Using Delivery Route Characteristics to Estimate Urban Freight Emissions

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Abstract. The estimation of pollutant emissions related to urban freight activities suffers from the same difficulty faced when trying to estimate the characteristics of individual urban freight routes or demand parameters. The great variety of urban freight practices forces to attain this objective only through strong hypotheses and simplifications. We propose here a methodology based on the generic characterization of urban freight routes, identifying the main features of each route type and the type of commercial activities typically served by each one of them. This results in an estimation of the overall urban freight route patterns in a city, which in turn can be used to derive aggregate emission values. The methodology is applied to the city of Seville, in the South of Spain, showing promising results.

Keywords: urban freight, routes, emissions.

1 Introduction

The analysis of urban freight deliveries is by definition a complex task, due to the multi-component systems involved and the diverse interactions between them. This is why the provision of urban freight solutions for a city should always start with an exhaustive view of the current scenario, from all the possible angles. The efficient management of urban freight transport supports the economic, social and environmental sustainability of the area. This work focuses on one of those angles, namely the impact of urban freight on the environment, related to the use of fossil fuel vehicles, the subsequent energy consumption and the resulting levels of pollutant emissions.

The existing literature shows some recent examples of models formulated to estimate emission levels associated to urban freight transport. Kanaroglou and Buliung (2008) combine a vehicle emissions model with a set of OD matrices by vehicle type, and use a traffic assignment algorithm to derive emission levels derived from vehicle flows. Muñuzuri et al (2010) apply a similar approach to estimate the ecological footprint for urban freight deliveries, basing their analysis on the estimation of freight vehicle flows, speeds and stops. Figliozzi (2011), on the other hand, applies a routing approach, combining vehicle routing techniques with an emissions model to estimate urban freight CO_2 emissions in Portland, Oregon.

Other models use empirical data to estimate freight vehicle movements, and then combine those movements with emissions models. For instance, Zanni and Bristow (2010) analyse the effect of several policies to reduce urban freight emission levels, and obtain their emissions data from the 2008 London Freight Data Report (Transport for London, 2008), which identify automatic traffic counts as the main source of information. Velikovic et al (2014) combine traffic counts with roadside interviews to estimate a shortest travel distance traffic assignment technique, used to calculate average trip lengths.

Our analysis, presented here, incorporates supply chain considerations into these emission models, linking emissions with the characteristics of each different type of urban freight delivery route. In the following sections, we start with the identification of the parameters that have an effect on fuel consumption and emissions for urban delivery vehicles. Depending on these parameters, we then establish the level of emissions depending on the type of service provided by the vehicle, through the classification of the different route types normally followed in a city. This links the last mile delivery with the even more complex upstream supply chain designs, allowing us to estimate the energy consumption and emissions for each route. This estimation procedure is then applied to a specific city, which requires prior knowledge on a series of relevant factors, like the characteristics of the delivery vehicle fleet, the climate conditions, the geographical and land use profiles, the urban design, etc.

2 Vehicle characteristics

The first step of the analysis consists of the identification of the relevant parameters to build energy consumption and emission correlations. The following sections show a discussion about the parameters taken into account and the different values assumed for those parameters in our analysis.

2.1 Engine characteristics

In our calculations, we will assume that all the commercial vehicles run on diesel, which best approximates the real situation according to the official statistics (Campestrini and Mock, 2011). We will consider four types of trucks, shown in Table 1. In order to simplify the existing scenario, where many different vehicle models fall into each one of the four categories, we have chosen a generic type of engine for each category, representative of all the vehicles included in it. However, the energy consumption and emissions level of delivery vehicles are not standard and static depending on the type of engine, but instead vary as a function of additional external parameters, normally related to the vehicle's environment and operating conditions. The following sections introduce the analysis of these parameters, establishing the main assumptions that were adopted for the completion of our research estimations.

Table 1: Characteristics of the representative engine for each type of urban freight vehicle.

