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Article

Designing Service Coverage and Measuring Accessibility and Serviceability of Rural and Small Urban Ambulance Systems

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Abstract: This paper proposes a novel approach to analyze potential accessibility to ambulance services by combining the demand-covered-ratio and potential serviceability with the ambulance-covering-ratio. A Geographic Information System (GIS)-based spatial analysis will assist ambulance service planners and designers to assess and provide rational service coverage based on simulated random incidents. The proposed analytical model is compared to the gravity-based two-step floating catchment area method. The study found that the proposed model could efficiently identify under-covered and overlapped ambulance service coverage to improve service quality, timeliness, and efficiency. The spatial accessibility and serviceability identified with geospatial random events show that the model is able to plan rational ambulance service coverage in consideration of households and travel time. The model can be applied to both regional and statewide coverage plans to aid the interpretation of those plans.

Keywords: accessibility; serviceability; coverage ratio; demand-covered-ratio; ambulance-covering-ratio; ambulance; fastest paths; GIS

1. Introduction

Planning for the provision of emergency medical service (EMS) is critical in rural areas because of the large service areas covered. In those areas, the average response time of emergency vehicles is generally longer because of road conditions and the longer distances that ambulances must travel from service locations to incident scenes. Consequently, rural ambulance services face challenges in providing timely responses to emergency incidents such as road crashes and health incidents. For small urban ambulance services, similar challenges result when their responses are impeded by traffic congestion [1].

In general, rural EMS areas are designed based on travel time and distance from fixed service locations. These units are frequently based in larger towns because the population level is large enough to support a hospital and other economic and social activities [2]. As a result, rural and frontier populations are likely to be located far from medical facilities and have longer response times for EMS. This level of medical emergency service affects not only residents and workers, but also travelers and visitors of the region.

Because an incident is a demand for ambulance service, the terms “incident” and “demand” are used interchangeably throughout this paper. In response to an incident, an ambulance is dispatched to the scene and then delivers victims to a hospital that can provide appropriate treatment. For example, the ambulance service is not required to take the victim to the nearest hospital, but may travel up to 30 additional minutes to reach another hospital with staffing or treatment that is more appropriate for treating the victim’s injury or medical condition [3]. Rural ambulance service providers face challenges providing high-quality EMS for several reasons: insufficient revenue, difficulty in recruiting ambulance service employees and volunteers, natural barriers, and changing demographics in rural regions [4]. Additionally, the collaboration that is necessary among service contractors (private and public), governments, hospitals, and communities requires strong leadership.

Based on the factors listed above, it is unlikely that the ambulance services provide the same level of service and response time throughout their service coverage areas. Nevertheless, rationalizing service coverage plans and assessing response predictions is an essential part of service planning in order to decrease response times and increase quality of service [2]. For practical considerations, the operational service coverage may not be identical to those described by the planning process, but planning is an essential component to achieving efficient and effective public service.

Coverage plans may place emphasis on “access and equity” to assure that disadvantaged groups and impaired individuals receive appropriate emergency responses [5]. The service coverage plan and response performance can be assessed by a combination of spatial analyses and analytical models. These tools measure the accessibility to residents and others from the service facilities and the capability of ambulances to provide service in order to improve the quality of life [6,7]. Geospatial tools can be used to assess policies and practices related to assuring the accessibility of primary care and to provide useful information and strategies for service providers to make continuous improvements in serving stakeholders [8]. Local 911 services can employ Geographic Information Systems (GIS) and geospatial database management systems (G-DBMS) to analyze operational efficiency and timely emergency response. The geospatial information systems demonstrate local and regional transportation networks in detail [9,10]. Internally, DBMS used for emergency medical service maintain residential address information, population densities, areas to be covered, and historical emergency information, such as crash data and EMS activities. This information is useful for planning timely response times and for providing appropriate levels of personnel and equipment. In addition, global positioning systems (GPS) can isolate individual events in conjunction with GIS and DBMS in order to implement plans that facilitate quick response [5].

Many emergency vehicle drivers still use a book of maps provided by service planners. In creating the map books, the planners adopt historical data and scientific measures for designing service coverage and distributing ambulance locations. These map books, which outline EMS service locations and coverage, are critical communication tools to reach out to the public. Demonstrating value and vision through transparent planning and operation of EMS systems improves credibility and accountability with stakeholders.

