Emissions Management of Urban Earthmoving Fleets

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Abstract

Earthmoving has historically been managed based on minimum unit cost. However, consistent with the debate on climate change and new carbon legislation, there has been an emerging interest in also reducing carbon emissions. Studies exist for earthmoving fleets operating off-road, but little attention has been given to on-road and urban conditions involving general traffic. This paper analyses hauling emissions and costs in such conditions, and explores possible means of reducing these emissions through changing fleet size, truck size, haul schedule and haul route. It is shown, using field data, that for regular working hours and operations, reducing unit costs via fleet and truck size selection also results in reducing unit emissions, and that larger but fewer trucks result in less or the same emissions compared to bigger fleets with smaller trucks. That is, historical management practices of pursuing least cost will also impact the environment the least. Hauling during night hours, although resulting in lower unit emissions because of decreased traffic, is shown to be not presently cost effective because of labour rates and the current low price of carbon. The paper demonstrates choices and trade-offs that need to be considered when managing an earthmoving fleet in urban conditions.

Keywords: Earthmoving, costs, emissions, traffic, urban.

Introduction

The transport sector represents approximately 13% of global emissions (IPCC, 2007), 29% of which comes from diesel fuel whose predominant users are trucks, including those associated with urban construction servicing growing populations and the need for more and changed infrastructure. Truck movement consumes large amounts of fuel, and in doing so produces large amounts of emissions. To reduce these emissions, more efficient trucks and new technology are being embraced along with more efficient management. This paper addresses the last matter, and looks at the management of transporting construction materials and waste between loading and unloading urban destinations in repeated cycles.

Diesel exhaust emissions are a mixture of gases, vapours, liquid aerosols and particles, and include carbon dioxide, nitrogen, water, hydrocarbons, carbon monoxide, aldehydes, nitrogen oxides, sulphur oxides, and particulate matter (HSE, 1999). Emissions are given in this paper in terms of CO2 equivalents (CO2-e), which take into consideration most emissions produced by the combustion of diesel fuel through a conversion based on their global warming potential (GWP). Based on DIICCSRTE (2013), the combustion of 1 litre of diesel produces approximately 2.7 kg of CO2-e.

Truck fuel consumption and emissions are influenced by many variables such as starts and stops, time spent idling, acceleration, speed, haul distance, presence of traffic, and road surface and condition (Ding, 2000; Clark et al., 2002; NSCCAF, 2009; Carmichael et al., 2012, 2014; Kaboli and Carmichael, 2014a, b; Carmichael et al., 2014). Some of these are

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determined by the truck operator, some by the urban environment, and some by management decisions. Although the effects of these parameters individually on emissions have been studied, there are no data linking urban traffic density with hauling costs and emissions. This paper also explores the influence of truck size in an urban earthmoving fleet and traffic conditions on emissions and costs.

The paper first explores the transport, technology, usage and management backgrounds. Two case studies – road construction and cable installation – are then outlined and analysed. These lead to conclusions on emissions and cost relating to construction in an urban setting. The paper will be of interest to those who design and manage construction in urban areas. The paper is original in that no other equivalent studies appear to have been done.

Background

Transport. The relationship between burning fossil fuels, such as used in urban earthmoving fleets, and greenhouse gas emissions is well documented (IPCC, 2007, 2013). 13% of global emissions come from the transport sector (IPCC, 2007), and 95% of global transportation energy comes from the combustion of petroleum-based fuels (EPA, 2014). Diesel provides approximately 29% of the global transport energy and its usage is predominantly by trucks (Fulton and Eads, 2004). Heavy and medium freight trucks are responsible for 19% of energy use in the global transport sector (WBCSD, 2004). Since 1970, the direct emissions from transport have grown by over 120% (IPCC, 2007), and transport emissions are expected to continue to grow.

Within Australia, transport is the third largest emitting sector, responsible for 15% of total emissions. Approximately 85% of these emissions come from road transport (DCCEE, 2012). In 2011, transport emissions were 85 Mt CO2-e, 38% above 1990 levels and they are predicted to grow to 92 Mt CO2-e by 2030 (DCCEE, 2012).

The most direct way to reduce emissions is through reduced fuel use, since the burning of diesel fuel is directly responsible for the emissions. New technologies also exist to process the emissions produced. The variables that are said to most affect emissions from trucks include truck class and weight, driving cycle, truck usage, fuel type, engine exhaust after-treatment, truck age and the terrain travelled (Clark et al., 2002).