Engine no	Vehicle type	Cylinder capacity	Cylinders	Power	Injection
1	Light van	1600 cc	4 line	75 HP	Direct
2	Large van	2300 cc	4 line	130 HP	Direct
3	Light truck	3000 cc	4 line	150 HP	Direct
4	Large truck	4500 cc	4 line	250 HP	Direct

2.2 Engine performance

An engine with capabilities of e.g. 90 HP and 180 Nm of torque does not normally develop that extreme performance. On urban routes, where vehicles yield to speed limits and congestion, thus resulting in low and discontinuous speed patterns, engines tend to develop a useful power performance of around 45% of its maximum theoretical power (Kruczynski et al, 2010). Common urban operating conditions of the four engines can thus be defined as follows: Engine 1: 30 HP, 175 Nm; Engine 2: 59 HP, 300 Nm; Engine 3: 67 HP, 350 Nm; Engine 4: 112 HP, 800 Nm.

2.3 Stops and starts

A stop is defined as a decrease in speed until the vehicle is completely still, but without turning off the engine. The impact of vehicle stops of vehicles is negligible in terms of consumption, but not so with respect to emissions. Hydrocarbon (HC) emissions increase significantly with stops, 100% for routes of 80 km/h of average speed. For routes with lower speeds, like those corresponding to urban environments, HC emissions are lower during stops, varying between 0.1 and 0.25 g/km. Emissions of carbon monoxide (CO) and nitrogen oxides (NOx) behave in a similar way. In general terms, the existence of stops in a route can increase emissions by as much as 100% with respect to the same route with the same average speed but no stops, whereas fuel consumption would only increase by 10%.
On the other hand, a start corresponds to the starting of the engine and initiation of the drive. Cold starts take place when engines have been turned off for a minimum 4 to 8 hours, so that all its fluids are at complete rest. The estimation of the emission of harmful gases expelled by the exhausts of vehicles as result of fuel consumption takes into account that the combustion of internal engines is incomplete, but in addition these emissions are accentuated when the ambient temperature is low or the engine is cold. These additional emissions are known as "cold start emissions".
Modern vehicles are equipped with catalytic converters, devices that reduce the amount of gases emitted by capturing them and modifying their composition or chemical character. But the optimum performance of a catalytic converter engine requires an operating temperature above 300 °C. Between the cold start instant and the reaching of this temperature, the emission rates are considerably higher, and the duration

of this transient period depends on the outdoor temperature, which in turn determines the initial temperature of the vehicle's mechanical components.
We have considered that engine starts have 3.5 sec duration, and 8 sec for cold starts, both independent from the type of vehicle.

2.4 Average cruising speed

The consumption of fuel on routes at constant speed decreases from a maximum at 10 km/h to a minimum around 80 km/h, and from there the average consumption rate returns to grow. There is a range variation of around 300% in the average consumption of fuel between the minimum and maximum consumptions for routes at different constant speeds (Kruczynski et al, 2010). With respect to pollutant emissions, the rates can be described as follows in relation to average speed:

- Hydrocarbon (HC) emissions grow as speed increases, with minimum emissions occurring at about 55 km/h. The difference between the minimum and maximum HC emissions is approximately 300% between 10 and 120 km/h.
- Minimum emissions of CO are obtained at 20 km/h and increase thereafter, with a variation between the minimum and the 120 km/h maximum of 600%.
- Nitrogen oxides (NOx) emissions follow a similar behaviour to CO, with a variation between maximum and minimum emissions of 350%.

In conclusion, a 1% increase in fuel consumption due to an increase of the average speed, the subsequent increase in emissions is 50% for HC and 100% for NOx and CO.

2.5 Idling

This is the state in which the engine rotates outside its normal range, with the vehicle stopped. The fuel consumption is practically non-existent, but not negligible, and the same can be said of emissions. In fact, idling operation of an engine is harmful to the vehicle systems, producing oil overheating and the generation of charcoal.

