E001: Methodology for Assessing Roadway Network Redundancy

NOTE: This document was generated by Google's Gemini (2.5 Pro Model) based on the UDOT ASSET RISK MANAGEMENT PROCESS document and the code used to calculate our version of the metric.

1. Introduction

Roadway network redundancy is a critical attribute of transportation systems, reflecting their ability to accommodate traffic flow when primary routes are disrupted. The analysis of redundancy typically involves quantifying the impact of a segment's unavailability on travel time and distance, thereby providing insights into network vulnerability and resilience. This document outlines a methodology for calculating roadway redundancy metrics, drawing upon established principles in transportation asset management and employing a computational approach to assess detour impacts. The objective is to provide a systematic and replicable framework for evaluating the consequences of localized network failures.

2. Conceptual Framework: The UDOT Approach to User Costs and Redundancy

The Utah Department of Transportation (UDOT) outlines a comprehensive Asset Risk Management Process, within which the concept of system redundancy is integral to calculating user costs associated with network disruptions. User costs represent the economic impact on roadway users—both passenger and commercial vehicles—resulting from increased travel time and distance due to closures.

The UDOT methodology for assessing redundancy, as detailed in their "Asset Risk Management Process" document (specifically Appendix C and D, with segment redundancy discussed on page A-12), focuses on the following:

- **Objective**: To quantify the additional travel time and distance incurred by users when a specific road segment becomes impassable and traffic is rerouted.
- **Process**:
    - **Segment Identification**: A specific road segment within the network is selected for analysis.
    - **Origin-Destination (O-D) Pair Definition**: To analyze the impact of the segment's closure, hypothetical start (origin) and end (destination) points for a trip that would typically use the segment are established. UDOT's methodology suggests defining these points up to three segments upstream and downstream of the segment under consideration.

    - **Base Path Calculation**: The shortest path (in terms of travel time and distance) between the defined origin and destination, assuming the network is fully operational, is calculated. This is the "base path."
    - **Simulated Closure**: The analyzed road segment is then treated as closed or unavailable (e.g., by applying a virtual barricade or a prohibitively high travel cost).
    - **Detour Path Calculation**: With the segment closed, the new shortest path between the origin and destination is calculated. This is the "detour path."
    - **Impact Metrics**: The differences in travel time and travel distance between the base path and the detour path are the primary metrics representing the direct impact of the segment's closure.
- **Analytical Tools**: UDOT's methodology references the use of GIS-based network analysis tools, such as **ESRI Network Analyst**, to perform these pathfinding and detour calculations.
- **Considerations**: The methodology also accounts for factors like avoiding rerouting significant traffic onto unsuitable road types (e.g., unpaved roads) and may involve manual validation of reroute results.

This framework provides a foundational understanding of how the consequences of segment unavailability can be systematically measured.

3. Implemented Methodology for Redundancy Calculation

The methodology employed in this study operationalizes the principles of detour analysis to quantify roadway redundancy. It involves a computational approach to identify alternative routes and measure the resultant increases in travel time and distance.

3.1. Illustrative Example of Detour Analysis

To demonstrate the core steps of the methodology, consider the following example involving a segment of Feura Bush Road:

- **The Edge Under Consideration**:
  The specific road segment analyzed is Feura Bush Road, extending from NY 335/Elsmere Avenue to Ackerman Avenue. This primary road segment has a length of 0.0799 miles. With an assumed speed limit of 35.0 mph, its unimpeded travel time is approximately 8.2 seconds. It is noted that such simplistic travel time calculations do not account for delays from traffic control devices like stop signs or traffic lights.

- **Defining the Origin and Destination for Analysis**:
  Following the principle of analyzing a trip that extends beyond the immediate segment, starting and stopping locations were algorithmically identified. UDOT's approach considers points up to three segments (or intersections) upstream and downstream.
  For this example:
  - The origin was identified three intersections upstream at the intersection of Feura Bush Road and Brightonwood Road.
  - The destination was identified three intersections downstream at the intersection of Feura Bush Road and Westphal Drive.

