

Freight flows, logistics costs and efficiency

Optimal Path Analysis

Public Disclosure Authorized



Background Paper

Economics Unit, Sustainable Development Department

Central America Country Management Unit

Latin America and the Caribbean Region

The World Bank

LATIN AMERICA AND THE CARIBBEAN REGION

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opportunities for all

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Contents

1. Overview	5
2. Freight flows from an Optimal Path Analysis perspective	7
2.1 Origins and destinations	9
2.2 Friction factors for cargo transportation	10
3. Results	18
3.1 Type of road	18
3.2 Topography effects	20
3.3 Quality of roads effects: primary and secondary unpaved roads.....	20
3.3.1 The special case of Nueva Guinea (Nicaragua)	21
3.4 Urban transit effects	21
3.5 Border Crossings effects	22
3.5.1 The special case of El Tuma (Nicaragua)	23
4. Conclusions	24
4.1 Conclusions related to the methodology.....	24
4.2 Conclusions based on the results.....	24
Bibliography	255

List of Figures

Figure 1: Road Quality Index for Central America	6
Figure 2: Friction Surface. Time/Cost as a grid	7
Figure 3: Cost-Cumulative Surface	7
Figure 4: 3D Friction Surface. Time/Cost as a grid	8
Figure 5: Structure of the agricultural exports in Central America.....	9
Figure 6: Origins and Destinations	10
Figure 7: Unified Central American Road Network.....	11
Figure 8: Digital Elevation Map (DEM) of Central America.....	12
Figure 9: Design speed of Highways and Streets (km/h)	12
Figure 10: Central American Road Network: Type and quality of roads	13
Figure 11: Metropolitan Area Influence Zone	14
Figure 12: Waiting Times at Border Crossings in CA.....	15
Figure 13: Central American Border Crossings	16
Figure 14: Friction Factors in the most complex scenario: Non Pixilated Version	17
Figure 15: Pixilated Version of the Friction Surface.....	18
Figure 16: Optimal Path for Chimaltenango, Guatemala	19
Figure 17: Optimal Path for Boquete, Panama	20
Figure 18: Optimal Path for Nueva Guinea, Nicaragua.....	21
Figure 19: Optimal Path for Zapotitan, El Salvador	22
Figure 20: Optimal Path for El Tuma, Nicaragua.....	23

Freight flows, logistics costs and efficiency:

Optimal Path Analysis

1. Overview

In Central America, cargo is transported almost entirely by road. The movement of imports and exports to and from international seaports is done by truck. Rail service is almost nonexistent and air transport serves less than one percent of the cargo generated within the Central American Common Market (SIECA, 2004).

Intra-regional trade is much more important in Central America than it might seem at first glance. The second largest trading partner of Central America is the region itself. In 2010, one quarter of the exports from Central America were destined for final consumption within the region.

Half of the exports of Central America (54% in 2010) correspond to agricultural products and a large proportion of them supply markets inside the region. Nearly 40% of intra-regional exports consist of food, beverages, animals and plants (SIECA, 2011). Perishable food products are transported on trucks, and spatially restricted by the geography and the road infrastructure.

In this context, inefficiencies in the supply chain and delays in freight flows lead to economic losses and amplify the negative impact of the distance to the markets on trade. A gravity model of trade showed that the negative effect of distance¹ on total intra-regional exports is 77% higher in Central America than in the European Union² (World Bank, 2010). More precisely, an increase in distance by 1% is expected to reduce intra-regional bilateral exports in Central America by 1.65%. In terms of volume, the negative effect of distance within the region exceeds the effect in Europe by 50% in grains and up to 550% in processed food. In the latter case, an increase in distance by 1% is expected to reduce intra-regional bilateral exports of processed food in Central America by 2.88%.

Due to its geological, hydrological and meteorological conditions that interact with its rugged topography, Central America is constantly exposed to a variety of natural disasters including floods, hurricanes, earthquakes, and landslides (World Bank, 2011). These events accelerate the deterioration of physical infrastructure and negatively affect economies across the region. Natural disasters take their greatest toll on bridges and roads, and disproportionately affect agricultural production. In 2011, Tropical Depression 12-E ravaged the region with flooding and landslides, generating significant losses on transport infrastructure and agricultural lands. The economic impact of 12-E on the transport and agricultural sectors alone was estimated at nearly US\$1 billion (ECLAC, 2011).

-
1. In this case, the distance corresponds to the Euclidean distance adjusted by the average time to complete an inland supply chain in Central America relative to the time in Europe. In fact, in Central America the average time it takes a supply chain is 70% higher than Europe.
 2. The most integrated part of the European Union (EU15): Germany, Austria, Belgium, Denmark, Spain, Finland, France, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, UK and Sweden.

Figure 1: Road Quality Index for Central America



Source: The Global Competitiveness Report 2011-2012.

Deficiencies in the design, location and construction of roads, retaining walls, dikes, drainage channels and other facilities for human settlements magnify the destructive power of natural disasters (SIECA, 2000). The quality of the road infrastructure is low. Except for El Salvador, the quality of roads in the region is below the average for Latin America and the World (World Economic Forum, 2011).

In this context, the notions of "minimum distance" and "minimum transportation time" from production zones to local markets and ports are vital to better

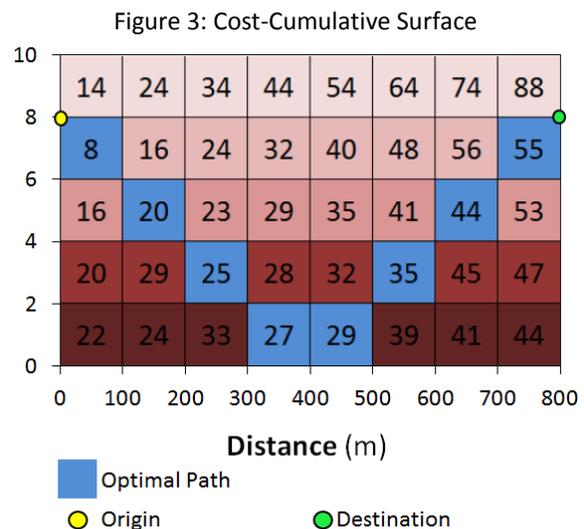
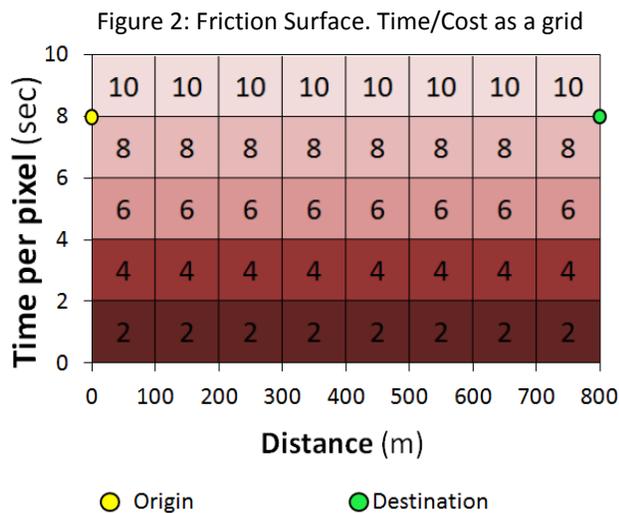
understand how to minimize costs and product losses and, subsequently, to increase regional competitiveness and economic growth. Accordingly, this study has adapted a spatial data analysis known as the Optimal Path Analysis to identify least-cost routes for the transportation of agricultural products in Central America.

