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Benefit-cost analysis of accelerated replacement of Hong Kong's pre-Euro IV buses

Abstract: Hong Kong's franchised buses contribute significantly to its high pollution levels, which in turn result in excess mortality and hospitalizations. I show that replacing all of Hong Kong's pre-Euro IV buses with cleaner Euro V buses would save 1260 statistical lives, among other benefits. The expected net benefit of such a project is HK$26.4 billion under a discount rate of 3.5%. This result is robust to a discount rate of 10% and a mortality decrease of half of what is expected. This is one of the first studies to estimate the public health impact of air pollution from franchised buses in Hong Kong. The city can therefore consider conducting accelerated replacement of its franchised bus fleet. Given the strongly positive result, other Asian cities with ageing bus fleets could also conduct similar benefit-cost analyses.

Keywords: buses; Hong Kong; pollution.

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1 Introduction

High pollution levels are common in Hong Kong. In 2011, the average roadside pollution level in Hong Kong was three times the maximum recommended under WHO's Air Quality Guidelines. Brajer, Mead, and Xiao (2006) asserted that if pollution had met WHO standards from 2003 to 2012, there would have been at least 45,000 fewer cardiovascular & respiratory hospital admissions in this period. According to a more recent estimate, pollution in excess of WHO standards was responsible for at least 8 million doctor visits in 2011 (Hedley, 2012).

Land transport is a significant source of air pollution, and franchised buses in turn are a substantial contributor to land transport emissions. In this paper, I perform a benefit-cost analysis of replacing Hong Kong's older franchised buses with newer environmentally friendly buses, starting 2013. Buses can be classified according to different emission standards, from "Euro I" to "Euro V." Euro I is the least stringent standard and Euro V is the most stringent standard – i.e., Euro V buses are generally the least polluting. Under my proposed scheme, the government buys over Euro I, II, and III buses and replaces them with Euro V buses. The government and bus operators would bear the cost of the new Euro V buses proportionately, such that the bus operators would not gain or lose under my proposed scheme.

This paper shows that the benefits of this scheme to society outweigh the opportunity costs, thus indicating that it would be better for older buses to be replaced earlier than required under the current replacement regime.

This is one of the first studies to estimate the public health impact of air pollution from franchised buses in Hong Kong. A previous study by Brajer et al. (2006) quantified the impact of reducing pollution in Hong Kong as a whole. Compared to Brajer's study, I have used more newly available health impact studies, one of which has been described by a Health Effects Institute review team as the most comprehensive in Hong Kong thus far (Health Effects Institute, 2010).

The next section introduces Hong Kong's current franchised bus fleet. Section 3 describes Hong Kong's pollution and its sources. Section 4 calculates my plan's expected impact on pollution, and also explains why replacing franchised buses is likely to be more cost-effective than replacing other heavy vehicles. Section 5 monetizes the costs and discusses how the costs of accelerated replacement should be divided. Subsequently, Section 6 calculates the benefits and Section 7 performs sensitivity analysis. Finally, Section 8 concludes.

2 Hong Kong's current franchised bus fleet

Hong Kong's entirely privatized bus system comprises minibuses, franchised buses, and non-franchised buses. Franchised bus owners are the largest owners of buses – the five of them collectively own almost 6000 buses. Another 11,000 non-franchised buses and minibuses are owned by at least a hundred small firms and individuals.

As of March 2011, around 70% of Hong Kong's franchised bus fleet is Euro II or earlier. For every kilowatt-hour, Euro II buses emit more than twice as much oxides of nitrogen (NOx)[1], particulate matter smaller than 10 μm (PM10)[2], and carbon monoxide (CO), compared to Euro V buses (Table 1). While all new buses

1 Oxides of nitrogen comprise mainly NO_2 (nitrogen dioxide) and NO (nitric oxide).

2 Also known as respirable suspended particles (RSP).

Table 1 Emission limits of each Euro category (g/kWh), and number of buses in each category as of March 2011.

	NOx	PM10	CO	# of franchised buses
Pre Euro	N/A	N/A	N/A	65
Euro I	8	0.36	4.5	1255
Euro II	7	0.15	4.0	2652
Euro III	5	0.13	2.1	1267
Euro IV	3.5	0.02	1.5	211
Euro V	2	0.02	1.5	226

must be Euro IV or higher, old buses are permitted to remain on the road. By law, Euro I, II, and III buses are only due to retire by 2015, 2019, and 2026, respectively – around 18 years after they were first introduced (Environmental Protection Department, 2011a).

3 Hong Kong's pollution and its sources

In 2011, the average roadside pollution level in Hong Kong was 326, 122, and 61 μg/m^3 for NOx, NO_2, and PM10, respectively. The levels of NO_2 and PM10 are much higher than the maximum recommended under WHO's Air Quality Guidelines, as well as Hong Kong's own standards (Table 2). Neither Hong Kong nor the WHO has guidelines on NOx levels.

Figure 1 shows the breakdown of NOx and PM10 emissions according to source. Table 3 further itemises road transport emissions according to type of vehicle (Environmental Protection Department, 2011b). It is evident from both sources that franchised buses contribute around 2.48% of Hong Kong's total NOx and 1.45% of PM10. Although this is not a very large fraction, it is not negligible either, especially since buses emit these non-uniformly mixing pollutants near population centers.

There is some uncertainty with regards to the percentages in the previous paragraph, for the models used to generate the emissions inventory do not consider

Table 2 Hong Kong & WHO air quality guidelines.