Considering a fleet of trucks cycling between defined origins and destinations, the total emissions are affected by: truck type and characteristics (including size, fuel consumption, load and material type, and maintenance); technologies; operator (speed, acceleration and gear-shifts selected); road condition (grade and roughness); traffic conditions (speed, acceleration, stoppages, and idle time); and management (efficient truck usage, haul route, fleet size, equipment matching, and idle time).

Larger trucks have a higher fuel consumption but need to make fewer trips to move a given load, resulting in lower total fuel consumption. Coonan and Woodward (2010) show that, with increasing truck payload, fuel usage per unit load decreases, emphasising the benefit of using larger trucks if possible.

Technologies. Technologies available to reduce fuel usage include:

- The use of aerodynamics via fairings and trailer streamlining, reducing drag (NSCCAF, 2009).
- Low rolling resistance tyres.
- Real-time on-board vehicle monitoring systems giving the current state of the vehicle, including temperature and fuel usage.

Technologies available to reduce emissions include:

- Exhaust after-treatment, for example combining an oxidation catalyst and a particulate trap (Clark et al., 2002).
- Engine modification so that the vehicle can use alternative fuels with higher efficiencies or lower emissions.
- Using a reformulated diesel or a diesel equivalent fuel, such as biodiesel, that does not require engine modifications (Clark et al., 2002; AR Fuels, 2014).
- Catalytic converters and modified fuels to reduce nitrogen oxides.

Truck use. Efficient truck use depends on many factors including:

- Engine operating parameters such as temperature and fuel quality.
- Load size – the optimum load size is not necessarily the most material that can fit in a truck's tray (RET, 2011).
- Tyre wear – this can create higher rolling resistance.
- Age and maintenance.

Haul conditions. Haul conditions that can affect fuel use include:

- Road condition – unsealed roads have a higher rolling resistance and hence lead to higher fuel consumption. Wet roads may also have a detrimental effect.
- Haul route – The fuel use is related to the length of the haul, although the speed along the route and the traffic present need to also be taken into account. A short haul route, which takes longer to traverse, may result in higher fuel use. Hauling up an incline increases fuel consumption (RET, 2011).
- Road occupancy licence (or similar name) – a permit issued by the local road authority that outlines the conditions under which the contractor may occupy the road. This includes the time, dates and type of work, traffic control plans and the duration that traffic may be stopped.
- Average speed, which may be governed by site restrictions, local speed limits or traffic conditions. Ding (2000) shows the influence of cruise speed on fuel consumption and emissions.
- Number of stops. With frequent stopping, as required by the layout of the road or by traffic conditions, fuel consumption and products of incomplete combustion increase. Ding (2000) shows the influence of number of stops on fuel consumption and emissions.

Equipment matching. For a fleet of trucks, cycling between defined origins and destinations, and working with an excavator, a balance is needed between the idle time of the excavator at the load point and the idle times of the trucks. Matching excavator and truck capacity, while also taking into account excavator cycle time, truck cycle time and truck fleet size, is desirable. If a fleet is under-trucked or over-trucked, either the excavator or trucks will spend too much time idling or non-productive, yet still creating emissions. Stockpiling might also be a possibility in some cases in order to reduce loading times.

Operator. The way in which a truck is operated impacts fuel consumption. Operation includes the selection of gears, driving speed, acceleration, switching a truck off instead of idling, and truck load. Aggressive acceleration consumes fuel as well as producing extra products of incomplete combustion. Ding (2000) shows the influence of acceleration on fuel consumption and emissions.

Management

When configuring a truck fleet, the aim traditionally has been to minimise the cost or cost per production (unit cost). Configuration and operation choices include:

- Excavator bucket size.
- Number of excavators
- Truck size.
- Number of trucks
- Dumping location
- Haul route
- Hours of operation

Main input assisting management choice decisions includes:

- Equipment (total owning and operating) hourly costs
- Equipment fuel consumption
- Local traffic conditions
- Local road conditions and restrictions
- Loading and unloading space requirements

This enables choices to be based on unit emissions (emissions/production), and unit cost (cost/production). Or these can be normalised through dividing by distance travelled by the trucks. A normalised cost is a cost per cubic metre per km; that is, the cost of hauling 1 m3 over 1 km. Normalised emissions are CO2-e emissions per cubic metre per km. This is demonstrated on two case studies.