The methodology of the Optimal Path Analysis, which is described in the next section, uses geographic and geo-referenced information provided, in most cases, by the ministries of transport and agriculture of Central America (Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica and Panama) during the last 2 years. Analyses were performed taking into account agricultural production zones of strategic importance to the region.

2. Freight flows from an Optimal Path Analysis perspective

The Optimal Path Analysis (OPA) is one of the main outputs that can be derived from the family of algorithms known as Accumulated Cost Surface Methods (ACS) implemented by the Geographic Information System (GIS). Given a friction surface, the OPA calculates the least-effort path or the most-efficient route to connect a point of origin to a destination. The friction surface corresponds to a pixelated representation of space –a raster dataset– that assigns to each pixel of space information on the effort required to cross it from side to side. The friction surface assigns to each cell the cumulative effort –the sum of all efforts– to the origin. The optimal route is one that, among all the possible ways to reach a destination, demands the least possible effort. The effort can be measure in terms of times or costs.

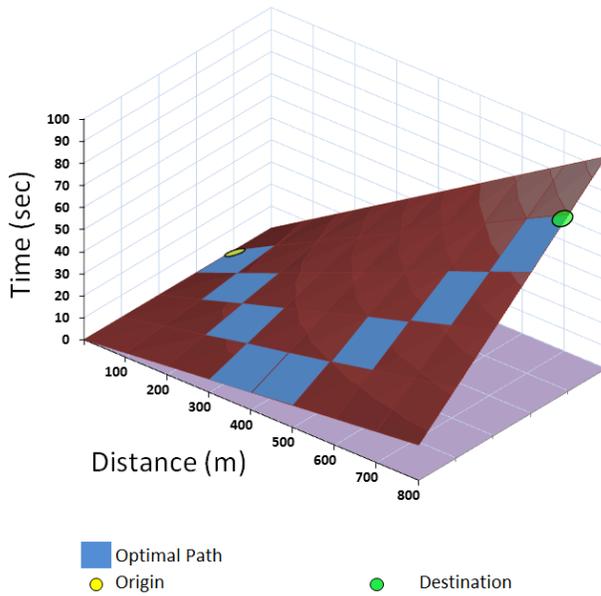
In the figure 1, the time (proxy of the effort) it takes to pass through a 100 square meters pixel from side to side varies in a range between 2 and 10 seconds depending on several factors. The time to travel 800 meters following a straight line from the origin (O) to destination (D) is 64 seconds (see Figure 2). That is equivalent to an average travel speed of 45km/h.



As shown in Figures 2 and 3, a straight line is not always most efficient way to connect two points in space. Following the optimal path (in blue, Figure 3) the travel time can be reduced to 55 seconds³. This optimal route implies a 14% reduction in total effort and an increase in the average speed up to 69 km/h, even though the total distance traveled has increased by 31%.

3. The time associated to diagonal movements take into account the Pythagorean Theorem.

Figure 4: 3D Friction Surface. Time/Cost as a grid



The most efficient way to climb up to the point of destination is by avoiding the steepest terrain, traversing the areas of least resistance. In Figure 4, even though the length of the optimal path is 249 meters longer than the straight line connecting the origin to the destination, the time needed to complete this route is 14% lower. Assuming the slope as the only factor that increases the effort (travel time), the friction surface and the optimal path can be represented three-dimensionally (as shown in Figure 4).

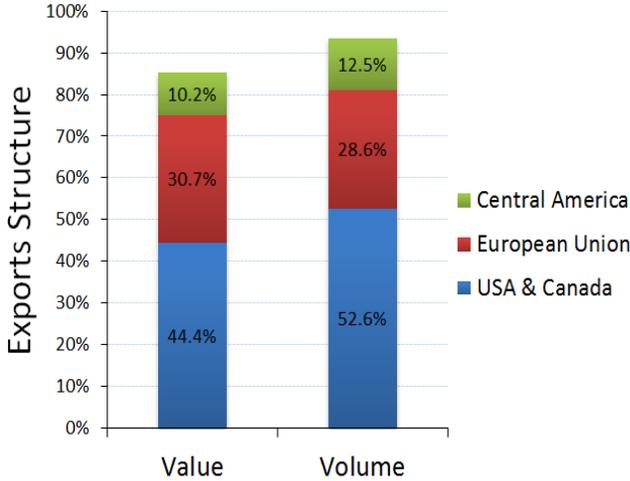
In India and Malaysia, researchers have used Optimal Path Analysis to understand how a range of friction factors affect the movement between an origin and a destination.

For instance, in order to identify the fastest routes for ambulances and fire trucks in Chennai –the fourth largest city in India–, from hospitals and fire stations to accident spots such as car accidents or fires, an augmented friction surface assigned to each pixel of the city surface information on traffic volume, type of road and road width, among other factors (Thirumalaivasan, 2002). An augmented friction surface including information on terrain slope, soil type, land uses and land cover types was used to calculate the least-cost pipeline path to the Langkawi Island in Malaysia (Wan Yusof & Baban, 2004). Pixel-level information on land use, land cover, terrain slope and drainages, rivers, existing roads and bridges were used to calculate optimal paths for extraction of forest produce in Andhra Pradesh, India (Murthy, 2003). Other examples in which augmented friction surfaces have been used to calculate optimal routes ranging from the delineation of green corridors in metropolitan areas (Cohen et al., 2009) to the analysis of wildlife corridors (Walker & Craighead, 2001).

In the case of freight transport in Central America, a friction surface was calculated to determine the optimal paths for the transportation of agricultural products, from strategic production zones to the main ports in the region. In addition, the OPA allowed the estimation of potential benefits emerging from improvements in variables affecting the times along the supply chains. The methodology and the results are described below.

2.1 Origins and destinations

Figure 5: Structure of the agricultural exports in Central America



Source: SIECA 2012 (Average 2007-2010)

Points of origin and destinations were defined to identify least-cost paths to the freight flow in Central America. To this end, three factors were taken into account: (i) time sensitivity; (ii) heavily reliance on trucking for cargo transport in Central America; (iii) the significance of Atlantic side ports, since nearly two thirds of the agricultural exports go to markets in Europe, USA and Canada (see Figure 5).

Primary agricultural zones for the production of each country’s top two perishable exports to the European Union and the U.S. were chosen as points of origin (See Annex I). In total, seven

agricultural zones –origins– were selected - two zones in Nicaragua and one zone in each of the other countries of the region. In turn, six ports were chosen as destinations; the five most important ports on the Atlantic side of the region, and one –the most accessible by road from the rest of the region– located on the Panama Canal (see Figure 6).