	Hong Kong's standards	WHO standards
NO_2	<80 μg/m^3 (yearly average)	<40 μg/m^3 (yearly average)
PM10	<55 μg/m^3 (yearly average)	<20 μg/m^3 (yearly average)

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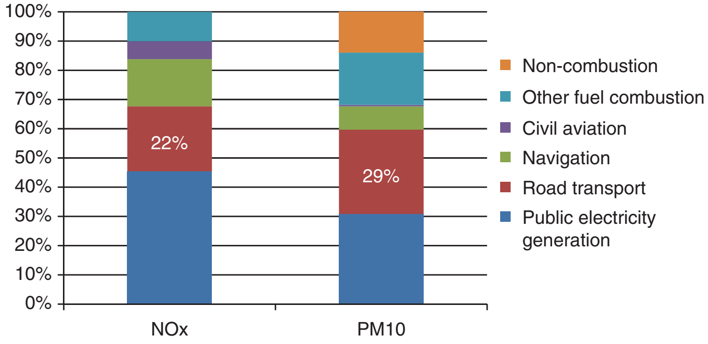

Figure 1 Emissions inventory by source (%).

Table 3 2009 Emissions inventory according to vehicle class (tonnes).

	PM10	NOx	VOCs	CO
Motorcycle	10	220	840	7530
Private car	10	860	1190	20,980
Taxi	60	1360	1970	15,580
Public minibus	80	250	270	3260
Private minibus	10	80	20	330
Light goods vehicles	350	2870	430	1090
Medium and heavy vehicles	710	9690	700	2550
Non-franchised buses	100	1260	110	330
Franchised buses	70	2110	70	250
Total	1400	18,700	5600	51,900

secondary emissions from the transformation of various precursor gases. If secondary emissions come less than proportionately from precursor gases released by franchised buses, then the calculated percentages overestimate franchised buses' contribution to pollution, and vice-versa. As I am unable to find any data to quantify the size of the inaccuracy, I halve franchised buses' contribution to both NOx and PM10 in the sensitivity analysis. (However, it seems unlikely to me that the inaccuracy is large.)

4 Impact of bus replacement plan on pollution

In the analysis, the previously mentioned figures (2.48% of total NOx and 1.45% of PM10) are used in assuming that franchised buses contribute evenly to Hong

Kong's pollution in all areas. However, two points are noteworthy. First, franchised buses ply densely populated Hong Kong Island and Kowloon in higher numbers than the New Territories. Second, buses in Hong Kong Island and Kowloon travel at much slower speeds than in the New Territories, and hence emit more pollutants per kilometer travelled.[3] Thus, a greater than proportionate amount of NOx and PM10 is released in densely populated areas, and therefore the plan's estimated impact on mortality and hospitalization reduction should be viewed as a conservative one. It is not possible to improve on this assumption without a comprehensive street-level model of Hong Kong.

The average daily mileage of buses in each Euro category is assumed to be identical. Further, in calculating the amount of emissions reductions it is assumed that every bus emits pollution in direct proportion to its Euro emissions standard, and that pre-Euro buses pollute at the rate of Euro I buses.[4] Table 4, which shows the emissions of buses in various Euro categories under urban driving conditions, indicates that this is a reasonable assumption.

As emissions standards become more stringent, actual emissions decrease, and the Euro emission standards are a good indication of the magnitude of

Table 4 Emissions of various Euro category diesel buses under urban driving.

Euro category	Emissions	Source/Notes
Euro 1 bus	NOx: 18–23 g/km	Lenaers (1996), study conducted in Brussels
Euro 2 bus	NOx: 25 g/km (±30%) PM: 0.7 g/km (±40%)	Rabl (2002), a weighted average of three studies
Euro 4 bus	11.4% less NOx and 79.1% less PM (*compared to Euro 3 bus*)	Wang et al. (2011), study conducted in Beijing
Euro 4 bus	NOx: 12.31 g/km	Fu et al. (2013), study conducted in Beijing
Euro 4 bus	NOx: 6.1–6.9 g/km PM: 0.049–0.073 g/km	López, Jiménez, Aparicio, and Flores (2009), study conducted in Madrid
Euro 4/5 bus	NOx: around 7.1 g/km	Erlandsson, Almen, and Hakan (2008), in Sweden
Euro 5 bus	NOx: 2.10 g/km PM: 0.028 g/km	Karlstrom (2005), calculation based on COPERT III[5] (average speed 20 km/h, urban conditions)

3 Data on average bus speeds are unavailable. However, consider that the average car journey speed in 2011 was 20.1 km/h in Hong Kong Island, 24.2 km/h in Kowloon, and 40.2 km/h in the New Territories (Transport Department, 2012b).

4 However, since pre-Euro buses are not affected by the accelerated replacement plan, the second half of the assumption is largely immaterial to the analysis.

5 This was the only instance where, because I could not find an actual in-use emissions study, I used a theoretical study.

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the decrease in pollutants.[6] The sole anomaly of Euro I buses emitting more than Euro II buses can be explained by the fact that the tests in Lenaers (1996) were conducted in a small city. Buses are likely to emit less pollution in small cities as smoother traffic flow allows them to travel at a faster pace. Section 7 investigates the sensitivity of estimates to these assumptions.

Finally, the relationship between the total number of buses and total pollution released is assumed to be linear, holding the average fleet composition constant.

Several steps are required to calculate the expected impact of the bus replacement plan on pollution between 2013 and 2015. First, the average NOx and PM10 emitted per kWh across all buses is calculated from Table 1, weighted by the number of buses in each Euro category. Next, the new weighted average amount of pollution emitted should all Euro I, II, and III buses be replaced with Euro V buses is calculated. The percentage difference between the two averages is then used to calculate the reduction in pollution levels due to cleaner franchised buses (results in Table 5. An example of the calculations is given in the Appendix).

Note that as Euro I buses would retire in 2015, the plan's expected impact on pollution would lessen. The impact of the plan from 2016 to 2019 is the reduction in pollution if Euro II and III buses only were replaced by Euro V buses. Likewise, to determine the pollution reduction due to the plan from 2020 to 2026, the same calculations are redone, except that only Euro III buses are replaced.

The decrease in NOx is also broken down into its components: decreases in NO_2 and NO. In general, NO_2 is of far greater concern to human health than NO.

Table 5 Bus replacement plan's impact on pollution.