- **The Base Path**:

  The shortest path between the identified origin and destination, assuming the network is fully operational and traffic flows through the edge under consideration, constitutes the base path. For this example, the base path is 0.832 miles long and takes approximately 85.5 seconds to traverse under free-flow conditions.

  The segments comprising this base path include:

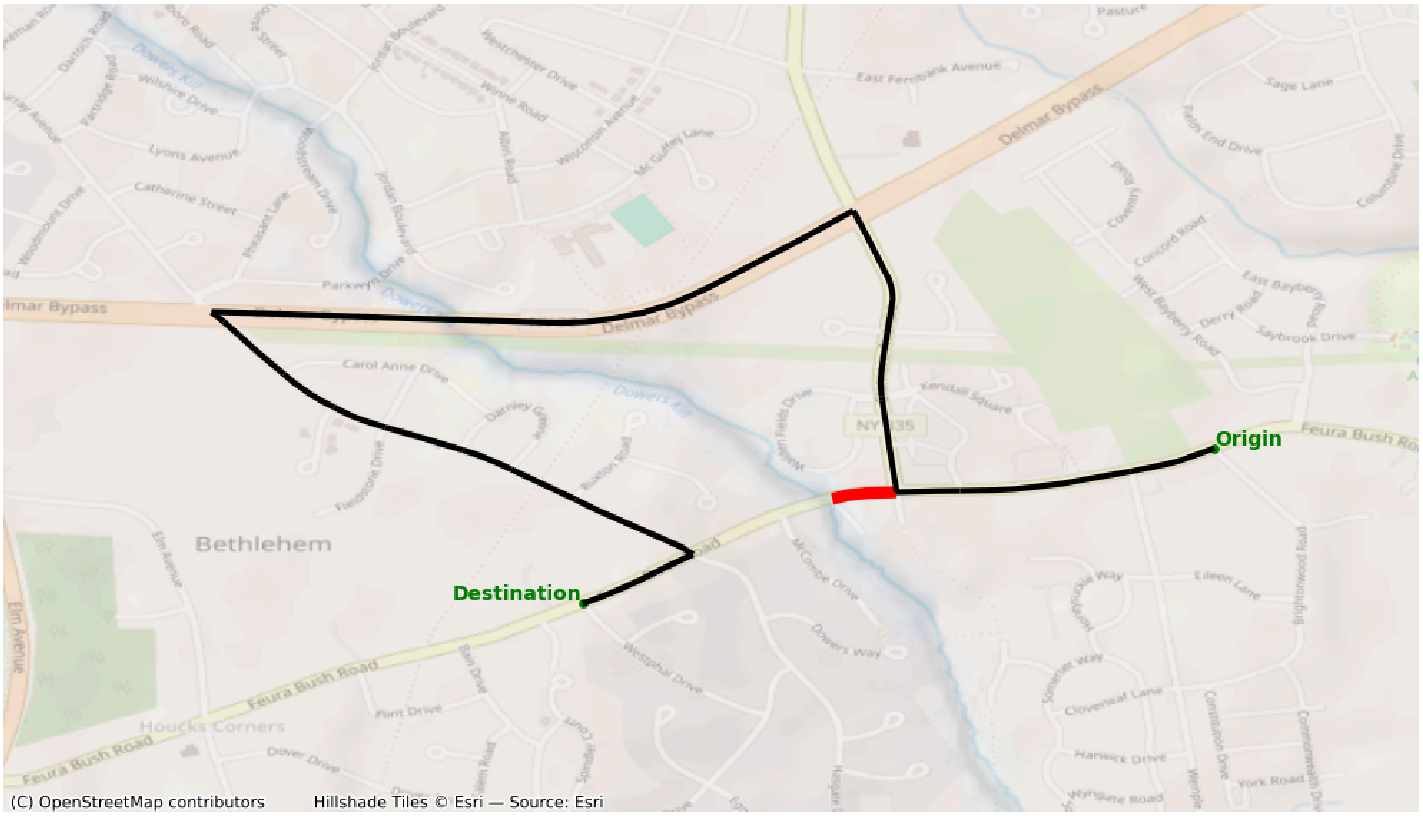
  - Feura Bush Road from Brightonwood Road to Wemple Road
  - Feura Bush Road from Wemple Road to Wayland Street
  - Feura Bush Road from Wayland Street to NY 335/Elsmere Avenue
  - Feura Bush Road from NY 335/Elsmere Avenue to Ackerman Avenue (the edge under initial consideration)
  - Feura Bush Road from Ackerman Avenue to McCombe Drive
  - Feura Bush Road from McCombe Drive to Hasgate Drive
  - Feura Bush Road from Hasgate Drive to Westphal Drive