Figure 6: Origins and Destinations

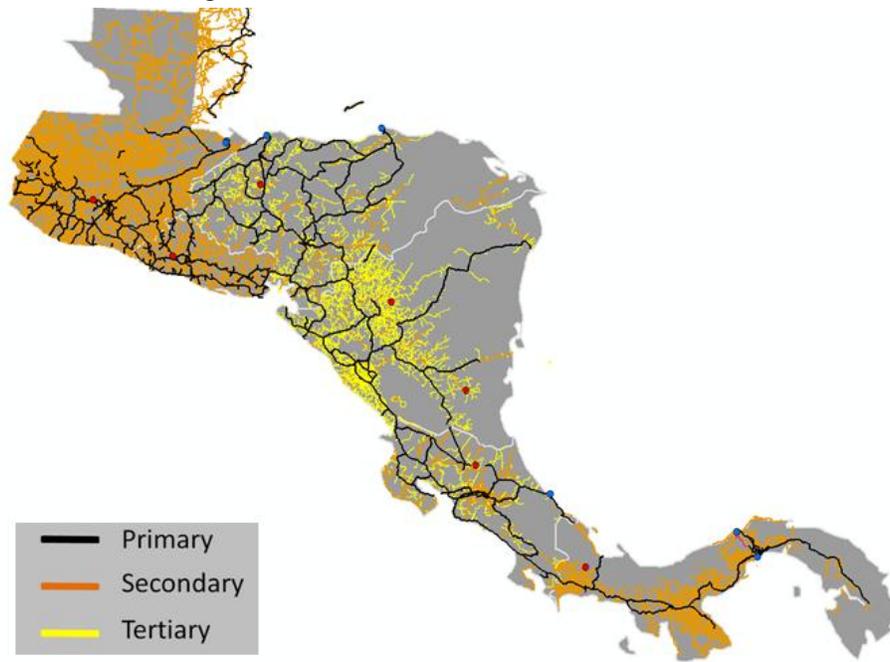


2.2 Friction factors for cargo transportation

As mentioned above, the friction surface corresponds to a pixelated representation of the space that contains information on the difficulty to move through the terrain. The effort required to move is increased or attenuated due to numerous factors that may be quantifiable and spatially linked to each pixel. In the case of land transportation of agricultural products in Central America, friction surfaces were created to analyze the cumulative effects of five friction factors on both the travel time—proxy of the effort—and the optimal paths for the movement of cargo.

The first factor of friction taken into account is the type of road. The cargo inevitably is restricted to flow through the paths created by the road network. In turn, the type of road influences the speed and magnitude of the flows within the road network. In the case of Central America, a unified digital map of the road network was generated based on information provided by the ministries of transport of the region. This digital map contains information on the functional type—primary, secondary or tertiary—and the surface condition—paved, unpaved—for all roads within the region (Figure 7).

Figure 7: Unified Central American Road Network



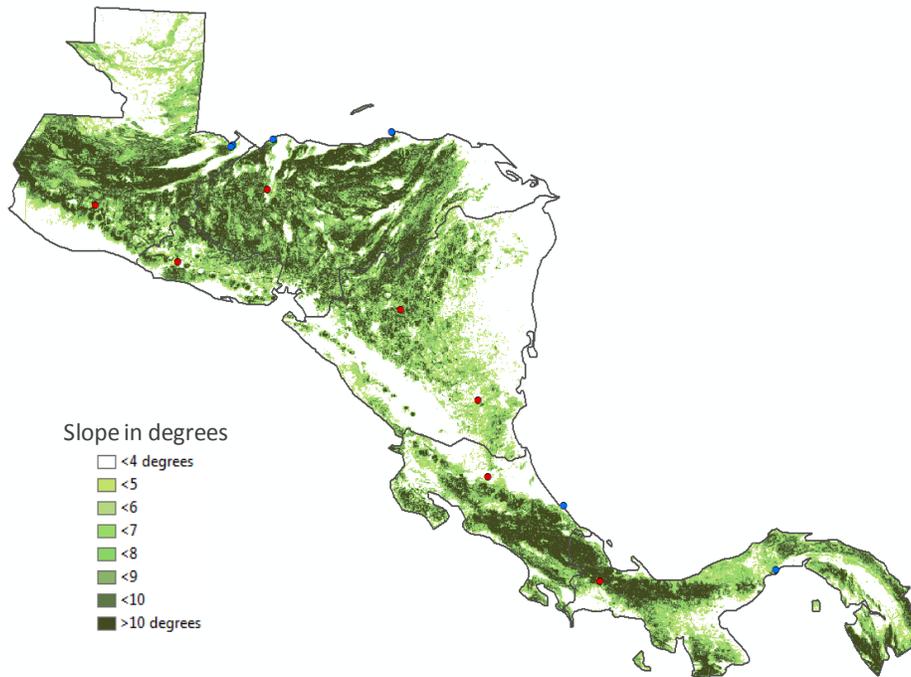
Source: Author's calculations

The primary roads are meant to connect major cities, trade centers and municipalities with more than 50 thousand inhabitants. The Annual Average Daily Traffic (AADT) of this type of road can easily exceed 1,000 vehicles a day. The secondary roads connect villages above 10 thousand inhabitants and are designed to reach an AADT around 250 vehicles a day. Finally, tertiary roads provide access to remote areas and channel the agricultural production from the farm gate to the distribution centers and local markets. These roads serve small towns and have an AADT lower than 50 vehicles a day (Navarro, 2008).

The second friction factor is the terrain slope. A friction surface containing pixel-level information on the terrain inclination was calculated based on the Digital Elevation Map (DEM) of Central America⁴(Figure 8). Since the resolution of this DEM corresponds to a minimum pixel size of 100 square meters, all additional calculations were performed at this level of detail.

4. The DEM contains information on the elevation of each pixel, so it allows a three-dimensional representation of the terrain and the calculation of the terrain slope.

Figure 8: Digital Elevation Map (DEM) of Central America



Source: SIECA 2012

The design speed of a road, the theoretical speed before a road is built, is strongly associated with the two friction factors mentioned above: the terrain slope and the type of road. For instance, the design speed for a paved primary road on level terrain can easily exceed 90 km/h per hour; however, in mountainous terrain (more than six degrees) it could be reduced to below 70 km per hour (Hoel, Garber & Sadek, 2010). In contrast, the design speed of a flat tertiary road is around 50 km/h, but it can be reduced to 30 km/h in mountainous terrain, defined as more than 10 degrees of elevation (Figures 9 and 8).