The objectives of this study are to (1) develop an analytical model to measure the potential spatial accessibility and serviceability based on simulated random incidents; (2) visualize the estimated ambulance service coverage and response time performance for planners and public communication [11,12]; and (3) identify under-covered and overlapped ambulance service coverage in order to improve service quality and efficiency.

The use of the two-step flow catchment area method (2SFCA) allows the identification of under-served areas, so that well-designed ambulance service coverage can be implemented throughout the region to decrease overlapping areas of service and improve service to under-served areas. The model uses centroids within geographical areas to maintain consistent gaps between central points and peripheral points within an analysis area. This paper proposes a novel approach to analyzing accessibility by combining the demand-covered-ratio and serviceability with the ambulance-covering-ratio. A GIS-based spatial analysis assists ambulance location planners. Ambulance service designers provide and assess rational service coverage. The proposed analytical model in this study is compared to the 2SFCA method.

Creating a model using the proposed methods to demonstrate service coverage and response time improves the heterogeneous spatial boundaries by considering transportation travel time and distance throughout the state road networks. The approach proposed in this study provides a tool to continually improve emergency management systems in response to changes in transportation networks and populations. The model can be applied to both regional and statewide coverage plans.

The remainder of this article is organized as follows: The next section provides a literature review of related studies. The third section describes the proposed model's assumptions, data sources, and service locations. The fourth section proposes the model's ability to assess accessibility by incorporating the combination of the demand-covered-ratio and serviceability with the ambulance-covering-ratio. The fifth section compares the output of the proposed model to the gravity-based 2SFCA. Finally, conclusions and further studies are discussed in Section 6.

2. Literature Review

Emergency response performance can be addressed by assessing several factors: (1) acceptable response time for incidents in rural areas [13]; (2) emergency response in agricultural areas; (3) improved response by avoiding congestion in urban areas [13,14]; and (4) reasonable service coverage designed to improve ambulance service. To measure the performance, operations research including set-coverage and facility location problems and accessibility with geographic information systems (GIS) are introduced.

Arentze *et al*. developed criteria based on ambulance dispatching scenarios to find the shortest path from crash locations to emergency service units, as well as a means to find the shortest path from crash locations to hospitals [15]. The study minimized the total distance from emergency service units to crash locations and then to a hospital by searching service coverage based on the population of zone improvement plan (ZIP) areas. Churches minimized the required number of facilities and EMS regions by using a location set covering model to serve the demand of crashes and emergency incidents [16].

The objective of the model was to provide maximum coverage with a fixed number of facilities. While accessibility is a measurement to represent the number of ambulance locations required to provide service, the ambulance locations establish the population that the ambulance can serve within a response-time criterion [17–19].

Radke and Mu used the spatial decomposition approach to predict accessibility to social services [20]. Their model provided equal access to the public and accommodated under-served regions by measuring accessibility and evaluating the availability of ambulance services. In order to set service coverage, point-to-point and point-to-polygon approaches are generally applied. For example, the point-to-point approach finds accessibility from a crash point to the closest hospital and EMS emergency service units, while point-to-polygon finds travel time and interpolates to create a service area polygon. The issue for the emergency routing problem is how to use this data in conjunction with EMS data on highway crashes or other accident event data. Radke and Mu used the polygon-to-polygon approach to establish a fixed contractor and created buffer polygons with a radius of 60 miles [20]. They also created polygons containing the density of households downloaded from a census tract and then disaggregated the census tract density by using the buffer of each contractor service area. By doing so, they calculated the accessibility in the overlapping areas served by multiple agencies within a response-time threshold. The model delineates the spatial pattern of the population under-served or over-served by contractors relative to other areas. A heuristic substitute model relocates the suppliers and creates buffers. The process integrates all the processes in order to have robust service probability-coverage maps in the region.