	Reduction in NOx density (as a percentage)	Reduction in PM10 density (as a percentage)
2013–2015	5.42 μg/m^3 (1.66%)	0.77 μg/m^3 (1.26%)
2016–2019	3.76 μg/m^3 (1.15%)	0.41 μg/m^3 (0.67%)
2020–2026	0.84 μg/m^3 (0.26%)	0.12 μg/m^3 (0.19%)

6 For example, a Euro 4 bus emits around 9 g/km of NOx, and Euro 1 and 2 buses emit around double to three times that amount. In the actual Euro emissions table, Euro 1 and 2 buses emit around 2 to 2.3 times the amount of NOx per kWh consumed. Consider also PM10 emissions. A Euro 4 bus emits around 0.05 g/km, and a Euro 2 emits fourteen times that amount. In the actual Euro emissions table, Euro I buses emit eighteen times of PM10 per kWh consumed compared to a Euro IV bus.

As the World Health Organization has not concluded that NO can cause substantial harm to human health, I assume that the effects of NO on human health are negligible.

The fraction of NOx emitted by vehicles as NO_2 ("f-NO_2") was estimated as 28% by Yao, Lau, Chan, and Fang (2005) from experimental measurements done on open-air roads.[7] This is taken as the point estimate. Another estimate which compares the NOx-NO_2 ratio at general (background) stations with the ratio at roadside stations operated by the Environmental Protection Department gives f-NO_2 as 13% (Tian et al., 2011). While I think that Yao et al.'s (2005) estimate is more accurate, Tian et al.'s (2011) estimate is not unreasonable and will be used in the sensitivity analysis.

From 2013 to 2015, NOx density will be reduced by 5.42 $\mu g/m^3$. Since the volume of NO_2 and NO vehicles emit follows the ratio 28–72%, and NO_2 is 53% heavier than NO, the reduction in NO_2 and NOx density will be 2.03 $\mu g/m^3$ and 3.40 $\mu g/m^3$, respectively. The methods used to calculate this are shown in the Appendix (as part of an illustrative example of the calculations); Table 6 summarizes the rest of the results.

Some other considerations also support this scheme's implementation. However, I am unable to assign a dollar value to them due to the lack of data. First, franchised buses often ply Hong Kong's most densely populated areas, which often resemble "street canyons."

For example, 31.4% of all traffic passing through Nathan Road – Kowloon's main thoroughfare – consists of franchised buses. In street canyon configurations prevalent in Hong Kong, pollution from franchised buses impacts the surrounding roads heavily, but dissipates quickly (Figure 2).

Pollutants build up between the buildings that protect the street from the wind. Therefore, the adverse health effect of vehicular emissions may be magnified in street canyons (Tian et al., 2011; Yassin, Kellnerova, & Janour, 2009).

Table 6 Breakdown of reduction in NOx emissions.

	Reduction in NO_2 density (as a percentage)	Reduction in NO density (as a percentage)
2013–2015	2.03 $\mu g/m^3$ (1.66%)	3.40 $\mu g/m^3$ (1.67%)
2016–2019	1.41 $\mu g/m^3$ (1.15%)	2.36 $\mu g/m^3$ (1.16%)
2020–2026	0.31 $\mu g/m^3$ (0.26%)	0.53 $\mu g/m^3$ (0.26%)

7 Yao et al. (2005) found that f-NO_2 is <10% in the middle of tunnels. However, once the pollutants leave the tunnels, NO is oxidized by other molecules to form NO_2.

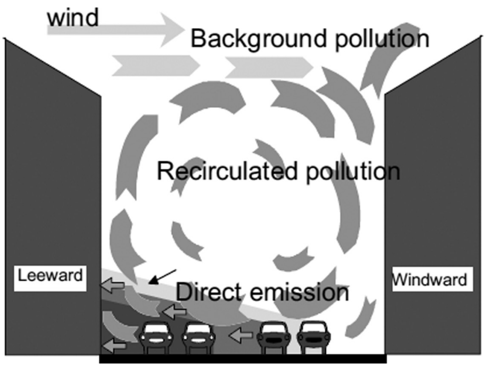

Figure 2 Traffic pollution in street canyons (Berkowicz, 1998; cited by Hertel, Hvidberg, Ketzel, Storm, & Stausgaard, 2008).

This is consistent with the fact that rooftop monitoring stations generally give lower pollution readings (around 25% less for PM10 and 50% less for NO_2) compared to roadside stations, the latter being only 3–4 m above the ground (Environmental Protection Department, 2012a). Therefore, targeting franchised buses would have a significant impact on pollution even on non-commuters.[8]

Second, the franchised bus companies had an average daily ridership of 3.8 million in 2010 – around half of Hong Kong's population of 7 million (Transport Department, 2012a). Thus having a cleaner franchised bus fleet may reduce commuter's exposure to pollution during their journey. US studies have shown considerable evidence of "self-pollution" in school buses, where pollutants from the vehicles' own exhaust enter the passenger compartment (Behrentz et al., 2004; Marshall & Behrentz, 2005). One must be cautious about generalizing these results to Hong Kong, since school buses tend to be of lower quality compared to public transport buses. However, self-pollution to some degree is a real possibility. In fact, since Hong Kong's Euro II buses are over 10 years old and unlikely to be of high quality too, it would not be surprising if self-pollution existed on a similar scale. Hence replacing old buses with new ones could reduce the exposure of bus

8 As an indication of how much this impact could be, a Netherlands study found that cardiopulmonary mortality was associated with living near a major road (excess risk 95%). The relationship with estimated ambient background concentration was less strong: an increase in pollution from the 5th to 95th percentile increased excess risk by 34% (Hoek, Brunekreef, Goldbohm, Fischer, & van den Brandt, 2002). Another study of Prague, Amsterdam, and Huddersfield found that at the street level, traffic volume had a major impact on NO_2 concentration (Briggs et al., 1997). It is unfortunate that no such study has been done in Hong Kong.

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Table 7 Average vehicle occupancy (Transport Department, 2011).