According to all the above, the amount of pollutants emitted in a given route can be approximately estimated as follows (we have considered 3.5 seconds for the duration of starts, and 5 seconds for cold starts):

Route emissions =
= Route distance (km) · Speed (min/km) · Driving emissions (mg/min) +
+ No starts · Start duration (min/start) · Start emissions (mg/min) +
+ No cold starts · Cold start duration (min/start) · Cold start emissions (mg/min) +
+ Idling time (min) · Idling emissions (mg/min)

3 Estimation of exhaust emission flows

Following this description of the four types of engine, our objective is to estimate the quantities of pollutants emitted by each one of them during daily operations. With respect to pollutant emissions we take into account the five main regulated pollutants generated by these vehicles: carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx) and particulate matters (PM). The literature also shows different examples of vehicle emission correlations, which provide the instant emissions levels for the different pollutants depending on the characteristics of the vehicle, the atmospheric and operating conditions, etc. Since they mostly rely on empirical tests, the usually concentrate on specific pollutants, like Keogh et al (2009) analysing the emissions of particulate matters, and Weiss et al focusing on NOx and CO levels. A formulation of models to estimate emission levels for the different pollutants and different operating conditions is provided by Demir et al (2011), whereas Yin et al (2013) study the effect of altitude on those emission levels under an idling regime.
The data used in the remainder of the paper is shown in Table 2. In our analysis, we have used the average emission correlations adapted from EMEP/EEA (2013), and the PM correlations are derived from Keogh et al (2009).

Table 2: Emission flows for the different pollutants depending on the type of engine.

Engine type		Start	Cold start	Flat driving	Idling
1	NOx (mg/min)	3443.784	2755.027	7379.537	1475.907
75CV-4000rpm	CO (mg/min)	4192.432	5390.270	1796.757	598.919
175Nm-1500rpm	CO2 (m^3/min)	0.698	0.620	1.163	0.310
1600cc	HC (mg/min)	8573.097	10716.371	5358.185	1393.128
	PM (mg/min)	104.8108	134.75675	44.918925	14.972975
2	NOx (mg/min)	5862.019	4689.615	10991.285	2051.707
130CV-3500rpm	CO (mg/min)	7047.166	8742.054	3211.367	713.637
`Nm-2000rpm	CO2 (m^3/min)	1.155	1.270	1.964	0.578
2300cc	HC (mg/min)	14365.132	19153.509	9257.529	2106.886
	PM (mg/min)	176.17915	218.55135	80.284175	17.840925
3	NOx (mg/min)	7337.672	2751.627	14675.345	2678.250
150CV-3500rpm	CO (mg/min)	9937.761	10049.421	6252.973	1339.923
350Nm-1500rpm	CO2 (m^3/min)	2.024	1.301	2.314	0.723
3000cc	HC (mg/min)	17981.285	29968.809	13585.860	3196.673
	PM (mg/min)	248.444025	251.235525	156.324325	33.498075
4	NOx (mg/min)	16974.076	14145.063	21217.595	6789.630
250CV-2500rpm	CO (mg/min)	15498.069	20664.093	5166.023	2686.332
800Nm-1500rpm	CO2 (m^3/min)	2.230	2.007	3.568	1.115
4500cc	HC (mg/min)	26806.125	36973.966	20243.246	7394.793
	PM (mg/min)	387.451725	516.602325	129.150575	67.1583

4 Route characteristics

Our objective in this research work is to link the engine characteristics and emission levels to the routes followed by the different vehicles while delivering goods in urban areas. While the types of engines used in urban freight can be roughly reduced to four, the variety in types of delivery activities and routes is much larger. This section will describe the main types of B2B routes that can be found in a city, and these routes will thereafter be matched with emission levels to obtain an estimation of freight-related emissions in a city. We have identified eight different types of routes, each one with different characteristics as follows.