- **The Detour Path**:

  Upon simulating the closure of the primary edge (Feura Bush Road from NY 335/Elsmere Avenue to Ackerman Avenue), an alternative path is computed. The detour path identified for this example is 2.597 miles long and has an estimated travel time of 250.2 seconds.

  The segments comprising this detour path include:

  - Feura Bush Road from Brightonwood Road to Wemple Road
  - Feura Bush Road from Wemple Road to Wayland Street
  - Feura Bush Road from Wayland Street to NY 335/Elsmere Avenue
  - NY 335/Elsmere Avenue from Feura Bush Road to Ives Street
  - (Sequence continues as detailed on pages 4 and 5 of tutorial.pdf)
  - ... Murray Avenue from Ruxton Road to Feura Bush Road
  - Feura Bush Road from Hasgate Drive to Westphal Drive



- **Analysis Results**:
  The comparison between the base path and the detour path yields the following quantitative impacts:
  - Base travel time: 85.5 seconds
  - Base length: 0.832 miles
  - Detour travel time: 250.2 seconds
  - Detour length: 2.597 miles
  - Difference in travel time: 164.7 seconds
  - Difference in length: 1.765 miles

This illustrative example encapsulates the core analytical sequence: defining the scope of analysis, establishing a baseline, simulating a disruption, and quantifying the impact of the alternative.

3.2. Core Computational Steps

The implemented methodology automates the detour analysis through the following general steps for each road segment of interest:

1. **Origin-Destination (O-D) Determination**: For a given road segment under analysis, origin and destination nodes for the shortest path calculations are established. This is achieved by programmatically identifying nodes along the same roadway, typically extending a defined number of intersections or segments upstream and downstream from the segment being analyzed. This

ensures that the calculated paths are representative of realistic trips rather than just the segment itself.

2. **Base Path Calculation**: The shortest path between the determined origin and destination nodes is computed using a standard algorithm (e.g., Dijkstra's), weighted by travel time. The cumulative travel time and length of this path are recorded.
3. **Simulated Segment Closure**: The road segment under analysis is functionally "closed" within the network model by assigning it a prohibitively high travel time or cost. This ensures it will not be part of any optimal path unless no other alternative exists.
4. **Detour Path Calculation**: The shortest path calculation is repeated between the same origin and destination nodes, but with the analyzed segment effectively removed or penalized. The system identifies the next best alternative route.
5. **Difference Metrics Computation**: Key metrics are then calculated:
    - **Additional Travel Time**: The difference between the detour path travel time and the base path travel time.
    - **Additional Travel Distance**: The difference between the detour path length and the base path length.
    - **Travel Time Ratio**: The ratio of the detour path travel time to the base path travel time, indicating the proportional increase.

3.3. Methodological Considerations

- **Selection of Analyzed Roadways**: The analysis can be resource-intensive. Therefore, it is often focused on "major roads" identified based on functional classification (e.g., primary, secondary, tertiary roads) or other criteria relevant to the study area.
- **Exclusion of Non-Paved Roads**: To ensure realistic detour routing for general traffic, non-paved roads are typically excluded from consideration as viable detour segments. This is achieved by assigning them very high travel times within the network model, effectively making them impassable for the shortest path algorithm under normal detour circumstances.