Motor-cycles	Private cars	Light goods vehicles	Medium & heavy goods vehicles	Non-franchised buses	Single-deck franchised buses	Double-deck franchised buses
1.1	1.5	1.5	1.3	13.6	12.8	31.9

Note: Three-quarters of all franchised buses are double-deck.

commuters to pollution. Even if trucks tend to pollute more on average, they carry far less occupants than franchised buses. As is evident from Table 7, franchised buses carry more passengers on average than non-franchised buses, hence it is more cost effective to target franchised buses.

Therefore, there is a prima facie case that, if deemed economically feasible, accelerated replacement of buses is at least as cost-effective as replacing non-franchised buses or trucks.

Consider also that alternative schemes to lower pollution from franchised buses have not been effective. For example, a subsidy for selective catalytic reduction under the Pilot Green Transport Fund has only been approved for 16 electric buses (Environmental Protection Department, 2012b). Tian et al. (2011) further notes that even though many vehicles were previously retrofitted with oxidation catalysts, this has only had an impact on roadside NOx levels and not NO_2 levels.

Another possible alternative is to encourage franchised bus companies to deploy cleaner Euro IV or V buses in heavily populated areas such as Kowloon. However, the Kowloon Motor Bus Company (KMB), which operates most Kowloon routes, uses mostly Euro II or earlier buses. It would be administratively cumbersome for KMB to exchange its old buses with cleaner buses of other companies, to say the least.

5 Costs and financing

5.1 Direct costs: buses and administrative staff

All costs of this program occur in the year of implementation.

A single-decker Euro V bus costs about HK$2 million; a double-decker costs HK$3 million (Environmental Protection Department, 2011c). Of all buses, 76.6% are double decker and the rest are single decker; however, the breakdown for each Euro category is not available. Therefore, the average cost of a bus is calculated as HK$2.766 million in 2011 dollars, or HK$2.896 million in 2012 dollars.[9] In the sensitivity analysis, HK$2.094 million is taken as the lower bound and HK$3.141 million the upper bound (again, these figures are in 2012 dollars).

My scheme replaces all Euro I, II, and III buses with Euro V buses starting 1 January 2013. Pre-Euro buses need not be replaced as they are due to retire by end 2012. Hence, a total of 5174 old buses need to be replaced, and the total cost of the new Euro V buses is estimated at HK$14.98 billion.

However, HK$14.98 billion does not accurately represent the opportunity cost to society of purchasing these buses under the accelerated replacement plan. This is because the bus operators are purchasing Euro V buses earlier than expected, rather than buying Euro V buses when they would not otherwise have bought the buses at all.

For example, the opportunity cost of replacing a Euro I bus 3 years ahead of schedule is $\frac{3}{18}$ the cost of a new Euro V bus, assuming the lifespan of both buses are 18 years and the Euro I bus has no scrap value.[10]

Therefore, the HK$14.98 billion cost of purchasing the new buses should not enter the benefit-cost calculation in its entirety. Rather, the opportunity cost to society is around HK$6.45 billion. This is calculated by summing $\frac{3}{18}, \frac{7}{18}, \frac{14}{18}$ of the cost of a Euro V bus for each Euro I, II, and III bus being replaced, respectively (see Table 8).

Table 8 Opportunity cost of accelerated bus replacement.

	Years before retirement	Opportunity cost of replacing each bus early (millions of HK$)	Total number of buses	Total cost of replacing buses in this category
Euro I bus	3	$0.483	1255	$606 million
Euro II bus	7	$1.13	2652	$2.987 billion
Euro III bus	14	$2.25	1267	$2.854 billion
Grand total				HK$6.446 billion

Note: Figures may not add up precisely due to rounding.

9 Inflation in 2012 was 4.7% without one-off government relief measures. The Hong Kong government releases two measures of inflation: with and without government one-off relief measures (mostly public housing rental waiver and electricity subsidies). I take the inflation rate without relief measures as a more accurate representation of cost increases.

10 The "no scrap value" assumption could underestimate the benefits of the plan. Note there is little need to be concerned that buses would be more expensive if purchased later, as the average inflation rate (3.5%) is similar to the discount rate used (3.5%). Both figures will be justified in subsequent sections.

Assuming this is a socially beneficial project, and the Hong Kong government maximizes the welfare of its residents, it will most likely bear the opportunity cost of HK$6.45 billion. This can be thought of as an equitable compensation payment to bus operators for introducing a mandatory accelerated replacement scheme, if the accelerated replacement scheme takes the effect of a law. Alternatively, it can be thought of as the minimum subsidy needed to incentivize private bus operators to replace all their pre-Euro IV buses.

The remainder of the HK$14.98 billion can be borne by the private bus operators, who are just as well off as before after taking into account the compensation payment.[11]

The Environmental Protection Department may need to hire an additional five full time staff to facilitate this plan, mainly to handle a tender to purchase new buses and to liaise with the five franchised bus companies. This is not an unreasonable assumption. Although this program is on a much larger scale than most existing programs, the Department would only be dealing with five franchised bus companies and at most several bus vendors. Therefore it is not necessarily much more administratively cumbersome than existing programs, which involve hundreds of companies, large and small. Even if this assumption is questionable, staff cost forms a very small portion of this plan's total cost, and therefore the results are robust to this assumption.

Using a monthly salary of HK$30,200 – the average of Master Pay Scale Point 14 and 27 (that of a fresh graduate and one with over 10 years of experience), and further assuming that non-salary costs of hiring an employee are equal to that of the employee's salary, administrative costs are HK$3.6 million – again, negligible for our purposes. It is possible that this scheme will reduce the time spent on administering other subsidies, such as those for installing of catalysts. However, it is unlikely that time spent will decrease significantly, since vehicles such as goods vehicles and minibuses would still be eligible for those subsidies which franchised buses no longer need.

5.2 How should the plan be financed?

If the Hong Kong government pays for the HK$6.45 billion, it will have to raise taxes now or sometime in the future (if it draws out of its HK$600 billion reserves). Virtually all taxes involve deadweight losses; however, no Hong Kong

11 Again, since the bus operators would have to purchase Euro V buses subsequently even without the accelerated replacement scheme, this sum need not be counted towards the scheme's opportunity costs to society.

studies which measured the deadweight loss of taxation could be found. Ruggeri (1999), who uses both partial and general equilibrium simulations to determine the marginal cost of public funds in various types of economies, provides the best estimate. For small open economies, he estimated that a proportional increase in personal income tax rates on all income would cost $1.13 per dollar raised, which is used as the point estimate. A proportional increase in income tax on labour income would cost $1.18 per dollar raised, which is used as an upper bound.

