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How the Street Network Slope Influences Fuel Consumption in Urban Freight Routing

Javier Yesid Mahecha Nuñez[a], Rafael Humberto Rojas Millan[b,*], Juan José Cabello Eras[c], Oscar Pinto Garralaga[d], Gustavo Gatica[d]

[a]Universidad Militar Nueva Granada, Sede Campus Nueva Granada, Colombia
[b] Department of Productivity and Innovation, Universidad de la Costa, Calle 58 # 55 - 66. Barranquilla, Colombia.
[c]Department of Mechanic Engineering. University of Cordoba. Monteria - Córdoba, Colombia
[d] Faculty of Engineering, Andres Bello University, Antonio Varas 880, Santiago, 750097,Chile.

Abstract

Although there are many investigations on the problem of vehicle routing, few consider the real slope changes in the road networks of cities. The objective of this work is to calculate the effect that the slopes of a road network can have on fuel consumption, combining a metaheuristic solution algorithm, traffic characterization and an algorithm for the calculation of road slopes. The results of the model show that considering the slope in the urban merchandise distribution model can increase the estimates of fuel consumption by 28.67%.

Keywords: Urban Freight Transportation; City Logistics; Vehicle Routing Problem; Eco-efficiency in transportation; Pollution problem.

1. Introduction

The problem of the efficient distribution of merchandise within cities is today one of the main challenges for companies and actors involved in transport logistics. In the urban context, there are several actors involved in achieving an efficient plan and they generally have different interests (Kijewska et al., 2019). For example, carriers

* Corresponding author.
E-mail address: rrojas@cuc.edu.co

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want to deliver while minimizing operational costs and delivery times. The other traffic actors, on the other hand, do not want trucks to circulate on their streets because they cause several problems considered as externalities: atmospheric emissions, congestion, and accidents (Holguín-Veras et al., 2019).

However, it is a fact that cities need supplies and it would be almost impossible to conceive of the functioning of cities without an urban distribution of goods. From the point of view of urban logistics, the vehicle routing problem (VRP) was initially raised in 1959 (Dantzig & Ramser, 1959). Congested flows and slow speeds are generally associated with delays and slow traffic speeds (Holguín-Veras et al., 2020; Kickhöfer & Kern, 2015). The costs associated with fuel consumption can represent 50% of the total operational costs of urban freight transport (Lang et al., 2014). Fuel consumption can be a function of the gravitational potential energy that a vehicle needs to overcome in its journey, however, most of the investigations do not consider the slope in fuel consumption (Deflorio et al., 2012; Franceschetti, 2015; Maternini et al., 2017; Russo & Comi, 2011, 2020).

This paper presents the optimal distribution routing within the real road network of a large city like Barranquilla located on the Atlantic coast of Colombia. Firstly, we present the method used for the optimal urban distribution model. As a solution method, we used the spreadsheet developed by Erdogan (Erdoğan, 2017) based on a metaheuristic solution algorithm. We use time windows to avoid the hour with the presence of high traffic. Secondly, we calculated the fuel consumption considering the road slope for the routing. Finally, we present a comparison of fuel consumption with and without including the road slope.

2. Related works

It is quite common that in routing problems the road slope is neglected (Franceschetti et al., 2013; Liu et al., 2020; Shao, 2020). According to some authors, a positive road slope leads to an increase in fuel consumption compared to a negative slope (Demir et al., 2011). Another author found that considering road slopes can lead to an increase in fuel consumption of up to 3% (Brunner, 2018), other studies this increase was 20%(Frey et al., 2008) and 33% (Schröder & Cabral, 2019). Another study uses detailed geographic information from a digital terrain model to calculate fuel consumption considering the road slope from a street segment every 10 m (Dündar et al., 2022). However, in our opinion, making digital terrain models and even collecting information from the field can be quite expensive. We observe that in urban networks the slopes tend to change between each intersection, so our contribution allows us to make this process much faster using computational resources and servers that include the topology of the streets, such as Open Route Service.

3. Method

This item describes the formulation of the vehicle routing model, the characterization of traffic, the algorithm for calculating slopes, and the calculation of fuel consumption.

2.1 Routing formulation model

We consider minimizing the function of the benefit of serving a client minus the fixed and variable costs and the penalty for the time windows avoiding the maximum congestion losses of tomorrow based on the analysis of the traffic characterization. For the drawing of the routes, we used the Bing Maps server based on the fastest route method. As a restriction, the trucks return to the Logistic Distribution Center (LDC) only once at the end. The unified formulation of the VRP followed the model proposed by Erdogan (Erdoğan, 2017).