Figure 9: Design speed of Highways and Streets (km/h)

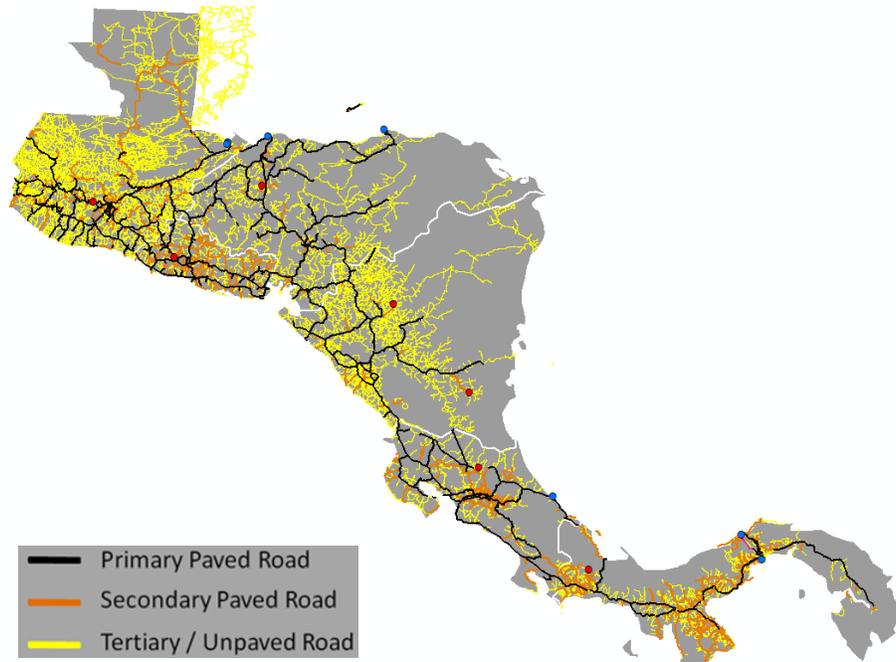
		Type of road		
		Primary	Secondary	Tertiary
Slope	Level	90	70	50
	Rolling	80	60	40
	Mountainous	70	50	30

Source: SIECA 2012

The third friction factor taken into account is the quality of the road, which can significantly affect the travel speed. In Central America, a road is considered in poor condition if the International Roughness Index (IRI) is above 9 —a roughness similar to the quality of an unpaved road (SIECA, 2001; Mexican Institute of Transport, 1998) —. The average speed of a heavy truck on a road under these conditions is below 50 km/h⁵. For the purpose of this study, it was assumed that the average speed of primary and secondary unpaved roads is the same as the tertiary roads (Figure 10).

5. The travel speed on dirt roads and dry-season roads can be reduced to less than 30 km/h (Menon & Warr, 2006).

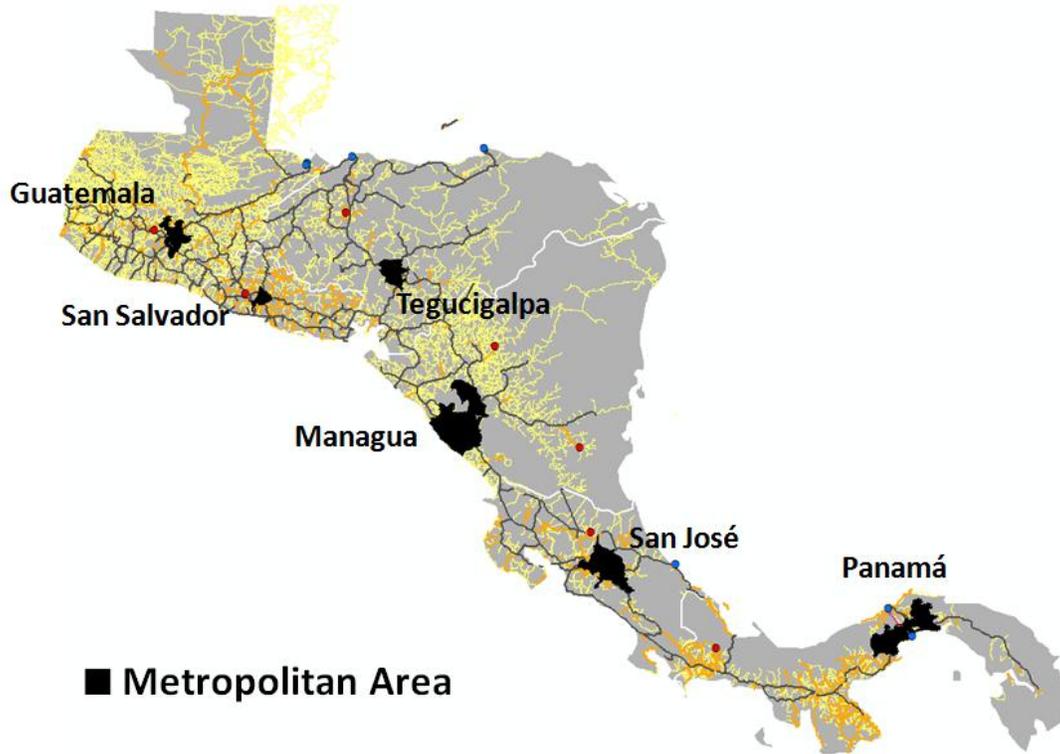
Figure 10: Central American Road Network: Type and quality of roads



Source: Author's calculations

A fourth friction factor is the urban transit effect. All the countries of the region have established speed limits for vehicular transit in urban areas. Urban speed limits for small cars vary between 45 km/h in residential areas and 80km/h on highways and primary roads, and for trucks between 40 and 50km/h. Since this study focuses on cargo transportation, it is assumed that the traveling speed for a truck within any of the metropolitan areas in Central America doubles the design speed. Thus, the average speed of a truck would be reduced from 90 km/h to 45 km/h in a level primary road and, from 50 to 25 km/h in a mountainous primary road.

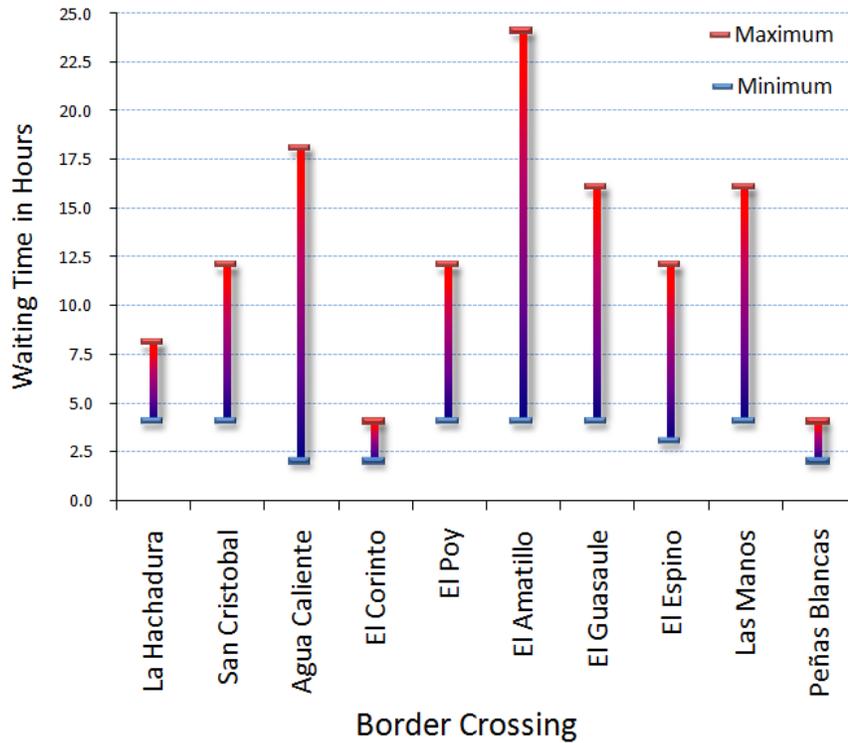
Figure 11: Metropolitan Area Influence Zone



Source: Author's calculations

Finally, the wait time at border crossings is one of the main friction factors for cargo transportation due to its effect on the travel times. The waiting time at border crossings is normally associated with customs procedures, security controls and sanitary and phyto-sanitary inspections (World Bank, 2011). However, deficiencies in access roads leading to the borders, corridors, parking lots, customs buildings, and in other facilities can greatly increase waiting times.