- **Routes A** (pharmacies): This is the type of route that includes shipments of products and replacements of medicines to pharmacies in a city. This type of routes are usually repetitive, with every vehicle coming out of the depot going through an assigned fixed area that usually covers two to three zip codes, covering the demand of some 20 chemists every day. The distance travelled in each route is about 100 km, depending on the distance between pharmacies. The vehicles used in this type of distribution are usually large vans or light trucks, because even though the unitary weight of the shipments is small the overall load tends to be bulky, including several shipments of medicines in cuvette (70% of shipments) and packages (30%). The delivery times are usually very low, between three and five minutes, since the freight volume per delivery is low and directly delivered to the pharmacist at the counter.
- **Routes B** (home deliveries): These routes provide reduced-volume shipments (20 kg max) for home deliveries, corresponding either to courier services or e-commerce shipments. Parcel service merchandise is delivered almost in exclusivity (90%) by the companies in the sector which are professionally engaged in distribution. These companies distribute their work by areas, which are served from different franchises of the company on independent routes. Each area usually covers between two and three zip codes. The distribution of this type of goods is usually done by vans. Each franchise employs between 4 and 6 distribution vehicles that often travel about 60 km daily following a fixed route with stops at the different delivery points. Each franchise corresponding to a large company usually sends from 400 to 500 packages a day, depending on the area of the city, in some 300 expeditions a day. Thus, the number of expeditions per vehicle is close to 50.
- **Routes C** (beverages): These routes provide the restocking of soft drinks, beer, juices and spirits to the bars, restaurants and cafés in a city. A key feature to consider in these routes is the typically high density of bars and restaurants in a city, especially in the central areas where deliveries are more complicated. This characteristic favors, in most cases, the application of multiple deliveries with the help of a hand truck. The urban distribution of drinks is usually carried out by medium-sized or large

trucks, since drinks are heavy goods, with the exception of the deliveries that occur in the downtown areas where access can only be done with light trucks. To facilitate the unloading of drinks, trucks are usually unloaded laterally through a sliding curtain, and each delivery usually takes an average 20 minutes per establishment. Since deliveries are usually multiple, vehicles can be stopped for over one hour at the same spot. The distances travelled in this type of routes are short due to the high concentration of bars. Each bar receives deliveries once or twice a week, depending on their amount of sales.

- **Routes D** (supermarkets): This type of distribution is characterized by the large variety of merchandise that is consolidated in the same trip; normally a vehicle is responsible for replacing a single supermarket and only makes that journey. The vehicles used tend to be medium-sized trucks and sometimes even heavy trucks, as long as regulations allow it. Vehicles at the same time can also have refrigerated compartments for the carriage of goods at controlled temperature, including perishables or frozen products. The consumption of refrigerated vehicles (and therefore the emission levels) is roughly 25-30% above that of regular delivery vehicles, depending on the operation pattern. Due to the large number of goods delivered per trip and the complicated and delicate handling involved, the unloading time is high, reaching sometimes more than one hour.
- **Routes E** (fresh food): These routes cover the distribution of perishable food such as meat, dairy products, fish, fruit, bread and vegetables through various providers. These services are aimed at small businesses of food, restaurants, schools, hospitals, hotels, etc. The routes followed by providers are quite stable and cover different areas, travelling long distances in an organized way. The time required for unloading and delivery at each establishment is usually less than twenty minutes. The frequency with which a provider supplies with its products to a particular establishment varies depending on the type of destination; for instance, a restaurant will need fresh fish every day while a small supermarket will need to replace stocks of meat products between two and three times a week.
- **Routes F** (tobacco): These routes service vending machines of bars, restaurants and cafés in a city and supply the local tobacconist's shops. This type of route is characterized by the large concentration of a number of vending machines on a same street, located in bars, pubs, restaurants and nightclubs. As with the distribution of drinks, this high density favors multiple deliveries to several premises at each stop. The vehicles typically used in these distribution routes are vans, since the goods to deliver are low-volume and low-weight. Although deliveries are very small in size the parking time is medium to high, due to the multiple deliveries.
- **Routes G** (shoes and clothing): A feature of this type of routes is that the largest concentration of establishments is commonly found in central areas with difficult access, or shopping areas, so most commonly vehicles used for distribution are light trucks that are capable of transporting a fair volume of goods and have easy maneuverability. The great speed with which the demand should be satisfied in these shops calls for a large flow of goods from centralized distribution centers. The frequency with which each store receives deliveries is about twice a week, and deliveries are unloaded directly into the warehouse for subsequent replacement by the shop staff. Each delivery usually requires less than twenty minutes and preferably takes place in the early hours of the morning so that customers can find what they are looking for in the establishment that same day.
- **Routes H** (home appliances and furniture): These routes encompass the urban distribution of electronic materials, appliances and home furnishings stores and superstores devoted to retail sale. This type of route is characterized by carrying a small number of packages of large volume and weight. The vehicles used to carry the deliveries from the premises of the manufacturer to the retailer are mostly medium-sized trucks, which support a great payload, although light trucks are also used. Deliveries are made in the city covering different areas and trying to encompass the widest possible number of stores that have requested the merchandise. The deliveries are carried out with individual stops for each establishment, covering a period of more than twenty minutes, due to the difficult maneuverability and fragility of the goods which are distributed.