2.2 Traffic Characterization

Currently, there are different sources of information available to perform the respective traffic analysis. In the first instance, we obtained information from the company HERE that provides real-time information on traffic in the city through its Application Programming Interface (API). To obtain this information, instructions were provided to access some network attributes, however, the data obtained is in a JavaScript object format (JSON: JavaScript Object Notation). This aggregate information needs to be refined to obtain historical data such as average speeds in the segments of the road network. It is worth noting that, according to the developers of HERE, real-time traffic information is not available in Colombia, however, information on historical speed patterns can be obtained by processing queries. The results of this analysis shown that from 5:00 and 5:15 in the morning, several of the city's roads began to become congested. In the same way, the traffic management office of the Barranquilla mayor's office provided information to carry out our analysis, specifically data on flow, capacity and level of service of the city's road network were requested. The level of service (LOS) from the point of view of traffic engineering is a qualitative indicator that describes the operating conditions of the roads, based on variables such as speed, travel times, delays and safety.

LOS of the roads is classified with the letters A to F, with A being the best operating condition and F the worst (TRB, 2010).

Table 1 presents a summary of the representative service levels of the main road corridors of the network from Monday to Friday during the months of April to June 2019 on 38 roads in the city. The results show that of these corridors analyzed, a higher percentage were in service level C during the three peak periods of the day, with the morning period being the one with the highest number of roads in this category.

Table 1. Summary of LOS of the main avenues of Barranquilla (Monday to Friday in the period from April to June 2019).

Level of Service (LOS)	Morning		Noon		Afternoon	
A	-	-	-	-	-	-
B	0	0%	2	5%	3	8%
C	23	61%	17	45%	16	42%
D	9	24%	10	26%	10	26%
E	5	13%	8	21%	7	18%
F	1	3%	1	3%	2	5%

On the other hand, Table 1 also shows that the mid-day period is where the highest levels of congestion occurred, with a percentage of 24% on levels E and F. In the afternoon, 23% of these corridors found in levels E and F and in the morning period 16% of the roads were in levels E and F. Only 5% and 8% of the roads in the midday and afternoon periods respectively, presented levels of service B, that is, with the best operating conditions of free flow and without delays. The corridors that presented the worst levels of service (F) correspond to: Cll 82 (Cra 58 – Cra 42H) for the afternoon period; Cra 49C (Cll90 - Cll75) in the midday period and Carrera 40 (Cll30 - Cll44) in the morning period. Additionally, subsequent analyzes will be carried out with the capacity information at 542 intersections in the city for three consecutive years during all the months from 2016 to 2019 and the months of January and February 2020. Only 5% of the corridors considered presented service levels D (high traffic density, restrictions on maneuvering and volume close to capacity). 95% of the highway corridors considered were in service levels B and C (speed and maneuverability are closely monitored due to higher volumes).

2.3 Algorithm for calculating slopes

To calculate the slopes, an algorithm programmed in R was created to use the open route service server API. The attribute of interest, in this case, is the distance of each segment and the elevation of each endpoint. From these data, the slope of each route is calculated as the relationship between the horizontal distance traveled Dh and the vertical distance Dv. In this case, the average of the positive slope in each run was considered. This is because we start from the hypothesis that fuel consumption impacts trucks more strongly when there are positive or ascending ramps (Demir et al., 2011). The algorithm of it is summarized below.