Figure 12: Waiting Times at Border Crossings in CA



Source: Apex Logistics 2012. Averages from February to March 2012.

Waiting times at border crossings vary widely within the region, within each country, and even among bi-national borders. While the minimum waiting time in the region is 3 hours on average, the average maximum is 12 hours. Wait times can reach up to 18 and 24 hours, as is the case with Agua Caliente (Guatemala/Honduras) and Amatillo (El Salvador/Honduras). Variation in border wait times exists depending on a country's neighbor. For example, the minimum wait time along the Guatemala/Honduras border is double the minimum time at any crossing point on the Guatemala/El Salvador border. Going south from Nicaragua, trucks wait a minimum of two hours, compared to 3.7 hours, heading north, into Honduras (Figure 12)

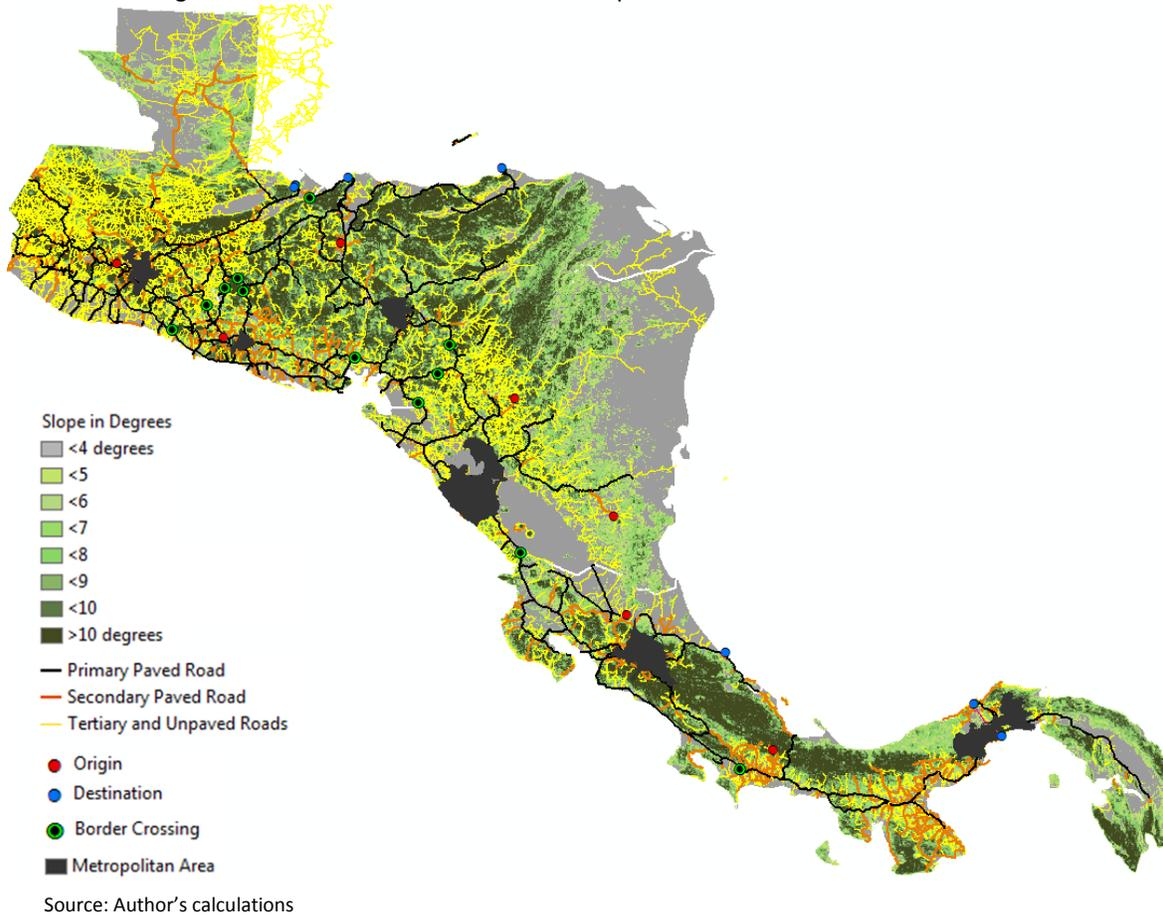
Figure 13: Central American Border Crossings



Source: Author's calculations

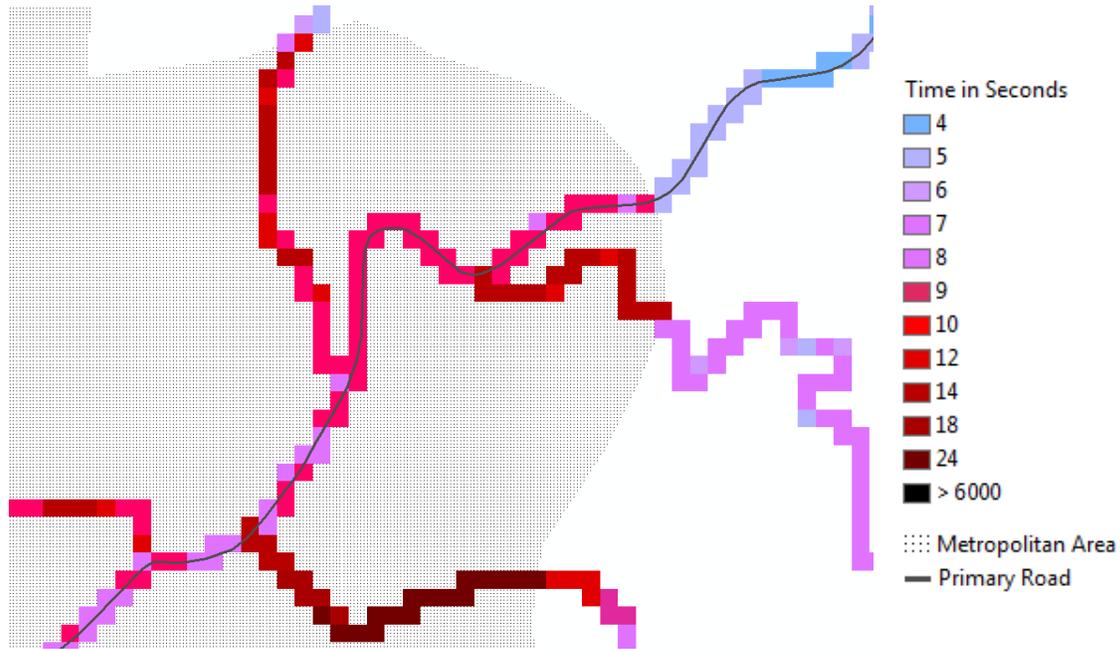
After all the layers of information associated with the friction have been generated, each of them was gradually superimposed to the previous one (Figure 14). First, the layers containing information on slopes and type of roads were combined to generate a base-scenario to calculate the optimal paths for cargo transportation based solely on design speeds. Then, the quality of roads layer was added to this base-scenario to produce a new set of optimal routes and times. Later, additional layers of paths and times were produced to account for the urban transit effect and the waiting time at border crossings.