Luo & Wang measured spatial accessibility in a GIS environment [21]. In their study, the service area was defined by travel time relative to physicians' availability and capacity of trauma centers. Joseph & Phillips [22] measured potential and spatial accessibility in a similar way. The potential accessibility focuses on the geographic patterns and availability of service resources. The gravity-based model is continuous, less intuitive, and computational, while the dichotomous floating catchment area (FCA) method uses intuitive threshold travel time. The gravity model overemphasizes the decay function leading to heavily spatially smoothed results [22]. Thus, McGrail & Humphreys measured spatial accessibility to primary care in rural areas by improving the 2SFCA method [13]. To do so, they used the shortest path algorithm embedded in Network Analyst® [23]. To improve the FCA method, they determined the variation ensured by accurate, reliable, and robust measures. The model assumes customers will only use services within their catchment area. In the model, two steps are used: Step 1 for service catchment and Step 2 for population catchment. Luo and Wang included regional availability and accessibility addressed by the spatial decomposition method of the 2SFCA method in GIS using travel time instead of straight-line distances [21]. Gravity-based modeling with a distance-decay function was added to the 2SFCA in order to improve the model. The gravity-based method and floating catchment areas are complementary for accessibility measurement.

In summary, the nearest service provider is commonly determined by travel distance. Using distance is simple and easy, but it only captures proximity between population and service providers. Only using the closest facility is not an effective measure of spatial accessibility because overlapping catchments exist. For example, this is often the case for primary care service [13], in which patients bypass the nearest service in order to choose another service from within the service area. Accessibility within the gravity model explains accessibility over an entire region, but it misses the exact information provided by the location information and general pattern.

Nevertheless, questions about the service coverage exist, such as how well the coverage matches the population distribution (*i.e.*, service demands), and how quickly the ambulances serve the demands. The public may question the amount of time required for an ambulance to arrive after calling for service. Several studies investigated location choice and human behaviors by examining travel patterns using conjoint analysis, the logistic choice model, and other analytical methods [24]. GIS has become a popular tool to measure accessibility and analyze the location and service coverage problem [12,20,25,26]. The proposed indicators in this study differ from previous work in that this study replaces the centroids of the service areas with many random incidents in order to measure and visualize the service response performance over space and time. Thus, this article demonstrates multiple services in a service area, which has not been visualized in previous studies using centroids and limited service boundaries.

3. Model Development

Annual or biannual EMS service coverage planning is an offline activity based on historical and regulatory information. By contrast, online EMS operations involve the ambulance, which is in-motion or ready, by utilizing global positioning systems (GPS) and automatic vehicle locator (AVL). In general, incidents in rural and frontier areas occur rarely, and the service providers respond to calls with adequate capacity. Of the 61,000 EMS calls per year in North Dakota, 16% of the calls were from rural areas while small urban areas accounted for 82% [4]. Thus, to assess service coverage and accessibility, this paper assumes that service units and trauma centers can serve all demands with unlimited capacity. The responses considered herein are only between ambulance locations and the scenes of incidents. The ambulance's deadheading is beyond the scope of this ambulance service-coverage plan study. The reason for this is the frequency of calls in rural and frontier areas, which is a low percentage of all calls in the state of North Dakota, representing an average of 27 calls per day [4]. Travel speed on the road networks varies with road classification and condition in the state, federal, and local system. Interstate highways have a speed limit of 75 miles per hour. U.S. and state highways are limited to 65 miles per hour, and county and city roads have an average speed limit of 45 mph in this study. For simplicity, road conditions are not considered in this study.

3.1. Data Sources

State, federal, and local road networks of eight counties in the study region were downloaded from the GIS portal of North Dakota (ND GIS Hub). This study excludes the "proposed" roads defined in the attribute of surface type because the road segments do not currently exist. The road segments in the county systems provide informative attributes, such as pavement and road classification for estimating travel speed. The major road networks include interstate, U.S. highways, state highways, business routes, federal-funded local roads, and ramps with classified travel speeds. The GIS portal provides the state-federal roads and the city and county roads separately. In order to connect the two datasets, this study extended the city and county lines to the nearest state-federal highway segments located within 10 m (*i.e.*, 32.8084 feet).

The ambulance service locations include address and service level; however, capacity-related information, such as the number of vehicles and quick-response units, is not available from the location attribute tables. The service level is categorized into advanced life support (ALS) and basic life support (BLS). The ambulance's service level is visualized in the maps. Those maps are meaningful for this service coverage plan and response time estimation because accessibility, coverage, and other measures do not consider what type of service it is. It is simply either available or not.