Case Studies

Two case studies are examined.

Case A. Road construction. Excavated soil was moved to other areas on- and off-site. Based on data collected, costs and emissions are calculated for a different sized trucks and different numbers of trucks. Different sized trucks require different loading times. Over longer hauls, the relative impact of extra loading time decreases. Different sized fleets lead to different truck idle times at the load point.

Case B. Cable installation. In the installation of an underground cable, excavated soil was hauled to another site. Based on data collected, costs and emissions are calculated for hauling during day and night traffic conditions. Daytime travel takes longer than night time travel, and this leads to lower production and higher costs. Because fuel is being consumed while a truck is stationary in traffic, and because truck fuel efficiency is greater at higher speed (Ding, 2000), fuel consumption will also be higher in daytime conditions.

Two types of hauling vehicles are involved in the case studies – a dump truck and a truck-and-dog. A dump truck has three axles, and empties via the elevation of the front of its tray. A truck-and-dog has a three-axle prime mover with a tray, towing a three-axle trailer with a tray; both trays are emptied by the elevation of their fronts, with the trailer requiring manoeuvring in order that it is not in the way when emptying the prime mover tray.

In the following, cycle time refers to the time taken for a truck to load, haul, unload, and return, together with any waiting and manoeuvring time at the load and unload points. Idle time refers to the time involved in manoeuvring, loading, unloading and waiting, as well as any time spent stopped otherwise. Travel time refers to time on the loaded haul and unloaded haul.

Case A. Road Construction

The urban project involved the construction of a 1.9 km road in order to connect two existing roads. There were one cut area and four fill areas (denoted Fill 1 to Fill 4). Some of the soil from the cut was suitable to be reused in the fill areas; the remaining material required hauling to a dump site.

Dump truck characteristics: 5.7 m3; $85/h; 28 litres/100 km (specification).

Truck-and-dog characteristics: 14 m3; $130/h; 49 litres/100 km (specification).

Cut to Fill 3. One excavator and a fleet of 6 dump trucks were employed. Trip data were collected over a period of two weeks, involving 918 loads and 506 hours. Table 1 gives the summarised site data together with calculated values.

Table 1. Case A: Cut to Fill 3, dump truck, data and calculated values.

Truck cycle distance	7.8 km
Average cycle time	33 min 4 sec
Average total idle time per cycle	3 min 25 sec
Average travel speed	15.8 km/h
Total fuel use	4745 litres
Unit cost	$8.22/m3
Normalised cost	$1.05/m3/km
Unit emissions	2.45 kg CO2-e/m3
Normalised emissions	0.314 kg CO2-e/m3/km

The equivalent number of truck-and-dogs and their corresponding trips per day are estimated based on hauling the same amount of material as the dump trucks; the resulting cost and emissions are then calculated. Table 2 gives the corresponding values.

Table 2. Case A: Cut to Fill 3, truck-and-dog, calculated values.

Truck cycle distance	7.8 km
Average cycle time	38 min 49 sec
Average total idle time per cycle	9 min 12 sec
Average travel speed	15.8 km/h
Total fuel use	3458 litres
Unit cost	$6.01/m3
Normalised cost	$0.77/m3/km
Unit emissions	1.78 kg CO2-e/m3
Normalised emissions	0.228 kg CO2-e/m3/km

For the dump truck to haul the same amount as the truck-and-dog it must do more trips, the ratio of payloads being 14/5.7 = 2.45. That is, the dump truck must make 2.45 times the number of trips needed by the truck-and-dog. The travel time is assumed to be the same for both truck types, but there is additional idle time (extra loading and unloading time) for the truck-and-dog, assumed to be the same as in the following (Cut to Dump) data set.

The hourly cost of the dump truck is lower and the fuel consumption is lower, but the payload difference outweighs these and results in a higher normalised cost and higher normalised emissions. Both the normalised cost and normalised emissions are lower by approximately 25% for the truck-and-dog compared to the dump truck.

Cut to Dump. One excavator and a fleet of 5 to 7 truck-and-dogs were employed. One week (241 hours) of haul data were collected. During this time, 231 trips were made. Table 3 gives the summarised site data together with calculated values.