6 Benefits

6.1 Statistical lives saved

This section goes into considerable detail as the entire analysis hinges crucially on the number of statistical lives saved, as well as the value of each statistical life (VSL).

6.1.1 Link between pollutants and mortality

There is overwhelming evidence that increases in NO_2 and PM10 are linked to increases in mortality from all natural causes (Health Effects Institute, 2010; Kan & Chen, 2003; Katsouyanni et al., 2001; Stieb, Judek, & Burnett, 2002). Studies have also shown relationships between air pollution and specific diseases, such as diabetes (O'Neill et al., 2005) and appendicitis (Kaplan et al., 2009). However, even the causal mechanism between increased air pollution and cardiovascular deaths is not well understood (Dales et al., 2007).

Despite the strong evidence linking air pollution with mortality, it is difficult to give a precise estimate of the magnitude by which increased pollution results in increased mortality. All Hong Kong-based studies give estimates of single pollutant models, which can possibly overstate the impact of changes in pollution as they do not control for the effects of other pollutants.

It is possible to use multipollutant models to control for other pollutants. However, it is not necessarily easy to decrease the amount of one pollutant and hold the other constant; for example, NOx may react with volatile organic compounds to form ozone. Also, multipollutant models ignore the interactive effects between different pollutants. Although there is no firm consensus over whether a simultaneous increase or decrease in the concentration of different pollutants has a synergistic effect, studies such as Wong et al. (1999) found significant interactions between PM10, NO_2, and O_3. Thus, even if Hong Kong-based multipollutant models linking pollution and mortality were available, they are likely to underestimate the effects of changes in pollution on mortality. This is especially so for the accelerated bus replacement program as it involves a reduction of many pollutants.

Still, multipollutant models would help to give a conservative estimate on the mortality effects of pollution, and they are used in the sensitivity analysis. Where multipollutant models are not available, the lower bound of the 95% confidence interval of the single pollutant model's point estimate is used in the sensitivity analysis.

6.1.2 Nitrogen dioxide (NO_2)

From the large amount of articles available, the Health Effects Institute (2010)'s results were chosen to calculate the number of lives saved. The HEI study is arguably Asia's most comprehensive study on the link between pollution and mortality. In addition, it also studied Hong Kong among other cities (Bangkok, Shanghai, and Wuhan). Table 9 shows the effect of changes in NO_2 on mortality from all natural causes (i.e., non-accidental) when pollutant levels change by 10 $\mu g/m^3$. Figures for PM10 are also included and these will be referred to subsequently.

The Hong Kong figures are used not only with a view to be conservative, but also because differences between cities may be due to differences in climate. The results were similar to a study of 29 European cities, which found that natural-cause mortality increased by 0.8% and 0.6% when NO_2 and PM10 increased, respectively (Katsouyanni et al., 2001). Furthermore, the HEI results for Shanghai were also not inconsistent with Kan and Chen (2003).

Table 9 Mortality reduction when a given pollutant decreases in concentration by 10 $\mu g/m^3$ (Health Effects Institute, 2010).

	Hong Kong	Average of four cities studied	Difference between HK and average
NO_2	0.90%	1.23%	26.8%
PM10	0.53%	0.55%	3.6%

6.1.3 Particulate matter (PM10)

Like NO_2, the literature linking PM10 with increased daily mortality is overwhelming. However, unlike NO_2, there exists sufficient evidence that long-term exposure to PM10 is much more harmful than short-term exposure. According to the World Health Organization, the best documented studies find that when PM10 increases in concentration by 10 μg/m^3, the excess risk of mortality is 0.6%, but over the long term, the excess risk increases by around six times (see Table 10).

Since the replacement plan would lead to a reduction in PM10 levels for 14 years, the long-term mortality figure (4%) is used in the analysis.

Given the lack of a Hong Kong based study on the link between long-term mortality and PM10, one may be concerned about the applicability of the WHO's result to Hong Kong. Indeed, the WHO notes that although the coefficients in Table 10 can be used to estimate the burden of disease attributable to PM10 and the potential impact of various scenarios of control, use of these risk relationships in any particular setting is subject to uncertainty related to their generalizability. However, any uncertainty is likely to be small, for the daily mortality estimate given by the WHO in Table 10 is similar to the Hong Kong based study's estimates in Table 9. Hence there is little reason to suspect that the long-term mortality estimate will be remarkably different.

The sensitivity analysis considers the case where a decrease in PM10 concentration by 10 μg/m^3 only decreases long-term mortality reduction by 1% (the lower bound of the 95% confidence interval of the point estimate).

6.1.4 Pollutants ignored

My analysis ignores the effect of decreases in carbon monoxide (CO). Currently, Hong Kong's carbon monoxide levels are well within stipulated limits, hence the decrease in CO by itself may not have much impact.

Nitric oxide (NO), although largely harmless to humans, can damage vegetation. Hence, the decrease in NO concentration would have economic benefits.

Table 10 Mortality reduction when PM10 decreases in concentration by 10 μg/m^3 (World Health Organization, 2006).

	Estimate	95% CI	Source
Daily mortality (all-cause)	0.6%	0.4–0.8%	WHO meta-analysis
Long-term mortality (all-cause)	4%	1–8%	ACS CPS II 1979–1983

However, I ignore this benefit because the economic value is likely to be negligible compared to the statistical lives saved.

6.1.5 Statistical lives saved

Between 2008 and 2010, there were on average 39,900 deaths from all natural causes annually (Hospital Authority, 2011). Therefore, based on my estimates of pollution's impact on mortality, there would be a total of 1260 statistical lives saved from 2013–2026. Table 11 gives a breakdown; refer to the Appendix for an example of how the calculations were done.