3.2. Service Locations

In order to digitize and simulate ambulance locations in the GIS model, this study considers fixed locations of the ambulance garages for providing rational service coverage as measured by accessibility and serviceability. The service coverage polygons cover a distance of 30 miles (d_0) from the EMS emergency service units (j), which equate to approximately 30 min of travel time (which is symbolized as catchment area j). The travel time (t_{ij}) is obtained by the length in miles divided by the travel speed in miles per hour (mph). Origin-destination cost matrix of travel distance and time was generated in ArcMap® and then exported to Excel® for analyzing the literature-based 2SFCA [4,13,21,27] and the proposed models in this study.

4. Geospatial Simulation for a Holistic Approach

Proposing Accessibility and Serviceability Using Random Incidents

Crashes and incidents may occur anywhere in the region regardless of highways, farm fields, rivers, or oil fields. All persons are equally likely to receive ambulance response service throughout the homogeneous areas, but the space and time is not homogenous across the service coverage area. In addition, the residential populations are heterogeneous [7]. Thus, without a holistic approach in a geographical (or political) boundary, some locations, which are far from populated towns and close to frontier areas, will be underestimated, resulting in a miscalculation of the realistic accessibility to the ambulance services. For that reason, this study proposes a geospatial simulation in conjunction with space-time performance measures.

The geospatial simulation approach generates hypothetical random incidents inside the ZIP codes using household attributes. U.S. Census Bureau provides the population and the number of houses based on several geographical boundaries, such as ZIP codes and Census Track. The rationale of using households instead of population is that the household is highly likely to represent the home locations of potential service users. In this study, one random incident is simulated for every 10 households within a designated ZIP code. There is a minimum one-mile distance between any random points. In a next step, each random incident is linked to the closest ambulance. The advantages of using the proposed geospatial simulation are the random connection to any transportation network links, the holistic approach for every corner in the study region, a minimization of bias caused by using the centroids of the zip codes, and the ability to provide an alternative, visual representation and realistic interpretation for service coverage plans.

This study measured: (i) the average response time and demand-covered-ratio with regard to accessibility and (ii) the serviceability and ambulance-covering-ratio based on average response time from ambulance location to any incidents connecting to the ambulance location. This article uses response time because it is more easily communicated with the public and policymakers. The potential performance measures of accessibility and serviceability are explained in detail in the rest of this section.

Inputs:

M = A set of demand locations (incidents) in a study region
W = A set of ambulance locations in a study region
$t_{ji} =$ The quickest travel time from an ambulance location *j* to an incident *i* for $\forall i \in M, j \in W$
$y_{ji} = 1$ if an incident *i* is connected to an ambulance location *j*, 0 otherwise for $\forall i \in M, j \in W$
$M_j = \{i \in M \mid y_{ji} = 1\}$: A set of demand location *i* served by an ambulance location *j* for $\forall j \in W$
$W_i = \{j \in W \mid y_{ji} = 1\}$: A set of ambulance location *j* serving a demand location *i* for $\forall i \in M$

Potential Accessibility

The average response service time for a ZIP code zone *Z* is total ambulance response time from ambulance locations *j*, which serves the incidents *i* in the zone, divided by the number of incidents in the zone in Equation (1). The set of incidents in a ZIP code zone *Z* is a subset of the set of incidents *M*.

$$\overline{T}_Z = \frac{\sum_{i \in Z, j \in w_i} t_{ji}}{N_{i \in Z}} \quad (1)$$

where $\overline{T}_z$ is the average response service time of all ambulance locations covering Z, t_{ji} is the fastest travel time from ambulance location *j* to incident *i* in *Z*, and the denominator $N_{i \in z}$ denotes the number of incidents in *Z*. Be aware that t_{ji} is not always equal to t_{ij} because divided highways and one-way links might result in different travel times. The ambulance locations can be restricted by the desired service time t_0^Z, depending on whether the ZIP code zone *Z* belongs to an urban, rural, or frontier area. Each incident is constrained to the closest ambulance only, so one ZIP code zone can be served by one or more ambulance locations.