5 Case study

We have applied all the above correlations to analyze freight delivery operations in the Spanish city of Seville. This is a 40 km2 city with 700,000 inhabitants and a radial structure which concentrates commercial activities in the downtown area and several other locations near the center. Seville is a flat city, which eliminates the distortions due to gradient changes in the consumption and emission models.

5.1 Route definition

Table 3 shows the correspondence between the different economic activities and the different types of delivery routes. In this table, some activity types are served by a single type of routes, like pharmacies with routes A or furniture stores with routes H. In these cases, the entire daily delivery frequency corresponds to that type of route. However, in the case of bars and restaurants and cafés and nightclubs, they are served by different types of routes. In these cases, the delivery frequency revealed by the establishment type has been split between the different types of routes, resulting in the daily frequency allotted to each one of them. For instance, the 2.5 deliveries received daily by each bar and restaurant in the city has been split equally between routes C, E and F, which represents that each establishment receives 0.8 deliveries from a C-type route, 0.8 from an E-type and 0.8 from an F-type on a daily basis. Identically, of their 2 daily deliveries, cafés and nightclubs receive 1 from a C-type route and 1 from an F-type route. Home deliveries have also been included in the table, even though their frequency cannot be estimated from any available demand data. Finally, Table 8 shows the average characteristics of the different route types for the city of Seville.
Knowing the number of establishments of each type located in the city (2nd column of Table 3) and the daily frequencies for each type of route associated with those establishments (3rd column), it is possible to estimate the actual number of customers served daily by each type of route. For example, G-type routes serve 956 shoes and clothing stores with a 0.4 daily frequency, resulting in $0.4 \cdot 956 = 382$ actual daily destinations. This information is completed for all the route types in Table 4, which table also contains the number of routes of each type completed daily, obtained dividing the number of actual daily destinations by the average number of customers served per route.

Table 3: Retailer activities and delivery routes.

Commercial activity	No of establishments in the city	Daily delivery frequency	Route type							
			A	B	C	D	E	F	G	H
Pharmacies	420	2	2							
Furniture	307	0.5								0.5
Home appliances and electronics	309	0.4								0.4
Bars and restaurants	3433	2.5			0.8		0.8	0.8		
Cafés and nightclubs	315	2			1			1		
Minimarkets	131	1					1			
Supermarkets	156	1				1				
Fruit and vegetables	476	1					1			
Butchers	470	1					1			
Fish	409	1					1			
Tobacco	281	1						1		
Shoes and clothing	956	0,4							0.4	
Home deliveries	-	-		X						

Table 4: Characteristics of the different types of routes for the city of Seville.

Route type	Clients per route	Average route length	Type of vehicle	Delivery time	Possible destinations	Daily destinations	Destinations per route	Daily routes
A	20	10 km	Van	< 5 min	420	420	20	21
B	50	5 km	Van	< 5 min	10852	10852	50	217
C	10	7 km	Truck	> 20 min	3748	8020	10	802
D	1	15-20 km	Truck	> 20 min	156	156	1	156
E	5	8 km	Light truck	< 20 min	1486	7132	5	1426
F	15	5 km	Van	< 20 min	281	691	15	46
G	1	6 km	Light truck	< 20 min	956	382	1	382
H	1	15 km	Large truck	> 20 min	616	554	1	554

5.2 Traffic light stops

Apart from the number of stops associated to deliveries, each route contains a number of short stops due to traffic lights, which force the vehicle to stop, remain idle for a fraction of time, and then restart and regain speed. In order to determine the number of traffic lights encountered by an average delivery vehicle along its route, we selected seven random routes in the city (see Table 5) and averaged the number of traffic lights counted in them to estimate the average number of traffic lights per km in the city.