There are two major points to note. First, my calculations assume that when pollution increases in mortality are evenly distributed across age groups. This is because the Health Effects Institute study found only a marginally higher increase in mortality in the elderly compared to the general population. At around 0.1–0.2 percentage points, the difference was certainly not statistically significant. The HEI's results are also consistent with Stieb et al. (2002), a study previously mentioned. Moreover, even if the differences were statistically significant, my conclusion will not be overturned.

Second, the expected annual decrease in mortality will be higher in the initial years. This is because in 2015, Euro I buses would have been retired even under the government's current scheme, and Euro II buses in 2019.

6.1.6 Value of a statistical life

The value of HK$27.4 million per statistical life is used.[12] This is Miller's (2000) best estimate for Hong Kong based on 68 studies spread across 13 countries, adjusted for inflation.

Table 11 Number of statistical lives saved *annually* due to reduction in specific pollutants.

	NO_2	PM10	Total
2013–2015	73	123	195
2016–2019	50	65	116
2020–2026	11	19	30
Grand total			1260

Note: Figures may not add up precisely due to rounding.

12 The value of HK$27.4 million is only half of the US Environmental Protection Agency's estimate; however, the difference in VSL between countries could be cultural, as studies of Asian countries tend to find lower VSLs compared to Western countries, even after adjusting for income.

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Miller also made “low” and “high” estimates of HK$23 and HK$33 million respectively, which were the minimum and maximum regression based estimates seen across eight regressions for a large number of countries. A Hong Kong wage-risk study gave an estimate of HK$20 million (Siebert & Wei, 1998); since this is close to Miller’s low estimate, HK$20 million is used as the lower bound. For my point estimate, Miller’s point estimate is still preferred, and not simply because his method was far more comprehensive. Miller’s low estimates were consistently around 120 times of a person’s annual wage for all countries, suggesting that this is the lower bound of a reasonable estimate.

When valuing the health impacts of air pollution on Hong Kong, Brajer et al. (2006) cited two more Hong Kong specific VSL estimates by Wong et al. (2002b) and Yee (1998), which were HK$10 million (2000 dollars) and HK$5 million (1997 dollars), respectively. I do not concur with Brajer et al. (2006) in using these estimates as a lower bound. Yee (1998) uses human capital accounting measures and willingness-to-pay (WTP) focus groups. The first method has fallen out of favour with economists as it provides an incomplete estimate of the loss to the individual. In addition, Yee’s (1998) WTP estimate is based solely on how much people would be willing to pay to avoid a 0.01% increased chance of dying from a cardiovascular or respiratory disease. No attempt is made to validate this by using other percentages, e.g., 0.1% or 1%. The small sample size of 29 in his WTP focus groups are also cause for concern, and no standard error is given. Wong et al.’s (2002b) WTP sample size was reasonable, with 108 valid responses. However, the survey only comprised one question, with 81.4% of respondents agreeing that the value of a life was at least HK$10 million. Hence the true VSL in Hong Kong is probably significantly higher.

From Table 11, the net present value (NPV) of total mortality cost is HK$33.5 billion in 2012 Hong Kong dollars using Miller’s estimate of HK$27.4 million per life, an inflation rate of 3.5%,[13] and a discount rate which is also 3.5%, as recommended by Boardman, Greenberg, Vining, and Weimer (2006) for intragenerational projects based on the optimal growth rate approach. The market-based interest rate approach, with a discount rate of 1.5%, is only used in the sensitivity analysis due to the many inconsistencies observed in consumer behavior.

6.2 Hospitalizations & loss in productivity

The 2012 estimated average daily cost of hospitalization is HK$4250, of which HK$4150 was a government subsidy (Hong Kong Budget, 2012). Loss in wages for

13 The average inflation rate between 2007 and 2012.

Table 12 Hospitalization admissions reduction due to pollution changes (Wong et al., 1999).

	Respiratory	Cardiovascular
Effect of NO_2 decreasing by 10 $\mu g/m^3$	2.00%	1.30%
Effect of PM10 decreasing by 10 $\mu g/m^3$	1.60%	0.60%

each day of hospitalization is taken as the average per capita GDP in a day, which was HK$780 in 2012. The average length of a hospital stay was 7.5 days in 2010 and 2011.

Table 12 shows Wong et al.'s (1999) findings on hospitalization admissions reduction due to pollution changes. Note that the current pollution level is higher than Wong et al.'s (1999) reference period of 1994 and 1995, so the health impact of my scheme may in fact be greater than as calculated by Wong et al. (1999).

When analyzing Hong Kong data from 1994 to 1995, Wong et al. (1999) found no statistical difference between changes in hospitalizations of different age groups due to a change in pollution. It is therefore assumed that the changes in hospitalization occur evenly across all age groups. Even if the differences (typically <0.3%) were significant, my results would not be affected significantly. Wong's study controlled for time trend, season, and other cyclical factors, temperature, and humidity. He also corrected for autocorrelation and overdispersion. The authors explained that in the APHEA protocol (Air Pollution and Health – A European Approach), concerns of collinearity between air pollutants preclude the inclusion of all pollutants into a multiple pollutant model (see also Katsouyanni et al., 1996). Note that Wong et al. (1999) found significant interactions between PM10, NO_2, and O_3, although he did not give details. Thus, if his conclusion were correct, a single pollutant model could possibly understate the benefits of pollution reduction, since the bus replacement program involves reduction of both PM10 and NO_2. Nevertheless, there is still a possibility that the single pollutant model could overestimate the benefits of pollution reduction. Thus the single pollutant model estimates are used as the point estimate.

According to the Hospital Authority (2011), there were a total of 146,824 hospitalizations for respiratory conditions and 86,993 for cardiovascular conditions in 2009. These figures are used alongside the excess risk estimates in Table 12 to calculate the estimated annual effect of pollution reduction on hospitalizations in Table 13. The process is similar to calculating the number of statistical lives that would be saved (shown in the Appendix).