The potential accessibility of the ZIP code (A_Z) is the ratio of the designated response time (t_0^Z) required by EMS rules to the average response time in Equation (2). Thus, the balanced index for the accessibility of the ZIP code is one. In other words, if the response time index is greater than one, the residents in the ZIP code enjoy faster service than the recommended service response time, while a poor index (less than one) indicates slower average response time than the recommend response time. Thus, the potential accessibility index (A_Z) is a ratio of the recommend travel time (t_0^Z) for a zone *Z* to the average response time of the zone *Z* in Equation (2).

$$A_Z = t_0^Z \big/ \overline{T}_Z \quad (2)$$

In addition to the average response time ($\overline{T}_Z$) and potential accessibility (A_Z), North Dakota EMS rules require the ambulance service to cover at least 90% of all calls within a recommend response time (t_0^z) based on area categories. Thus demand-covered-ratio (C_Z) is proposed in this study in Equation (3). The demand-covered-ratio, C_Z(%) is the ratio of the population in a ZIP code zone within in a recommended response time ($N(t_{ji} \le t_0^Z)$) to the total population in the ZIP code zone, which is represented between 0% and 100%.

$$C_Z(\%) = \frac{N(t_{ji} \leq t_0^Z)}{N_i} \times 100, \forall i \in z, j \in W_i \quad (3)$$

Potential Serviceability

This study defines the potential serviceability of an ambulance location as the closest location's average response time from an ambulance service location to random incidents. The calls are not limited by the service boundaries of the ambulance's designed service coverage in Equation (4). Typically, when an incident results in a 911 call, the call center dispatches an ambulance, which is either already in motion or available at a service location. The required response time of an ambulance in motion is not considered in this study because the operational performance measure is different from the purpose of the service coverage plan. Furthermore, most rural ambulances are staffed by volunteers, so the chance of an *in-motion* response rate is low. Average response time by an ambulance location j covering demand locations i is shown in Equation 4 only if t_{ji} is the fastest path between ambulance location j and demand i. The ambulance's average response time ($\overline{T}_j$) to the hypothetical incidents is the total response time from an ambulance location j to the connected demand i divided by the number of incidents connected to the ambulance location j in Equation (4).

$$\overline{T}_j = \frac{\sum_{i \in M_j} t_{ji}}{N_{i \in M_j}} \quad (4)$$

where t_{ji} is the fastest travel time from the closest ambulance location j to the hypothetical incident i. $N_{i \in M_j}$ represents the number of random incidents i linked to the ambulance location j.

Serviceability index (S_j) is the relative ratio of recommended response time (t_0^j) to the average response time of the ambulance location j. The ambulance location j belongs to either an urban, frontier, or rural area in Equation (5).

$$S_j = \frac{t_o^j}{\overline{T}_j} \quad (5)$$

In addition to an ambulance's potential response time ($\overline{T}_j$) and the potential serviceability index (S_j), this research also measures the ambulance-covering-ratio, $C_j(\%)$, which is the percentage of the responses achieving the designated service response time (t_0^j) recommended to the number of all incidents served by an ambulance location j, $N_{i \in M_j}$ (6). The ambulance-covering-ratio is in the range of 0% to 100%.

$$C_j(\%) = \frac{N_{(i \in M_j, t_{ji} < t_0^j)}}{N_{i \in M_j}} \times 100 \quad (6)$$