Table 3. Case A: Cut to Dump, truck-and-dog, data and calculated values.

Truck cycle distance	37.8 km
Average cycle time	1 h 2 min 35 sec
Average total idle time per cycle	9 min 12 sec
Average travel speed	42.5 km/h
Total fuel use	5258 litres
Unit cost	\$9.69/m3
Normalised cost	\$0.26/m3/km
Unit emissions	4.39 kg CO2-e/m3
Normalised emissions	0.116 kg CO2-e/m3/km

Equivalent dump truck calculations are given in Table 4.

Table 4. Case A: Cut to Dump, dump truck, calculated values.

Truck cycle distance	37.8 km
Average cycle time	56 min 49 sec
Average total idle time per cycle	3 min 25 sec
Average travel speed	42.5 km/h
Total fuel use	7323 litres
Unit cost	\$14.12/m3
Normalised cost	\$0.37/m3/km
Unit emissions	6.10 kg CO2-e/m3
Normalised emissions	0.161 kg CO2-e/m3/km

The comparison again shows that the truck-and-dog performs better in terms of unit cost and unit emissions (by approximately 28%) than the smaller dump truck.

Comparing Cut to Fill 3 with Cut to Dump, the longer haul with higher speeds and less stoppages performs better in terms of both unit costs and unit emissions.

Case B. Cable Installation

The project involved opening an existing road in order to lay an underground cable. The dump site was located approximately 10 km away, via urban streets and dense traffic. During different stages of the project, there were restrictions on when the work was allowed to take place, as outlined in the government-issued road occupancy licence.

Day operation. Excavation at one location occurred between the hours of 10 am and 3 pm, as specified in the road occupancy licence, in order to avoid the morning and afternoon peaks in traffic, and not inconvenience residents. An excavator and a fleet of 5 dump trucks were used. The dump trucks were the same, and had similar load and unload times as the dump trucks in Case A. Data over a 1-week period (125 hours) were collected, involving 162 trips. Table 5 gives the summarised site data together with calculated values.

Night operation. Excavation at another location occurred between the hours of 9 pm and 5 am, as specified in the road occupancy licence, in order to not block the heavily trafficked road during the day. An excavator and a fleet of 4 dump trucks, of the same type as the Day operation, were used. Data over a 1-week period (160 hours) involving 249 trips were collected. For Night operation, the contractor allowed a 50% increase in costs because of the higher night labour rates required. Table 6 gives the summarised site data together with calculated values.

Table 5. Case B: Day operation, data and calculated values.

Truck cycle distance	9.9 km
Total volume	923 m3
Total fuel use	1520 litres
Unit cost	$11.51/m3
Normalised cost	$1.16/m3/km
Unit emissions	4.44 kg CO2-e/m3
Normalised emissions	0.449 kg CO2-e/m3/km

Table 6. Case B: Night operation, data and calculated values.

Truck cycle distance	9.5 km
Total volume	1419 m3
Total fuel use	2290 litres
Unit cost	$14.37/m3
Normalised cost	$1.37/m3/km
Unit emissions	4.35 kg CO2-e/m3
Normalised emissions	0.415 kg CO2-e/m3/km

A comparison of Tables 5 and 6 shows that the normalised cost of hauling during the day is lower (approximately 15%) than hauling at night, primarily because of the increased labour rates at night. However, for emissions the reverse applies – night work gives lower (approximately 8%) normalised emissions than day work, primarily because of the absence of traffic, and the ability of the trucks to travel faster with less stops.

Traffic counts on the roads travelled by the dump trucks show morning and afternoon peaks with a plateau in between, and small vehicle counts at night. The Day operation coincides with the plateau between morning and afternoon peaks. The Night operation corresponds with low traffic volumes. See Figure 1.