Based on these estimates, the net present value of total direct hospitalization costs saved is HK$209.3 million, and total productivity regained is HK$38.4 million.

Table 13 Decrease in hospitalizations due to decreases in specific pollutants.

	NO_2	PM10	Total annual reduction in hospitalizations
2013–2015	824	221	1045
2016–2019	571	117	689
2020–2026	97	32	129
Grand total			6795

Note: Figures may not add up precisely due to rounding.

The total benefit of my plan, which comprises the statistical lives saved, hospitalizations prevented, and productivity regained, is therefore HK$33.7 billion. This greatly exceeds the estimated total cost of HK$7.3 billion, which comprises government spending and the deadweight loss.

Table 14 gives the monetary value of each benefit in each year, and Figure 3 summarizes the table.

7 Sensitivity analysis

The expected net benefit to Hong Kong is HK$26.4 billion. In the Section I will examine how the results change in response to different discount rates, values of a statistical life, and cost of buses, among others. There is little need to consider population growth, for since 2000 Hong Kong's population growth has averaged around 0.5% annually and never gone above 1%.

First, the results are robust to the choice of discount rate. Even at a discount rate of 10%, the scheme's net present value is HK$18.4 billion.

Second, even when using Siebert and Wei's (1998) estimate of the value of a statistical life (VSL), the NPV is still positive at HK$17.3 billion. Even if I were to use Wong et al. (2002b), an even lower VSL estimate which I had rejected earlier, the NPV would still be HK$5.1 billion.

Third, the results are also robust to using the lowest reasonable estimates of the link between pollution and mortality. For NO_2, this would be Stieb et al. (2002)'s multipollutant models,[14] a meta-analysis of 109 studies of pollution's impact on mortality. Stieb's et al.'s (2002) pooled estimates indicate that when

14 It is unfortunate that the HEI (2010) study, whose single pollutant models formed my point estimates, did not report any multipollutant results. In addition, another Hong Kong based study that gave multipollutant estimates (Wong, Tam, Yu, & Wong, 2002a) only focused on increases in mortality for cardiovascular and respiratory diseases.

Table 14 Summary of benefits.

	Lives saved	Reduction in hospitalizations	$/Life	Average daily hospitalization cost ($)	Daily wage ($)	Value of lives	Value of hospitalization	Regained productivity	Total
2013	156.0	724.6	27,440,000	4250	780	4,280,640,000	23,097,581	4,239,086	$4,307,976,666.75
2014	156.0	724.6	28,400,400	4399	807	4,430,462,400	23,905,997	4,387,453	$4,458,755,850.09
2015	156.0	724.6	29,394,414	4553	836	4,585,528,584	24,742,706	4,541,014	$4,614,812,304.84
2016	90.6	470.0	30,423,218	4712	865	2,757,560,524	16,609,980	3,048,420	$2,777,218,923.40
2017	90.6	470.0	31,488,031	4877	895	2,854,075,142	17,191,329	3,155,114	$2,874,421,585.71
2018	90.6	470.0	32,590,112	5048	926	2,953,967,772	17,793,025	3,265,543	$2,975,026,341.21
2019	90.6	470.0	33,730,766	5224	959	3,057,356,644	18,415,781	3,379,838	$3,079,152,263.16
2020	24.0	111.7	34,911,343	5407	992	837,523,118	4,529,871	831,365	$842,884,353.18
2021	24.0	111.7	36,133,240	5596	1027	866,836,427	4,688,416	860,462	$872,385,305.54
2022	24.0	111.7	37,397,903	5792	1063	897,175,702	4,852,511	890,578	$902,918,791.23
2023	24.0	111.7	38,706,830	5995	1100	928,576,851	5,022,349	921,749	$934,520,948.93
2024	24.0	111.7	40,061,569	6205	1139	961,077,041	5,198,131	954,010	$967,229,182.14
2025	24.0	111.7	41,463,724	6422	1179	994,714,738	5,380,066	987,400	$1,001,082,203.51
2026	24.0	111.7	42,914,954	6647	1220	1,029,529,754	5,568,368	1,021,959	$1,036,120,080.64

Note: In 2013, the value of a statistical life ("$/life"), hospitalization cost, and daily wage are all in 2012 prices. Strictly speaking, they should be adjusted e.g. due to inflation. However, they are not adjusted, with a view to be conservative.
In 2012, the opportunity cost of replacing buses early is HK$6.446 billion, and the deadweight loss of taxation is HK$0.838 billion.

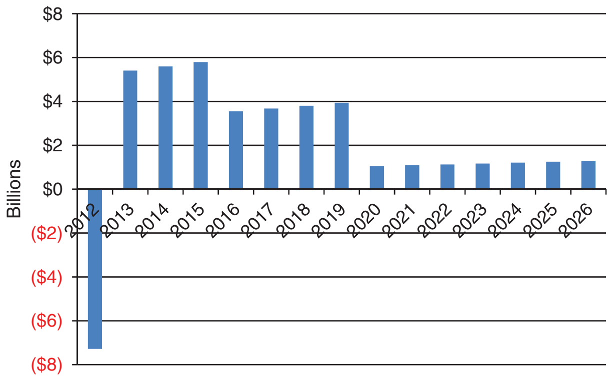

Figure 3 Estimated net benefit of accelerated replacement.

NO_2 concentration increases by 10 μg/m^3, natural-cause mortality rises by 0.20%.[15] The lowest reasonable estimate for the link between long-term PM10 exposure and mortality is given by the World Health Organization (2006), which indicates that a rise in PM10 by 10 μg/m^3 causes natural-cause mortality to rise by 1%.[16] Using both these results, the NPV is HK$959 million.[17]

I had earlier assumed that buses emit pollution in proportion to the emission limits of their Euro category. In case this overestimates the amount of pollution older buses produce, I consider the scenario where Euro I buses emit at the midpoint of Euro I and II limits, Euro II buses emit at the midpoint of the Euro II and III limits, and likewise with Euro III and IV buses. However, the buses which are not going to be replaced by my scheme – i.e., the Euro IV and V buses – emit at the maximum allowable levels. Under these assumptions, the NPV is still positive at $23.6 billion.