5. Case Study

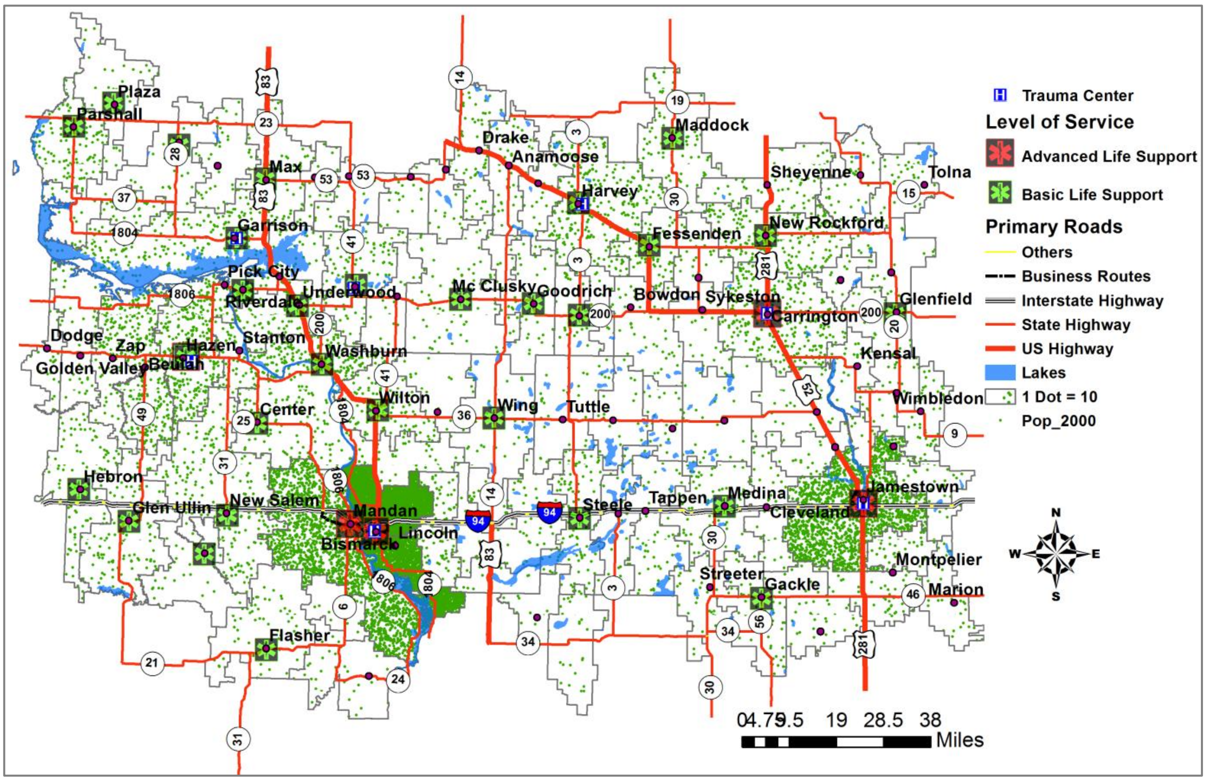
5.1. Study Area

For the case study of ambulance coverage, the study selected the North Dakota capital city of Bismarck and surrounding areas (Figure 1). The Missouri River flows from Lake Sakakawea through

Bismarck. The terrain around the river is hilly, and Interstate Highway 94 passes eastbound and westbound through Jamestown and Bismarck. A total of 34 ambulance locations serve the region with advanced life support (ALS) and basic life support (BLS).

Figure 1 presents the high density of BLS services in the Northwest region. As reflected in the service density, Bismarck/Mandan and Jamestown show higher densities of population than other areas. North Dakota Emergency Management Rules classify three regional categories: urban services in Bismarck/Mandan; rural services along I-94 and U.S. Highway 83 (counties with more than six people per square mile); and frontier services (in counties with fewer than six people per square mile). The regional categories require difference service levels: nine-minute response time for urban services, 20 min for rural services, and 30 min for frontier services.

Figure 1. Population density and road networks.



5.2. The Gravity-Based Two-Step Floating Catchment Area (2SFCA) Method

This gravity-based 2SFCA uses the centroid of the ZIP codes based on the year 2000 population census data available from the U.S. Census Bureau's TIGER® website. The population data is joined to the centroids of the ZIP codes. Ambulance locations are available from the ND GIS Hub. In this analysis, demand as population and supply as ambulance locations are involved in the issue of emergency service coverage analysis. Thus, the model has two steps: service catchment and population catchment.

Bismarck/Mandan has lower connectivity than other regions with regard to the number of ambulance locations because ambulance services operate in areas of dense population and do not share the overlapped service catchment to achieve the requirement of a nine-minute response time. On the contrary, ZIP code 58535, south of Bismarck/Mandan, and ZIP codes 58430, 58444, and 58454, between Underwood and Harvey near the center of the northern part of the region show higher connectivity as indicated by densely located service units and less-dense populations. Rural areas show higher connectivity as measured by the location-to-population ratio. However, that is not the case when travel distance and time to reach the closest ambulance location are considered. In other words, the regions indicate higher choice effect, but do not have an advantage in terms of transportation travel distance and time.

To calibrate the measure, the location-to-population ratio considers a distance by using a decay function in the gravity model (Figure 2). The travel-friction coefficient (β) is equal to 1.8, which is similar to the 50 min travel distance in 2SFCA [21]. The coefficient covers the regions for the emergency service from ambulance service units to the ZIP code centroids. The accessibility, which is indexed with the distance decay function for the population locations, significantly changes as shown in Figure 3. As a result, accessibility in Bismarck/Mandan and Jamestown increases because the travel distance from the ambulance locations to the incidents in the regions becomes shorter. In contrast, the ambulance services at ZIP codes 58535, 58430, 58540, and 58631 show lower accessibility levels because of the long distances from service units located in rural areas.