Figure 14: Friction Factors in the most complex scenario: Non Pixilated Version



All the layers of information in Figure 14 were transformed into a discrete pixelated surface, each pixel being 100 square meters of area. Just the pixelated road network consisted of more than 1.2 million pixels. Origins, destinations and border crossings are represented as single pixels located on top of sections of road. Each pixel contains information on the time to cross from side to side. In the best case—a primary paved road on level ground outside the urban area—it takes 4 seconds to cross a pixel implying an average speed of 90 km/h. In the worst case, a truck has to wait several hours at a border post—more than 6000 seconds— (Figure 15).

Figure 15: Pixilated Version of the Friction Surface.
Section of the Central American Road Network



3. Results

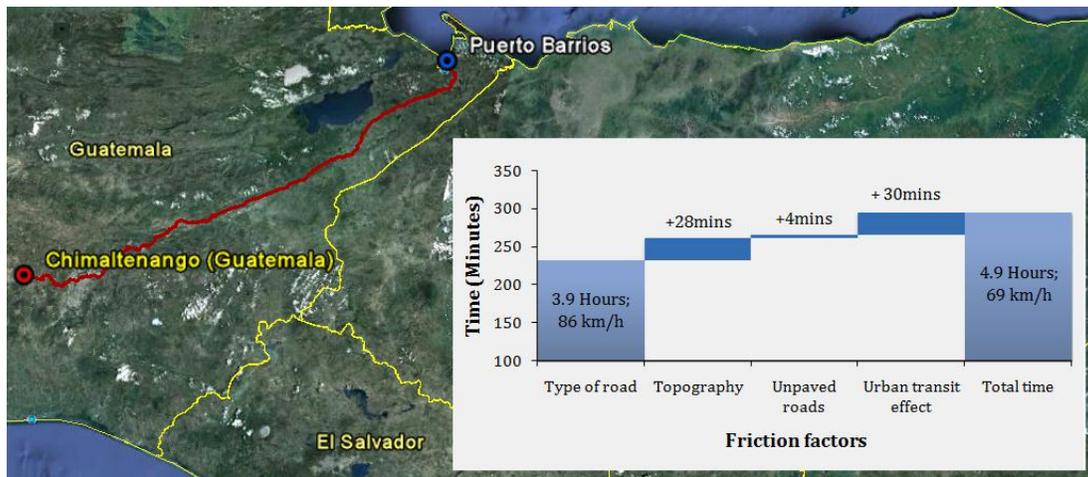
Below are presented the effects of friction factors on the least-cost paths for freight flows in Central America. As mentioned, this exercise aims to identify least-cost paths for cargo movement from strategic production zones to the main Atlantic ports and the port of Balboa in the Panama Canal. Costs are expressed in terms of travel time.

3.1 Type of road

The first set of results corresponds to the optimal paths assuming that the type of road is the only friction factor. In this "flatland" scenario, travel speeds for trucks are restricted only by the design speeds associated to each type of road in level terrain: 90 km/h for primary roads, 70km/h in secondary roads and 50 km/h in tertiary roads.

The optimal path for cargo transportation from Chimaltenango (Guatemala) to Puerto Barrios (the closest Atlantic Port) corresponds to a 330 km route length comprised mostly of primary (95%) and secondary roads (Figure 16). In the absence of other factors of impedance, the time it would take to travel from the origin to the destination would be 3.9 hours at an average speed of 86 km/h.

Figure 16: Optimal Path for Chimaltenango, Guatemala



Source: Author's calculations

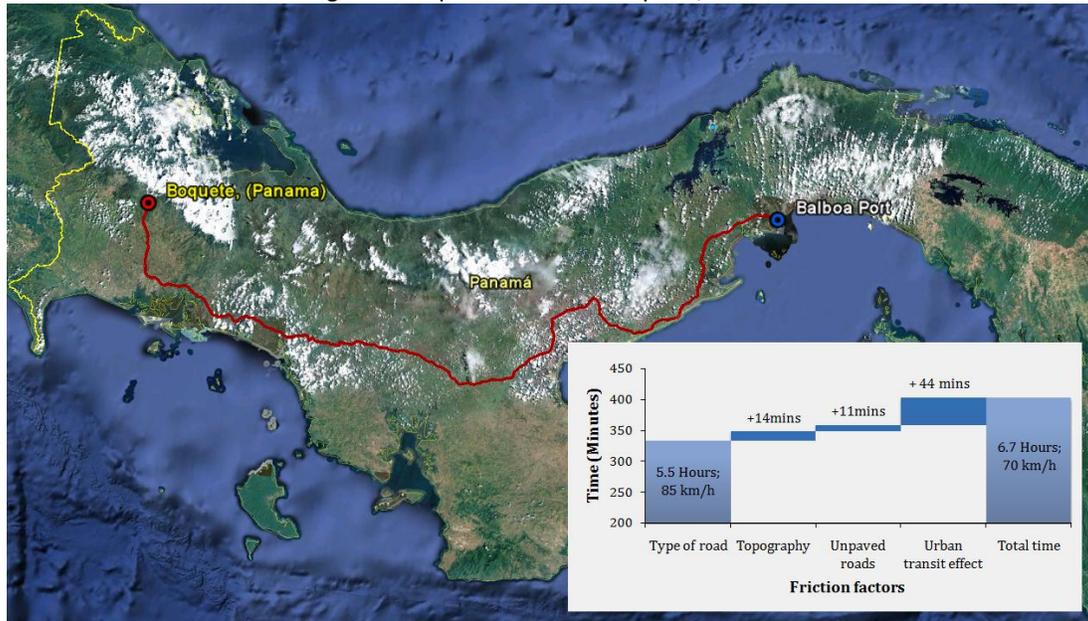
For freight flows from Zapotitan (El Salvador) to the closest port in the Atlantic coast, the optimal path implies goes through Guatemala to Puerto Barrios in a 327 km route length. The time it would take to travel from the origin to the destination would be 3.8 hours at an average speed of 86 km/h (Figure 19)

The cargo transportation from Nicaragua to the Atlantic ports necessarily implies passing through Honduras or Costa Rica. Without introducing other friction factors, Puerto Cortés (Honduras) is the closest port to the production zone of El Tuma (Pink line, Figure 20). This route, which is mainly comprised of primary (93%) and secondary roads (7% only in Nicaragua), has a length of 621 km and could be traveled in 7.3 hours at an average speed of 85 km/h. In the other hand, 802 km would separate New Guinea from Port Limon, the nearest port in Atlantic. This distance could be covered in 9.6 hours at an average speed of 85 km/h (Figure 18).