Table 5: Number of traffic lights along seven random routes through the city of Seville.

Route	Origin	Destination	Distance	Traffic lights
1	Betis stadium	Barqueta	6 km	30
2	Barqueta	Prado	4 km	15
3	Paz Avenue - South	Paz Avenue - North	2.5 km	10
4	Santa Justa station	Palmera tunnel	5 km	11
5	Prado	Hytasa	4 km	15
6	Gran Plaza	Puerta de la Carne	2 km	10
7	San Bernardo station	Puerta de Carmona	2km	20

According to the collected data, the city of Seville has a traffic light intersection every 250 m and while driving at the usual speed, approximately one in every four forces to stop. In any case, it is true that this distribution varies according to the type of streets, with different values in downtown streets, neighborhoods and large avenues.
The cycle time in Seville is 120 seconds during most of the daytime, and red periods tend to last between 10 and 60 seconds. We chose an average 30 seconds idling for each traffic light stop, and with this value derived the figures shown in Table 6 for the average number of stops and idling time for each type of route in the city.

Table 6: Estimation of traffic light stops and associated idling time for each type of route.

Route type	Route distance (km)	No traffic lights	Traffic light stops	Idling time (min)
A	210	840	210	105
B	1085	4340	1085	542
C	5614	22456	5614	2807
D	3120	12480	3120	1560
E	11408	45632	11408	5704
F	230	920	230	115
G	2292	9168	2292	1146
H	8310	33240	8310	4155

5.3 Emission values

The laws of road traffic in the cities restrict vehicles to 30 km/h if the road is a unique lane by direction, for instance a street, at 50 km/h if the path has more than one lane by direction, for instance the avenues, and speeds of 60 to 80 km/h for intercity stretches of highway. To set an average speed of defined routes we will rely on a study conducted by the Seville Company responsible for buses, TUSSAM public transport. This company estimated that the average speed of its fleet throughout Seville, covered in it streets, avenues and small sections of bypasses, was 10 km/h.
As explained in section 2 (consumption correlations) for each driving specific situation there were some emissions of certain pollutants. Thus the corresponding mass (mg/min) flow rates emissions of the main pollutants were calculated depending on the type of engine. The different types of stops in each route also involved different emission rates, as follows:

- Less than 5 minutes: when the parking space is close to the destination and the delivery to the customer is fast, involving only one displacement between the vehicle and the customer's premises. This type of stop was considered to be followed by a normal start.

- Between 5 and 20 minutes: this type of stop may involve several fast deliveries to different customers reachable from the same parking place, or one longer delivery to a single customer. It is followed by a cold start
- More than 20 minutes: usually involving several long deliveries to different customers from the same parking space, also followed by a cold start.

As a result, the emission estimates for each type of pollutant generated by each type of route in the city of Seville are shown in Table 7.

Table 7: Emission estimations for the different route types in Seville.

Route type	Pollutant				
	NOx (kg/day)	CO (kg/day)	CO_2 (m3/day)	HC (kg/day)	PM (kg/day)
A	9.56	2.48	1521.6	7.22	6.20
B	76.67	26.29	13843.9	71.58	65.73
C	746.69	194.84	97391	724.93	487.10
D	410.4	103.92	68848.8	395.31	259.80
E	1025.9	446.67	160027.1	969.19	1116.68
F	10.53	2.79	1822.82	8.04	6.98
G	205.71	89.21	32942.3	193.86	223.03
H	1093.39	277.14	178784.1	1053.52	692.85
Total	3578.9	1143.3	555181.7	3423.6	2858.25

6 Conclusions

The characterization of urban freight delivery routes provides a basis to incorporate supply chain considerations into the analysis of city logistics issues. In this research, we have categorized urban freight deliveries into eight different types of routes, each one of them with distinct characteristics, frequencies and numbers of stops. Following this classification, it is then possible to estimate aggregate values for urban freight movements, distances covered and related emissions.

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