Road Network Impedance Factor Modelling Based on Slope and Curvature of the Road

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Abstract Travelling in hills like Himalaya is very time-consuming due to presence of high slope and curvature in the road. Travel time is also affected by condition of the road i.e. surface roughness, rut depth, pavement conditions etc. However, for this research paper only slope and curvature is considered. To plan the journey in proper way, exact time required for travelling plays key role for any person. Google is providing best route to travel and estimated time required between source and destination. This travel time estimate by Google is up to the mark in plain region but not satisfactory in hills. Because road transportation network in hills contains a lot of curvature and slope of the network in also very high and varying due to undulating terrain of the mountains. Therefore, in this research a technique is proposed to calculate better travel time estimate. Proposed technique considers natural obstacles to the travel speed in the hills like slope and curvature. In this a network model is proposed which assigns average driving speed to the road segment, and this driving speed is calculated by percentage rise in the slope & radius of curvature of the road segment. Model takes road network and raster image of slope in degrees. Open source tools and languages (Python, GDAL, and QGIS) are used to make this model. Results of proposed network model are near to the ground truth value.

Keywords Curvature; GIS; Impedance; Python

1. Introduction

Significant modelling of any real world phenomenon requires proper representation of the object. Geographic information system (GIS) provides facility to represent real world. But over the year’s real world has become very complex to model properly using any information system (Sadeghi-Niaraki et al., 2011). Better representation allows us to use GIS tools and produce accurate outputs. One of the GIS tool is network analysis tool, which is having functionalities to calculate optimum path, closest facility, service area etc. based on the impedance of the network. Road networks are geometric networks, a geometric network is composed of nodes and edges where nodes are junction points and edges are road segments. According to Lupien et al., (1987) network is a line graph composed of links & nodes where links represent linear channels of flow, and nodes represent connections of links. For each real world road network, direction and impedance must be assigned with each edge to calculate travel cost/time (Husdal, 1999). Transportation planning requires network analysis in situations like finding the shortest path, service area within a specified travel cost (Husdal, 1999).
Impedance factor of road network plays a key role to get accurate output of network analysis. Hence, attempt to make more accurate modelling under different conditions is being carried out by researchers across the world since last two decades. Chunithipaisan et al., (2004) used distance as the mono-dimensional variable, Leonard et al., (2000) used speed as mono-dimensional variable, Shadewald et al., (2001) used traffic as mono-dimensional variable to model impedance factor of road network. Various researches are available where multiple variables including environmental conditions are used to model the impedance factor. Thirumalaivasan et al., (1997) used volume of traffic, type of road, road width, number of junctions, turns etc. to model the impedance factor. From the earlier researches, it can be concluded that mono-dimensional variable based impedance factor modelling is not capable of modelling the real world. Multiple variables can help to model impedance factor in an accurate way, but required variables changes from one ecosystem to another ecosystem. E.g. for high population zone, dominating variables can be traffic, road width, vehicle count per hour, for less population region dominating variables can be road width, road condition, environmental condition and for hilly region with less population or traffic dominating variable can be road width, slope of the road, road condition, curvature of bends, distance between two bends, environmental condition etc.

Since travel time in hilly region is high compared to plan region due to non-availability of straight and plane roads. This study is focused to incorporate natural limitations to the speed or impedance factor. The objective of this study is to calculate impedance for each segment of road based on slope and curvature at the bends. Also condition of speed limit as per the government rules is to be incorporated.

One possible form of impedance factor is average driving speed on the road which will give us optimum travel time in case of any route. Driving speed/impedance factor is mostly calculated based on length, width, type and traffic on the road. But if the road network belongs to hilly area where a lot of ups & downs and steep curvatures are present. In such kind of scenario apart from the mentioned criteria effect of slope and curvatures should also be considered to calculate optimum impedance. In this research slope and curvatures of the road network are considered to calculate average driving speed, since traffic is very low in my study area so this factor is neglected.

1.1. Study Area and Data Sets

The study area includes one of the state of India, Uttarakhand. Geographical area of this state is around 53,483 sq. kms. This state is mostly covered by Himalayan hills. Yearly average temperature of study region is around 25°C, pleasant weather and natural beauty attracts tourists from whole India.

| Table 1: Datasets |
|-------------------|
| **Data** | **Source** |
| DEM | 30 m spatial resolution Cartosat data |
| Road network | Downloaded from OSM |

Table 1 shows the dataset used to carry out this research. Road network was downloaded from OpenStreetMap (OSM) and digitization errors were removed to make it usable for my research. Cartosat DEM having 30m resolution is used to calculate slope of the road segments.

2. Methodology

In this research, curvature and slope of the road are the limiting factor to the average driving speed. Slope is derived from satellite derived DEM whereas curvature of the road is calculated using the vector data of road network.
2.1. Radius of Curvature of the Road

Minimum three points are required to calculate radius of curvature, this is clear from the equation of the circle:

\[(x-a)^2 + (x-b)^2 = r^2\]

Where \(x, y\) are the coordinates of the points and \(a, b\) are the coordinates of the centre of the circle & \(r\) is the radius of circle.

For this research entire road network is divided in multiple segments bends in the road network is identified based on the change in angle between two successive segments, in my case if change in angle is more than 45 degrees then it considered as bending. Similarly, all such segments participating in a bend are stored and circular regression is done to calculate the radius of curvature. Finally, radius of curvature is stored in attribute table of the participating segments of the bend.