4. Output Metrics and Data Dictionary

The application of this methodology yields a structured dataset where each analyzed road segment is associated with a set of quantitative redundancy metrics. These metrics provide a direct measure of the impact of that segment's potential closure. The primary output fields are described below:

Column Name	Data Type	Description
`base_travel_time_sec`	Real	The travel time (in seconds) of the shortest path between the analysis origin and destination, assuming the analyzed edge is open.
`base_length_miles`	Real	The length (in miles) of the shortest path between the analysis origin and destination, assuming the analyzed edge is open.
`detour_travel_time_sec`	Real	The travel time (in seconds) of the shortest detour path between the analysis origin and destination when the analyzed edge is closed.
`detour_length_miles`	Real	The length (in miles) of the shortest detour path between the analysis origin and destination when the analyzed edge is closed.
`difference_sec`	Real	The additional travel time (in seconds) incurred due to the detour (`detour_travel_time_sec - base_travel_time_sec`).
`difference_miles`	Real	The additional travel distance (in miles) incurred due to the detour (`detour_length_miles - base_length_miles`).
`difference_ratio`	Real	The ratio of detour travel time to base travel time (`detour_travel_time_sec / base_travel_time_sec`), if base travel time is greater than zero.
`origin_node_id`	Integer	The unique identifier of the network node designated as the origin for the shortest path analysis.

Column Name	Data Type	Description
`origin_node_upstream_count`	Integer	The number of road segments/intersections traced upstream from the analyzed edge to determine the origin node.
`origin_intersection_name`	String	A descriptive name for the intersection at the origin node (e.g., "Main St AND First Ave").
`origin_lon`	Real	The longitude of the origin node.
`origin_lat`	Real	The latitude of the origin node.
`destination_node_id`	Integer	The unique identifier of the network node designated as the destination for the shortest path analysis.
`destination_node_downstream_count`	Integer	The number of road segments/intersections traced downstream from the analyzed edge to determine the destination node.
`destination_intersection_name`	String	A descriptive name for the intersection at the destination node.
`destination_lon`	Real	The longitude of the destination node.
`destination_lat`	Real	The latitude of the destination node.

5. Alignment with Foundational Principles

The implemented computational methodology for assessing roadway redundancy directly aligns with the foundational principles articulated in frameworks such as UDOT's Asset Risk Management Process. Both approaches share the core objective of quantifying the impact of network segment unavailability by analyzing detours. The calculation of additional travel time and distance provides fundamental inputs necessary for more extensive user cost models or comprehensive risk assessments, which might further incorporate traffic volumes, the economic value of time, and probabilities of disruption. This systematic measurement of redundancy is crucial for informed transportation planning and infrastructure management.

Glossary of Technical Terms

- **ESRI Network Analyst:** A specialized geospatial software extension developed by Esri for performing advanced network-based spatial analysis, including route optimization, service area definition, and closest facility identification. It is widely used in transportation planning for tasks such as finding optimal routes and modeling impacts of network changes.
  - *More information:* https://www.esri.com/en-us/arcgis/products/arcgis-network-analyst/overview
- **GeoDataFrame:** A data structure, primarily associated with the GeoPandas library in Python, that extends the functionality of a Pandas DataFrame (a tabular data structure) to include geospatial data. Each row can represent a geographic feature (e.g., a point, line, or polygon) along with its associated attributes, enabling integrated geospatial and tabular data analysis. (See References section for citation).
  - *Library Link:* https://geopandas.org/en/stable/index.html
- **NetworkX:** A Python software library designed for the creation, manipulation, and study of the structure, dynamics, and functions of complex networks. It provides data structures for graphs, digraphs, and multigraphs, along with a large number of standard graph algorithms (e.g., shortest path, centrality). (See References section for citation).
  - *Library Link:* https://networkx.org/
- **OSMnx:** A Python package that facilitates the downloading, modeling, analysis, and visualization of street networks from OpenStreetMap (OSM). It simplifies the process of acquiring and preparing street network data for network analysis tasks, often used in conjunction with NetworkX, and can automatically correct network topology and impute missing data like speeds and travel times. (See References section for citation).
  - *Library Link:* https://osmnx.readthedocs.io/en/stable/
- **Origin-Destination (O-D) Pair:** In transportation analysis, an O-D pair refers to the starting point (origin) and ending point (destination) of a trip. Analyzing O-D matrices and path choices is fundamental to understanding travel demand, traffic flow, and network performance.
- **Segment (Road Segment):** A defined portion or stretch of a roadway, typically located between two distinct network nodes, such as intersections, interchanges, or administratively defined points. Road segments are the fundamental units for network analysis and attribute assignment.

7. References

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