The ZIP code zones in the triangle region of Bismarck/Mandan, Goodrich, and Jamestown indicate poor service in terms of estimated response times. Note that ZIP codes 58368 and 58467 along the I-94 corridor would have better service than the other ZIP codes with respect to travel time because those areas are served by a higher-quality road infrastructure. Interstate Highway I-94, U.S. Highway 83, and State Highway 200 provide high accessibility with reasonable response time. The advanced life support (ALS) ambulance locations have longer response times than services in other areas because of the wider service coverage provided in urban areas by this highly specialized service.

Figure 2. Gravity indexed accessibility using the two-step floating catchment area 2SFCA (d_0 = 30 miles).

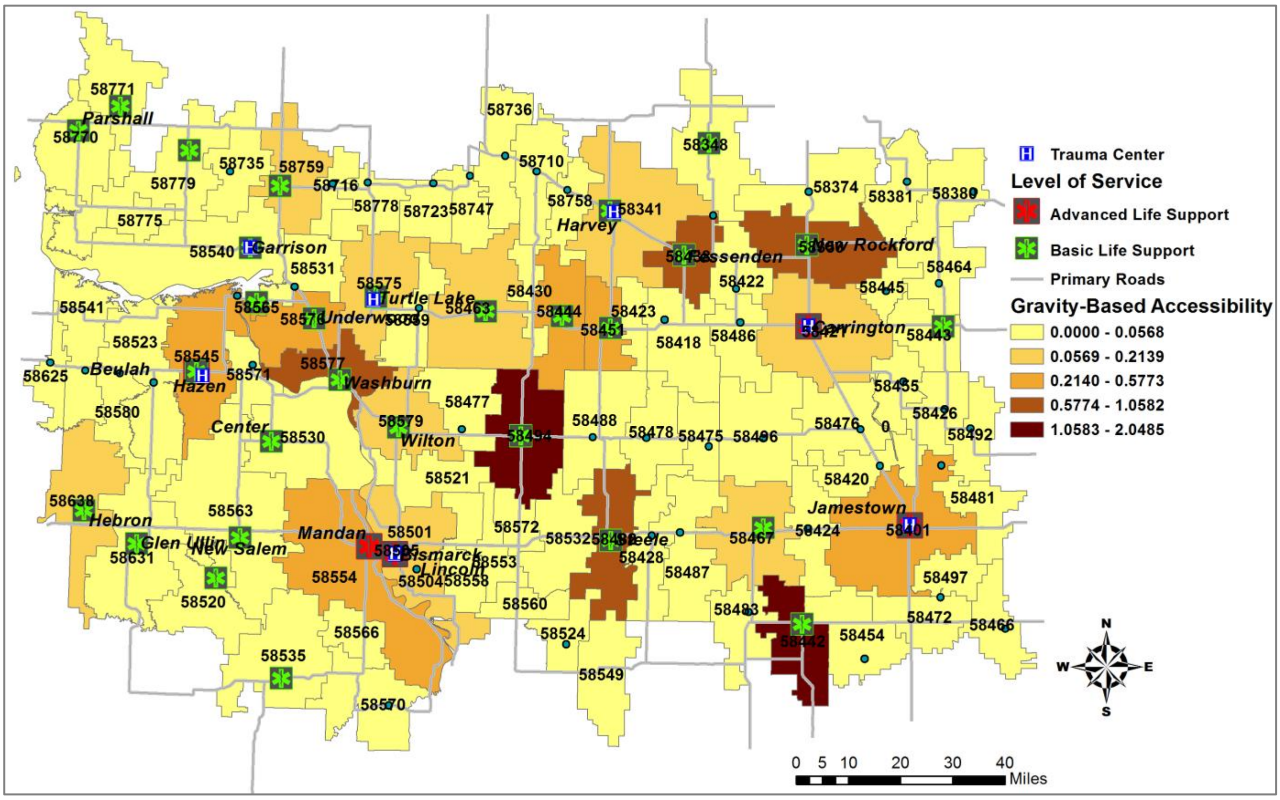


Figure 3. Fastest routes from ambulance locations to random incidents.