2.2. Circular Regression

Suppose \((x_1, y_1), (x_2, y_2), (x_3, y_3), \ldots, (x_n, y_n)\) are the middle points of segments participating in the bend. Then equation of circle becomes:

Consider \(R = r^2 - a^2 - b^2\)

\[
\begin{align*}
R + 2ax_1 + 2by_1 &= x_1^2 + y_1^2 \\
R + 2ax_2 + 2by_2 &= x_2^2 + y_2^2 \\
R + 2ax_3 + 2by_3 &= x_3^2 + y_3^2 \\
\vdots \\
R + 2ax_n + 2by_n &= x_n^2 + y_n^2
\end{align*}
\]

\[
\begin{bmatrix}
x_1 & y_1 & 1 \\
x_2 & y_2 & 1 \\
\vdots & \vdots & \vdots \\
x_n & y_n & 1
\end{bmatrix} \begin{bmatrix}
a \\
b \\
R
\end{bmatrix} = \begin{bmatrix}
x_1^2 + y_1^2 \\
x_2^2 + y_2^2 \\
\vdots \\
x_n^2 + y_n^2
\end{bmatrix} \quad \ldots \text{eq. (1)}
\]

\[
AX = B
\]

\[
X = A^{-1}B
\]

Solving eq. (1) will give \(a, b\) and \(r\).

This information is updated in attribute table.

Using the radius of curvature, maximum allowed speed is calculated from the condition of toppling. Since dynamics of the moving body on the curve suggest the condition at which it will topple. For a moving body on a curve, the condition for toppling of the body can be expressed as:

\[
v \leq \sqrt{Fr/m} \quad \ldots \text{eq. (2)}
\]

Where \(F\) is force acting on the body (gravitational force in this case), \(r\) is the radius of curvature and \(m\) is mass of the body.
Eq. (2) leads to maximum allowed velocity as:
\[ v = \sqrt{r g \tan \theta} \text{ ... eq. (3)} \]

Where \( g \) is gravitational acceleration, \( \theta \) is across slope angle of the road segment.

Using the equation 3 and radius of curvature, maximum allowed speed is calculated at the bends and updated in the attribute table of road network.

2.3. Slope of the Road

Slope of whole study area is calculated in degrees from the Cartosat DEM using QGIS software. Road network is overlaid over the slope image and corresponding slope values for road segments were filled in attribute table of road network.

A relationship is established between slope of the road and maximum allowed speed as per the Indian Road Congress (IRC). From the established relationship speed corresponding to slope of segments is updated in the attribute table of road network.

Table 2 shows then terrain classification as per IRC and table shows the allowed speed type and terrain of the road.

| Terrain classification | Cross Slope (%) |
|------------------------|-----------------|
| Plain                  | 0 - 10          |
| Rolling                | 10 - 25         |
| Mountainous            | 25 - 60         |
| Steep                  | >60             |

Table 3: Design Speed in km/hr as per IRC (ruling and minimum)

| Type     | Plain  | Rolling | Hilly  | Steep |
|----------|--------|---------|--------|-------|
| NS & SH  | 100-80 | 80-65   | 50-40  | 40-30 |
| MDR      | 80-65  | 65-50   | 40-30  | 30-20 |
| ODR      | 65-50  | 50-40   | 30-25  | 25-20 |
| VR       | 50-40  | 40-35   | 25-20  | 25-20 |

The website of the national highways authority of India (www.nhai.org) gives the classes as:

1. Expressways
2. National highways
3. State highways
4. Major district roads
5. Rural and other roads
6. Other road classes

On the basis of regression model for the speed and slope provided by IRC, following relationship says that velocity and slope of the road are exponentially related.
\[ v = 59.825 e^{-0.016s} \quad \text{... eq. (4)} \]

Where \( v \) is speed and \( s \) is the slope of the road segment.

Let’s say speed from the slope is denoted by \( v_s \) and speed from radius of curvature is denoted by \( v_r \), then final speed or impedance factor \( (v_f) \) for a road segment is:

\[ v_f = \min(v_s, v_r) \quad \text{... eq. (5)} \]

### 2.4. Calculation of Time from Point A to Point B

Suppose A and B are the points/locations for which travel time need to calculated, there are \( n \) road segments between A & B, then:

\[ \text{Travel time} = \frac{d_1}{v_1} + \frac{d_2}{v_2} + \cdots + \frac{d_n}{v_n} \quad \text{... eq. (6)} \]

Where \( d_n \) is the length and \( v_n \) is final speed of road segment for \( n = 1, 2, 3 \ldots n \)

### 3. Results and Discussion

To perform validation of the proposed technique road segment from Rishikesh, Uttarakhand to Deoprayag, Uttarakhand (as shown in Figure 1) was taken. Total length of the segment is 74.018 kilometers, and it consists only hilly region where roads are very steep and curvy. The figure below shows the actual scenario of the road segment.

![Figure 1: Road Segment](image-url)
Figure 2 shows the overall structure of the data stored in shapefile format. "X" and "Y" are the coordinates of midpoints of the line segment, "slope" is the slope (in degrees) corresponding to that segment as per Cartosat DEM, "f_vel" is the final allowed velocity for each segment, "len" and "time" are the length (in meters) of the segment and time (in minutes) required to cover length of the corresponding segment respectively.

Finally, total time required to cover the desired road from Rishikesh to Devprayag using proposed technique is coming as 207.49 minutes or 3 hrs 27 minutes. This time is much more realistic to cover this distance. As per the Google map, time required to travel same route is around 2 hrs. Covering 74 km distance in plain region is possible but it is nearly impossible to cover 74 km in complex terrain of Himalaya. So, proposed technique is giving much more realistic results.

4. Conclusions

The calculated travel time considering the impedance factor proposed is subsequently greater and more realistic than the estimated travel time given by the Google Maps for same route. This shows that to determine impedance factor, curvatures and slopes plays an important. There can be other factors also like traffic, road condition, weather etc. However, it is assumed that roads are of good condition, hilly regions are less traffic prone.

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