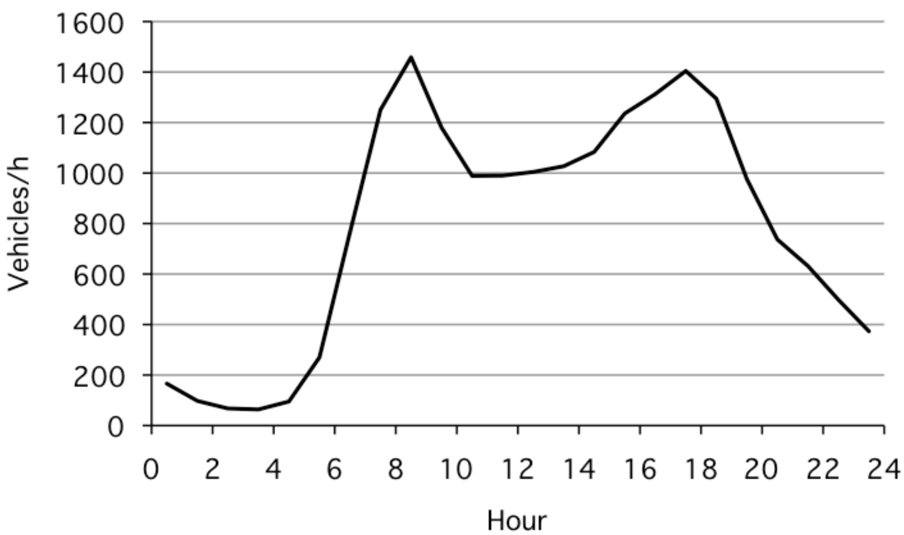

Figure 1. Hourly traffic distribution – average vehicle numbers per hour (RMS, 2014).

Discussion

Case A. Road Construction. Case A results show that normalised cost and normalised emissions decrease in line with:

- Larger trucks.
- Larger cycle times (where idle time is a smaller proportion of the total cycle time).

Simulations, varying the truck cycle time, give the results in Figures 2 and 3.

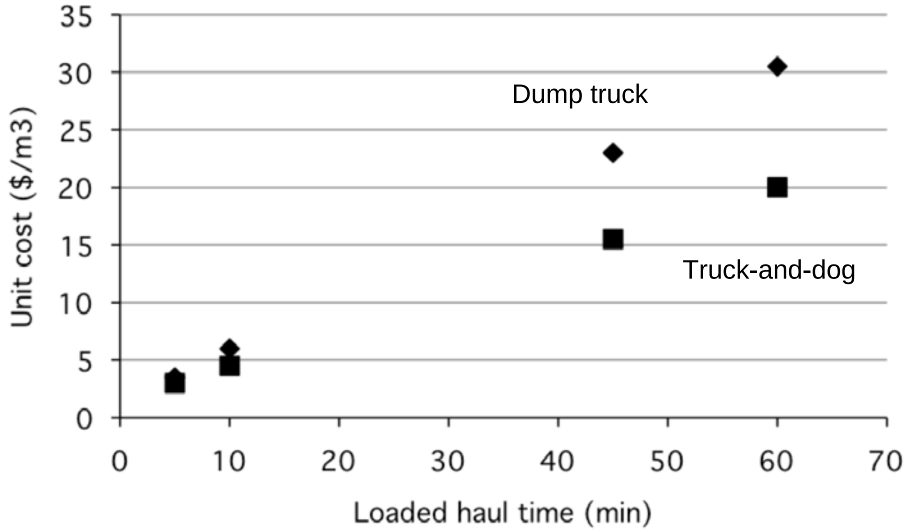

Figure 2. Unit cost; simulation; upper – dump truck, lower – truck-and-dog.