Algorithm 1*:* Road network slope calculation

```
library(openrouteservice)
library(sp)
library(rgdal)
o<-list(coordinates) # Insert the coordinates North West (start,end) for each truck
Dh<-matrix(data = 0,nrow = length(o),ncol = length(o))
Dv<-matrix(data = 0,nrow = length(o),ncol = length(o))
incl<-matrix(data = 0,nrow = 1000,ncol = 1)
dist<-matrix(data = 0,nrow = 1000,ncol = 1)
  for (k in 1:length(camion[,1])-1)
     {  disth<-(((xy[k+1,1]-xy[k,1])^2)+(xy[k+1,2]-xy[k,2])^2)^0.5
    distv<-(camion[k+1,3]-camion[k,3])
    if (isTRUE(disth==0)){
      }else {
       camion<-as.data.frame(camion)
       camion[k,4]<-disth
       camion[k,5]<-distv/disth*100
```

```
Mincl<-matrix(data = 0,nrow = length(o),ncol = length(o))
Minclmax<-matrix(data = 0,nrow = length(o),ncol = length(o))
Minclposprom<-matrix(data = 0,nrow = length(o),ncol = length(o))
Sumdistanup<-matrix(data=0,nrow=length(o),ncol=length(o))
Distatotal<-matrix(data=0,nrow=length(o),ncol=length(o))
for(i in 1:length(Dh)^(.5)){
  for (j in 1:length(Dh)^(.5)) {
    if(j>i){
    ruta<-list(o[[i]],o[[j]])
    ruta1<-ors_directions(api_key = "",ruta,profile = "driving-hgv",
elevation=TRUE, output = "parsed", preference="fastest")
    camion <- ruta1[["features"]][[1]][["geometry"]][["coordinates"]]
    xy=project(camion, "+proj=utm +zone=18 +datum=WGS84")
                    } }

Minclposprom[i,j]=mean(camion[which(camion[,5]>0),5])
   Sumdistanup[i,j]=sum(camion[which(camion[,5]>0),4])
   Distatotal[i,j]=sum(camion[,4],na.rm = T)
   } }}
Minclposprom2<-Minclposprom[,-1]
inclposprom3<-diag(Minclposprom2)
Sumdistanup2<-Sumdistanup[,-1]
Sumdistanup3<-diag(Sumdistanup2)
Distatotal2<-Distatotal[,-1]
Distatotal3<-diag(Distatotal2)
```

2.4 Calculation of fuel Consumption

For the calculation of fuel consumption, we use the model proposed by other authors (Barth et al., 2005) shown in Equation 1. In this model, the values of the constants were regrouped so that it is easier to visualize the components in the consumption equation. The fuel consumption F in liters is expressed in Equation (1). In this equation the first term corresponds to the engine modulus, the second term corresponds to the speed modulus and the last term corresponds to the weight modulus (Franceschetti et al., 2013).

$$F = C_1 \frac{d}{v} + C_2 v^2 + C_3 \alpha d \tag{1}$$

Where: d is the distance traveled, v is the speed and a=(sinθ*g+cosθ*g) being θ the angle of each track segment.

3. Results and discussion

Next, the results of the considered distribution model, fuel consumption and emissions considering the slope of the city streets are presented. The analyzed models were performed using the routing tool VRPSpreadsheetsolverv.3.52, which uses a metaheuristic solution algorithm (Erdoğan, 2017). Our model takes into account the hourly traffic generated from peak hours and the location of a LDC in a more efficient way the demand of the warehouses that are more concentrated in the northern part of the city.

We consider a LDC located in the periphery of the city. A time window between 5:00 and 5:30 in the morning and 16 different stores. For this analysis, we considered the use of seven (7) NPR Diesel type trucks. These vehicles must start the journey from the dispatch center and after passing through the warehouses they return to the same LDC. The values of the constants in Equation 1 are the same values of the constants adopted by Franceschetti. Thus, the values of the constants are: C1=1.018x10-3 g/s, C2=1.412x10-7 g*s2/m3, C3=5.449x10-4g/m. Table 2 shows the results of fuel consumption according to the optimal result of the linear programming model.