The optimal paths from Pita (Costa Rica) to the port of Limon (Costa Rica) and Yojoa (Honduras) to Puerto Cortes (Honduras) would reach average speeds of 77 km/h. The first has a length of 190 km and the latter a length of 116 km. The speed reduction is due to the higher percentage of secondary and tertiary roads (Annex).

In the case of Panama, the time it would take to travel from Boquete to the closest destination (Puerto Balboa) would be 5.5 hours at an average speed of 86 km/h. This optimal path would imply a 471 km route length comprised of primary (92%) and secondary roads (Figure 17). The primary road segment mainly corresponds to the Pan-American Highway.

Figure 17: Optimal Path for Boquete, Panama



Source: Author's calculations

3.2 Topography effects

Although the entire region is crossed by the mountain system of Central America, the effects of the terrain slope on optimal paths and travel times are relatively low. The optimal path simulation yielded increases in transport times of around 14% from New Guinea (Nicaragua), and 12% on routes from Chimaltenango (Guatemala) and Zapotitan (El Salvador). In other production zones, increases in travel times were shown to be less than 5%. The terrain slope does not affect the path followed by optimal routes under the previous scenario.

3.3 Quality of roads effects: primary and secondary unpaved roads

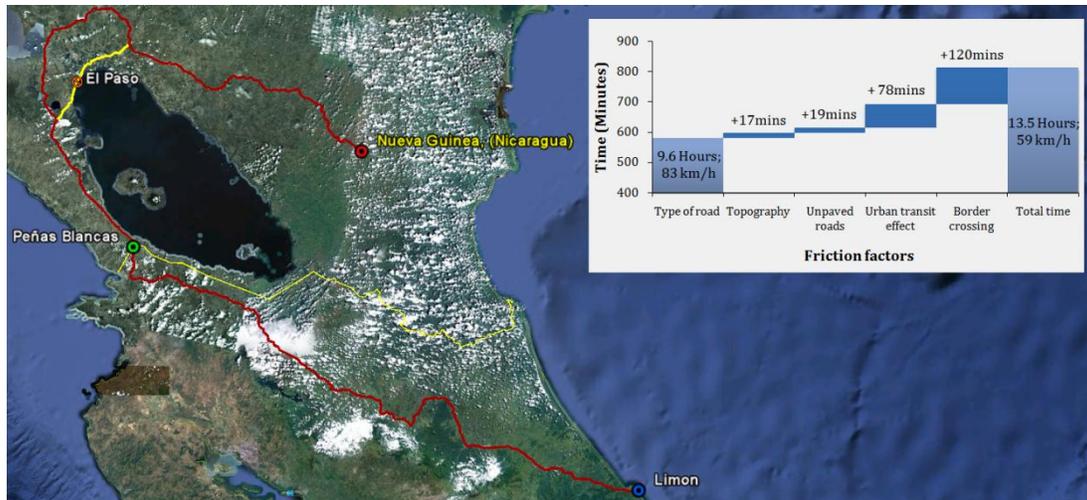
By quality of roads is meant the effect that unpaved primary and secondary roads (International Roughness Index (IRI) greater than 9) have on times and paths, assuming the average speed on unpaved roads is the same as the observed in tertiary roads. All the tertiary roads by design were assumed unpaved and remained unchanged. Future research will consider the effects that would result from paving tertiary roads.

When the quality of primary and secondary roads is taken into account, travel times increase, in some cases, up to 3%. For example, 4% of the optimal route between Boquete (Panama) and Balboa Port corresponds to unpaved primary roads. However, the delay generated by this friction factor is similar in magnitude to that produced by the terrain slope (11 and 14 minutes respectively). The same result is observed between Nueva Guinea (Nicaragua) and the port of Limon (Costa Rica).

3.3.1 The special case of Nueva Guinea (Nicaragua)

The optimal route from New Guinea (Nicaragua) to Port Limon (Costa Rica) is comprised of 2 sections. On the Nicaraguan side, 31% of the route corresponds to secondary roads, of which over 40% are unpaved. The Optimal Path includes a 60 km detour around the town of El Paso, where a bridge on the road map is, in actuality, a simple barge, impassable for heavy cargo trucks. The optimal path including the deviation in El Paso has a total length of 802 km (Figure 18).

Figure 18: Optimal Path for Nueva Guinea, Nicaragua



Source: Author's calculations

3.4 Urban transit effects

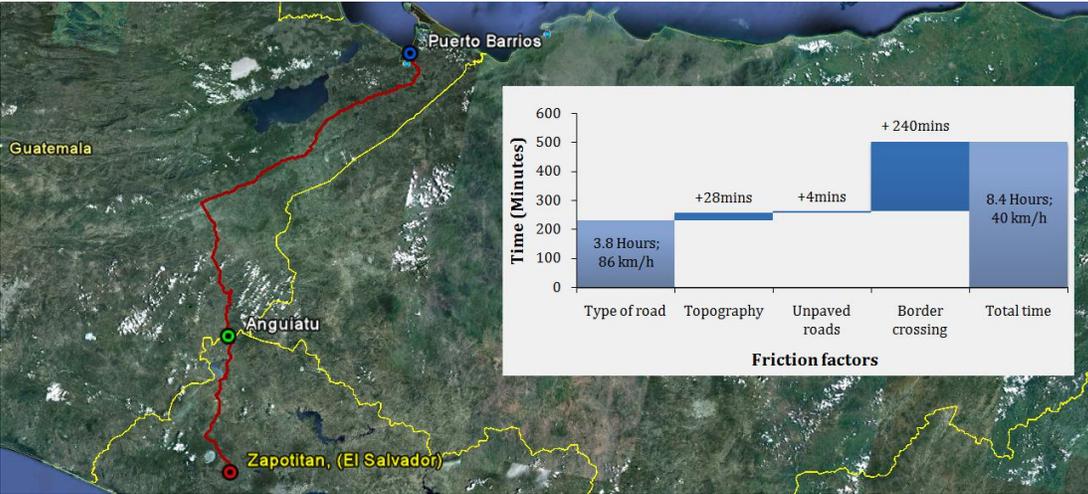
In all cases where the optimal path passes through metropolitan areas, the travel time increases about 11% - an effect greater in magnitude than that produced by topography. The Managua metropolitan region generates a delay of 78 minutes travel time between Nueva Guinea and Port Limon, reducing the average speed from 83 km/h to 70km/h. This result is due to the detour around El Paso and the existing road network that requires cargo transportation to circumvent Lake Nicaragua to reach Costa Rica (Figure 18). The situation is not much better for cargo transportation from Nicaragua to Puerto Cortes (Honduras). The existing road network restricts the flow to pass through Tegucigalpa, adding 55 minutes to the optimal path for cargo from El Tuma and reducing the average speed from 85 km/h to 67 km/h (Figure 20). Finally, Panama and Guatemala City add at least 40 and 30 minutes to the travel times, decreasing travel times below 79 km/h and 76 km/h from production areas in Boquete and Chimaltenango respectively. Country governments can reduce the urban transit effect by building bypasses or alternate roads.