The fifth assumption I examine is my choice of monitoring stations. Although air quality is measured at both roadside stations and rooftop stations, I have taken the roadside stations as the reference point. First, roadside stations are

15 Though this estimate is not significant at the 5% level, it is significant at the 10% level.
16 This is the lower bound of the 95% confidence interval of the WHO's point estimate of 4%, which comes from a single pollutant model. I am not using a multipollutant model as I cannot find any long-term multipollutant study of comparable reliability to that of the WHO's. Stieb et al.'s estimate is not considered as it only refers to short term exposure.
17 Multipollutant models that link pollution and hospitalizations are available [e.g., Wong et al. (2002c)]. However, since the project has a positive NPV even if there was no link between pollution and hospitalizations, it is not necessary to use Wong et al.'s (2002c) results.

only located around 3–4 m above ground level whereas rooftop stations are typically located high above ground level. One of the rooftop stations, Tap Mun, is located far away from any population center; in fact, it is 15 km away from the nearest built up area.

Still, it is useful to see how results change if I were to take the initial level of pollution as the simple average of roadside and general stations. This would mean that the PM10 starting value would change from 61 $\mu g/m^3$ to 54.5 $\mu g/m^3$, and the average level of NOx change from 326 $\mu g/m^3$ to 208.5 $\mu g/m^3$. The project would still remain worthwhile with a net benefit of HK$19.4 billion.

Finally, the results are not sensitive if franchised buses' contribution to pollution is 50% lower than calculated, and likewise if f-NO_2 (the fraction of NOx emitted as NO_2) is 50% lower than estimated. Also, even if the cost of public funds or the cost of buses is 50% higher than anticipated, the result remains unchanged. In all cases, the NPV is above HK$5 billion.

8 Conclusion

I have shown that replacing all of Hong Kong's pre-Euro IV franchised buses immediately yields an expected net present benefit of HK$26.4 billion under a discount rate of 3.5%. The net benefit is around double of the initial expenditure required, and is in large part due to the 1260 statistical lives that would be saved by this accelerated replacement program.

I have also shown that this result is robust to a discount rate of 10%, using the lowest reasonable estimates of the link between pollution and mortality, or using the lowest reasonable estimates of the value of a statistical life, among others.

One may argue that under the accelerated replacement program, buses replaced in 2015 and 2019 may be of better quality, such as Euro VI or even Euro VII buses. Ignoring this possibility may result in an overestimation of the benefits of the program. However, this argument ignores the fact that under the accelerated replacement program, the new Euro V buses will be replaced in 2030, perhaps with Euro VII or Euro VIII buses. Thus it is unlikely that this argument holds.[18]

Furthermore, my analysis could underestimate the benefits of pollution reduction; Section 4 elaborates on some conservative assumptions. For example,

18 One may also wonder whether the differences between the values of the buses in 2026 (or a future year) under my plan and the existing plan should be considered. It should not because the opportunity cost to society, calculated in Section 5, has already taken this into account.

the analysis assumes that franchised buses ply all areas of Hong Kong's proportionately, when in fact they ply heavily populated areas disproportionately and also travel more slowly in these areas. Additionally, non-pollution related benefits are also ignored. For example, I have ignored society's gain from noise reduction, for Euro V buses emit considerably less noise than older buses. I also ignore the multiplier effect on Hong Kong's economy, for some bus parts may be produced in Hong Kong, and the fact that purchasing a large number of buses may result in bulk discounts. Finally, I also ignore the scrap value of the old buses. All these may result in an underestimate of the benefits of this project.

Given the HK$26.4 billion benefit which Hong Kong would experience if it took all its pre-Euro IV buses off the road, other densely populated cities with ageing bus fleets, such as New Delhi, could examine whether a similar scheme is worthwhile.

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Appendix

Illustration of how reduction in NOx was calculated (Table 5)

NOx emissions from franchised buses before the replacement plan (number of buses in each Euro category multiplied by emissions per g/kWh):

$$65\times 8+1255\times 8+2652\times 7+1267\times 5+211\times 3.5+226\times 2=36{,}649 \text{ arbitrary units}$$

NOx emissions after the replacement plan:

$$65\times 8+211\times 3.5+5400\times 2=12{,}058.5 \text{ arbitrary units.}$$

Percentage reduction in NOx emitted by franchised buses: 67.1%.
Contribution of franchised buses to NOx: 2.48%.
Total percentage reduction in NOx: $67.1\%\times 2.48\%=1.66\%$.

Reduction in NOx density$=1.66\%\times 326=5.42\ \mu g/m^3$
(cell in the top left hand corner).

The calculation process is similar for PM10.

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Illustration of how reduction in NO_2 was calculated (Table 6)

Decrease in NO_2 density:

$$\frac{fNO_2 \times Mr(NO_2)}{fNO_2 \times Mr(NO_2) + (100\% - fNO_2) \times Mr(NO)} \times \text{reduction in NOx density}$$
$$= \frac{28\% \times 46}{28\% \times 46 + 72\% \times 30} \times 5.42$$
$$= 2.03\ \mu g/m^3$$

where *Mr*(*X*) refers to the relative molecular mass of molecule X, and fNO_2 (more accurately, f-NO_2) refers to the fraction of NOx released that becomes NO_2.

Illustration of how reduction in mortality was calculated (Table 11)

How the top-left cell in Table 11 (reduction in mortality by 73 in each year from 2013 to 2015 due to reduction in NO_2) was derived:

From 2013 to 2015, NO_2 density decreases by 2.03 $\mu g/m^3$ (Table 6).

Since a reduction in NO_2 density by 10 $\mu g/m^3$ is associated with a mortality decrease of 0.9%, and there were 39,900 deaths from natural causes annually in Hong Kong, the expected mortality decrease due to the plan's effect on NO_2 concentrations is around 0.18%.

Hence there would be a total of 72.8 statistical lives saved for each year from 2013 to 2015 due to the decrease in NO_2.

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