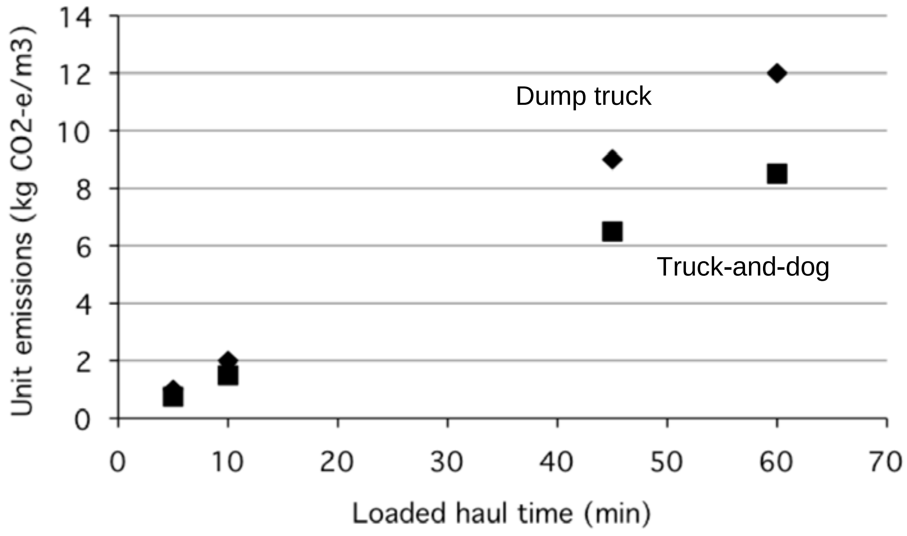

Figure 3. Unit emissions; simulation; upper – dump truck, lower – truck-and-dog.

For normalised cost, at very small haul durations, the smaller dump truck is the better alternative, but for more usual haul times, the larger truck-and-dog becomes more economical. For normalised emissions, the larger truck-and-dog is always better.

Case B. Cable Installation. Figure 4 shows the change in normalised emissions with change in traffic density. Average speed, number of stoppages and idle time all contribute to fuel consumption. With higher traffic levels, the average speed decreases while the number of stoppages and idle time increase.

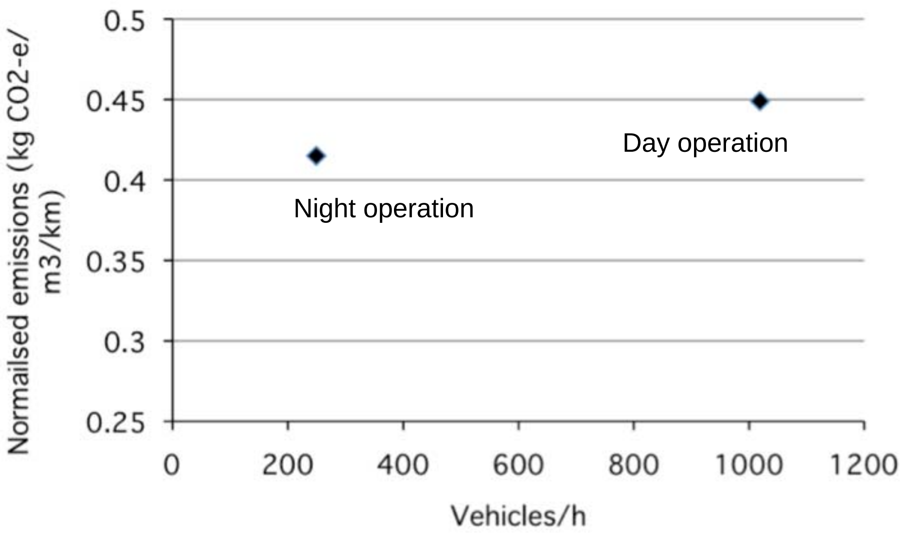

Figure 4. Relation between hourly traffic and normalised emissions.

Hauling at night results in a higher production, and this can be almost entirely attributed to the faster haul times because the loading and unloading times remain unchanged whether day or night. However, this increased production is not enough to outweigh the extra labour cost of night work. Without this extra labour cost, night operation would lead to a lower normalised cost.

Conclusion

Under ordinary operating conditions, the least unit emissions solution coincides with the least unit cost solution. This only changes with increased labour rates resulting from night work, and may change if non-ordinary constraints existed on the earthmoving operation.

Accordingly, in order to impact the environment the least, contractors should continue historical management practices of minimising unit costs.

The case studies demonstrated the following:

- A smaller fleet of larger trucks results in lower emissions and costs than a larger fleet of smaller trucks.
- Normalised emissions and normalised cost decrease with longer truck cycles, with the reduction more worthwhile for very long cycles.
- A direct link, as anticipated, exists between traffic conditions and emissions.
- Additional labour rates for night work (low traffic conditions) are not matched by the reduction in emissions at current carbon prices, or an increase in production.

Future work. The effect of individual operators on production and fuel use was not examined. The manner in which a truck is driven can influence both fuel use and production. The study looked at average operator behaviour only.

The emission of products resulting from incomplete combustion of diesel fuel increases at lower speeds and with higher acceleration. A detailed emission breakdown of products, rather than only looking at CO2-e based on the fuel consumption, would be helpful in showing the effects of traffic in more detail.

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