costs of congestion. Hence, the external costs of congestion are:

$$\text{SC}_{\text{cg}} = Q \int (S(q) - I(q))\, dq \tag{A4}$$

The average speed in 2005 was 21.5 km/h (Beijing Transportation Research Center, 2005). Beijing road network is concentric with ring roads having speeds well above 70 km/h in free-flowing conditions (Beijing Transportation Research Center, 2007). Broad arteries allowed an average speed of 45 km/h in 1994 (World Bank, 2004). The largest proportion of overall traffic is on ring roads and main arteries. Hence, the overall average speed on free road situation is estimated to be 45 km/h. The road usage is calculated from the average distance travelled per vehicle per year; 23.000 km for Beijing (Beijing Transportation Research Center, 2005) multiplied by the number of motor vehicles; 2.58 million (Beijing Statistical Yearbook, 2007). This is value is adjusted to take only that proportion (0.72, personal communication, Beijing transportation research center) into account that is driven inside the 6th ring. The road density q is assumed to be directly proportional to Q_b. From s and α one can derive the parameter β. The value-of-time *VOT* used is estimated for 2004 by Beijing transportation research center, to be 31.4–50.3 RMB/h for 2005. As *VOT* is the parameter with the highest uncertainty, variation of *VOT* determines the estimation range of this calculation. The average number of passengers per car is 1.26 (Beijing Transportation Research Center, 2005). We assume that co-passengers have only half the value of travel time as drivers, resulting in an effective occupation of 1.13 per car. The resulting social cost of congestion is 22.8 billion RMB/a.

The external cost of congestion can also be calculated by differentiating between different types of roads r and times t, i.e., peak and off-peak traffic. An estimation of $s(r,t)$, $\alpha(r,t)$ and relative fraction $q(r,t)$ is given in Table A1 based on Wang et al.

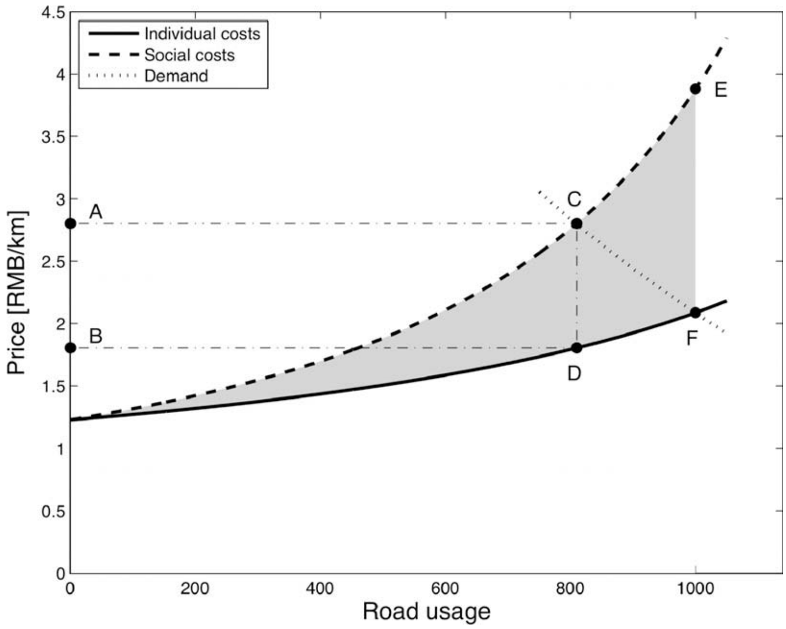

Fig. A1. Congestion costs as a function of road usage.

Table A1
External congestion costs as a function of road usage.

		Speed (km/h)	α (km/h)	Rel. fraction	SC_{cg} (10^9 RMB)
Expressway	Peak	25	60	0.154	4.6
Arteries	Peak	16	35	0.140	9.2
Residential	Peak	15	24	0.052	1.4
Expressway	Off-peak	51	60	0.168	0.3
Arteries	Off-peak	23	35	0.362	6.1
Residential	Off-peak	21	24	0.124	0.9
					$\sum = 22.5$

Notes: cg: congestion; ap: air pollution; cc: climate change; ac + no: accidents and noise. Solid line represents individual costs, the dashed line social costs and the dotted line is the demand curve.

(2008), data are from 2003. The resulting social cost of congestion is 22.5 billion RMB/a here, comparable to our approximation above. This is probably a considerable underestimation as car ownership increased by 24% from 2003 to 2005.

Operational bus speed is only around 10 km/h in Beijing. This low speed is partially due to congestion by individual motorized transport. Operational bus speed could be up to 18 km/h on free roads. Given the number of passenger distance travelled by bus (ca. 22.3 10^9 km/a in 2006, (Beijing Bus Group, 2007)) and the value of travel time of bus passengers 5.8 to 10.6 RMB/h, (Beijing Transportation Research Center, 2005), we estimate the external cost of car congestion paid by bus passengers to be 5.8 billion RMB/a.

Appendix B. Cost internalization

The scale of external costs caused by urban car traffic in Beijing justifies measures to curb negative impact. The social (or Pareto) optimum is where marginal welfare benefit equals marginal social costs. If incentives are such that car usage is well above this point, a change in monetary costs of road usage can move the equilibrium towards the theoretical optimum (Pigou, 1920). The optimal charge for road usage corresponds to the difference between individual and social costs at that level of road usage where the demand curve – representing the social value of car transportation – and the social cost curve meet (the difference CD in Fig. A1). External costs are reduced in proportion to the area CDEF. Car drivers are restrained in their mobility and have to bear opportunity costs corresponding to the area CDF. Hence, the benefit of (congestion) charging corresponds to the area CEF. The revenue of charging, area ABCD, is not part of this accounting as the revenue is redistributed. From this perspective, the purpose of charging is not to boost budget income but to change users' incentives. The demand function is crucial in determining an estimate of the optimal congestion charge. The demand function is usually characterized by price elasticity. The price elasticity is given as the relative change in road usage in response to 10% change in price.

For example, if 10% price increase leads to 6% reduction in traffic, the price elasticity equals $e = 0.6$. The demand function is described with:

$$D(q) = p_0 - \phi \log(q/q_0) \tag{B1}$$

$$\pi = \log((1 - 0.1e)/(0.9p_0)) \tag{B2}$$

and p_0 and q_0 are the coordinates where the individual cost curve $I(q) = D(q)$. The demand function is sometimes approximated by a linear curve. As more than 10% change in price is covered, the exact logarithmical function is appropriate at 0.6.

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