3.5 Border Crossings effects

The waiting time at the border crossings introduces the greatest delays and distortions into travel times and optimal paths. Its effect is bigger than all the other friction factors combined. From El Salvador and Nicaragua, the two countries that lack direct access to an Atlantic port, Atlantic-bound cargo faces border delays that almost double total transit time (Figures 19 and 20).

Freight flows from El Salvador to the Atlantic ports necessarily have to cross a border with either Guatemala or Honduras (Figure 19). For cargo from Zapotitlan (El Salvador), the optimal path is through the border post Anguiatú to Puerto Barrios (Guatemala). Before factoring in border delays, the route has a length of 335 kilometers and could be covered in a time of 4.3 hours at an average speed of 77 km/h. However, the waiting time at any of the borders crossings with El Salvador is at least equivalent to the total time spent in transit. Once the waiting time is considered (at least 240 minutes), the average speed is reduced by almost half while the travel time exceeds 8 hours.

Figure 19: Optimal Path for Zapotitan, El Salvador



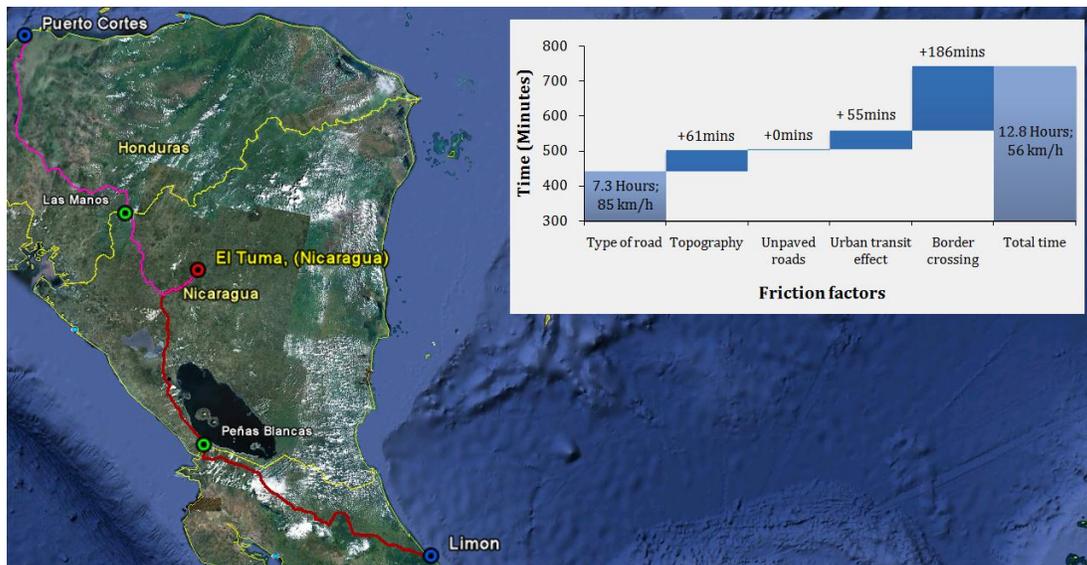
Source: Author's calculations

3.5.1 The special case of El Tuma (Nicaragua)

Taking into account wait times at the Nicaraguan border crossings, the Nicaragua optimal paths experience increases in total travel times above 30% (120 minutes more from Nueva Guinea and 186 additional minutes from El Tuma). This notorious increases in travel times for the two selected production zones in Nicaragua is accompanied by a reduction in the average travel speed from 70km/h - before including the waiting time at the border post- to 59 km/h in the case of New Guinea, and from 67 km/h to 55 km/h for freight flows from El Tuma (Figures 18 and 20).

However, for freight flows from El Tuma, the long delay at border crossings with Honduras actually divert the flow of cargo away from what would otherwise be the shortest and fastest route through Puerto Cortés in Honduras; instead, the optimal route is 67 km longer, and travels through the metropolitan area of Managua to Port Limón (Costa Rica).

Figure 20: Optimal Path for El Tuma, Nicaragua



Source: Author's calculations

4. Conclusions

4.1 Conclusions related to the methodology

The Optimal Path Analysis is an innovative and flexible tool to improve our understanding of barriers to cargo movement. This report barely touches the surface of its potential. The methodology can be adapted to analyze different freight flows scenarios, or expanded to include new layers of information, including social or environmental factors. Also, the Optimal Path can be coupled with Gravity Models of Trade in order to estimate a precise value to each hour of transport time, or combined with Supply Chain Analyses to point out where cargo deviates from the optimal route, and the potential time savings from addressing a logistics bottleneck, by type of productive sector.

Further applications and extensions of the Optimal Path tool may include: (i) studying these effects on a wider selection of trade routes, specifically for El Salvador and Honduras; (ii) collecting data on urban congestion to more accurately capture the effect of urban bottlenecks on transit times; (iii) calculating the effect of building urban bypasses or new roads on freight flows; (iv) estimating the effect of paving rural roads; (v) introducing port efficiency as a friction factor, drawing on port performance analysis.

Governments should consider maintaining platforms of geographic information in order to reproduce and expand upon this type of exercise. Policymakers can use the optimal path to calculate and compare benefits from infrastructure improvements and to make more informed decisions.

4.2 Conclusions based on the results

More than all other studied friction factors combined, border crossings increase time and distort optimal cargo flows in the region. Border crossings introduced the greatest delays into travel times, and, in two cases, diverted the flow of cargo towards a different port, or along a different route. For example, the two Nicaragua paths show that border delays increase total travel times by 120 minutes from Nueva Guinea and 186 minutes from El Tuma to Port Limón, equivalent to approximately 50 percent and 30 percent of respective travel times. For the El Tuma path, long delays at border crossings with Honduras actually divert the flow of cargo away from what would otherwise be the shortest and fastest route through Puerto Cortés in Honduras; instead, the optimal route is 67 km longer, and travels through Costa Rica to Port Limón. From El Salvador and Nicaragua, the two countries that lack direct access to an Atlantic port, exports face border delays that almost double total transit time.

Without accounting for urban congestion, speed reductions in the capital cities of Central America are a primary factor in slowing cargo movement. For example, all goods traveling to an Atlantic port from the western production regions of Guatemala must pass through Guatemala City, which does not have a good bypass. For the optimal route from Chimaltenango, urban transit speeds add approximately 30 minutes, equivalent to 11.4 percent of total transit time. Similarly, goods traveling from Boquete must cross the Panama Canal using the Bridge of the Americas. Slow transit speeds going through Panama City add 44 minutes, equivalent to 12.3 percent of overall travel time –the highest urban transit effect in the region.

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