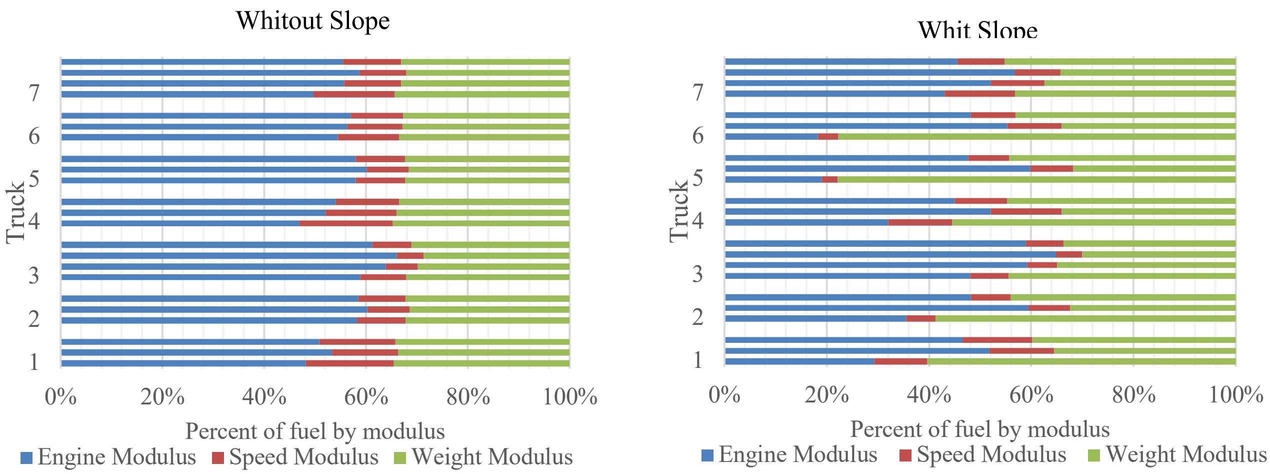
It is observed that when the slope is not considered, the consumption values increase from 104,409 to 134,344 liters, the average increase being 28.67%. As observed in Table 2, the maximum routing speed for the 7 trucks is 14.11m/s (50.8 km/h), the minimum speed is 8.29m/s (29.84km/h). The average speed of the course is 11.16 m/s (40.2 km/h).

Figure 1 presents the results of the change in consumption without considering the slope and considering the slope. In this figure, we can see how the percentage of distribution of the components of each module of fuel consumption changes. In the first case, considering that the streets do not have a slope, the module that most contributes to consumption is the Engine Modulus. However, in the second case, the Weight module component starts to have a preponderant contribution in fuel consumption of the order of 60% of the total.

Table 2. Fuel consumption of the optimal distribution considering slope and without slope

Truck	Route	Client label	Distance (km)	Speed (m/s)	Fuel consumption (l)	
					Without Slope	With Slope
1	LDC					
	Cliente2	2	24.642	13.69	3.799	6.254
	Cliente16	16	28.254	12.07	4.471	4.599
	LDC	0	51.606	12.84	8.046	8.789
2	LDC					
	Cliente11	11	19.639	10.56	3.250	5.329

	Cliente3	3	20.893	9.95	3.544	3.595
	LDC	0	42.192	10.50	6.999	8.485
3	LDC					
	Cliente15	15	12.469	10.39	2.077	2.539
	Cliente14	14	16.585	8.92	2.964	3.195
	Cliente6	6	18.404	8.29	3.420	3.482
	LDC	0	31.958	9.68	5.487	5.697
4	LDC					
	Cliente7	7	27.100	14.11	4.162	6.856
	Cliente1	1	29.862	12.44	4.689	7.635
	LDC	0	53.935	11.83	8.584	14.661
5	LDC					
	Cliente10	10	19.122	10.62	3.157	6.105
	Cliente9	9	20.436	10.02	3.456	4.696
	LDC	0	40.833	10.63	6.739	10.313
6	LDC					
	Cliente4	4	21.792	11.72	3.478	9.631
	Cliente5	5	23.377	11.13	3.794	3.471
	LDC	0	45.322	10.95	7.398	8.189
7	LDC					
	Cliente13	13	15.051	13.20	2.334	2.692
	Cliente12	12	17.654	11.32	2.849	3.046
	Cliente8	8	19.379	10.42	3.224	3.332
	LDC	0	40.303	11.39	6.491	7.920
	Total		640.808		104.409	134.344



(a) (b)

Fig 1. Change in the components of fuel consumption. (a) without slope (b) with slope

4. Conclusions

This work presents a practical method, a computational method for estimating fuel consumption considering the slopes of a real street network. This method offers the advantage of combining computational processes based on a metaheuristic solution algorithm, traffic characterization and an algorithm to calculate the slopes of the routes using an Application Programming Interface (API). The main conclusions are the following:

The slope of the streets during urban freight distribution routes has a strong impact on fuel consumption: In the case presented in a city of considerable size, fuel consumption reached increases of the order of 28.67%. However, these results may be different according to the topographic characteristics of the city.

The analysis of the components of the fuel consumption model considered shows that the weight modulus is the one that contributes the most when considering the slope. This could be explained because the weight component increases rapidly as the slope increases, requiring more energy to overcome that slope. Future research can be directed at: analyzing other alternatives such as an additional distribution center that allow optimization of routing and reduce fuel consumption, including variables related to traffic in real-time within the routing optimization algorithm, and comparing fuel consumption using other optimization methods and other cities.

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