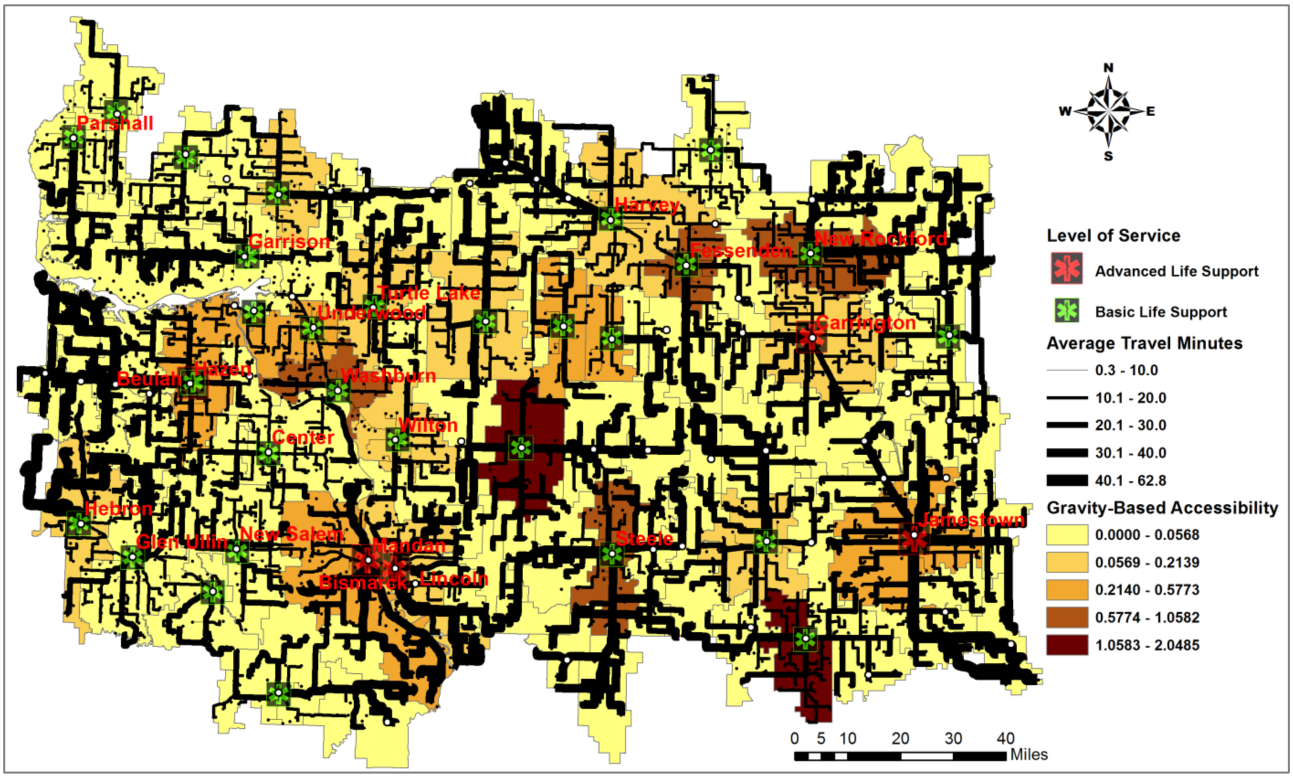


Table 1 summarizes the output of the simulated accessibility and the demand-covered-ratio. Each ZIP code is assigned service time (t_0) depending on the regional class. Accessibility (A_Z) is the ratio of the required service time to average value of response time. The index value of 1.0 represents a standard level of service. The demand-covered-ratio (C_Z) is the ratio of the number of random events covered by the required service time to the number of random events in a ZIP code. For example, ZIP code 58504 requires an average response time of 9 min from the ambulances surrounding the ZIP code. The random point generator generated 26 random points in the ZIP code area, and 21 were served within 7 min. The service distances range from 2 miles to 37.7 miles. The minimum response time was 2.2 min and the slowest response was estimated at 46.7 min. Thus, the accessibility was rated as 0.4, which is poor service (lower than the standard service of 1.0), and the demand-covered-ratio was 15.38%. Based on these two measures, ZIP code 58504 has inferior service from its ambulance service locations in terms of both accessibility and demand-covered-ratio. In reality, the travel time in the urban areas would decrease because some other ambulances outside the study regions clipped are missing in the analysis.

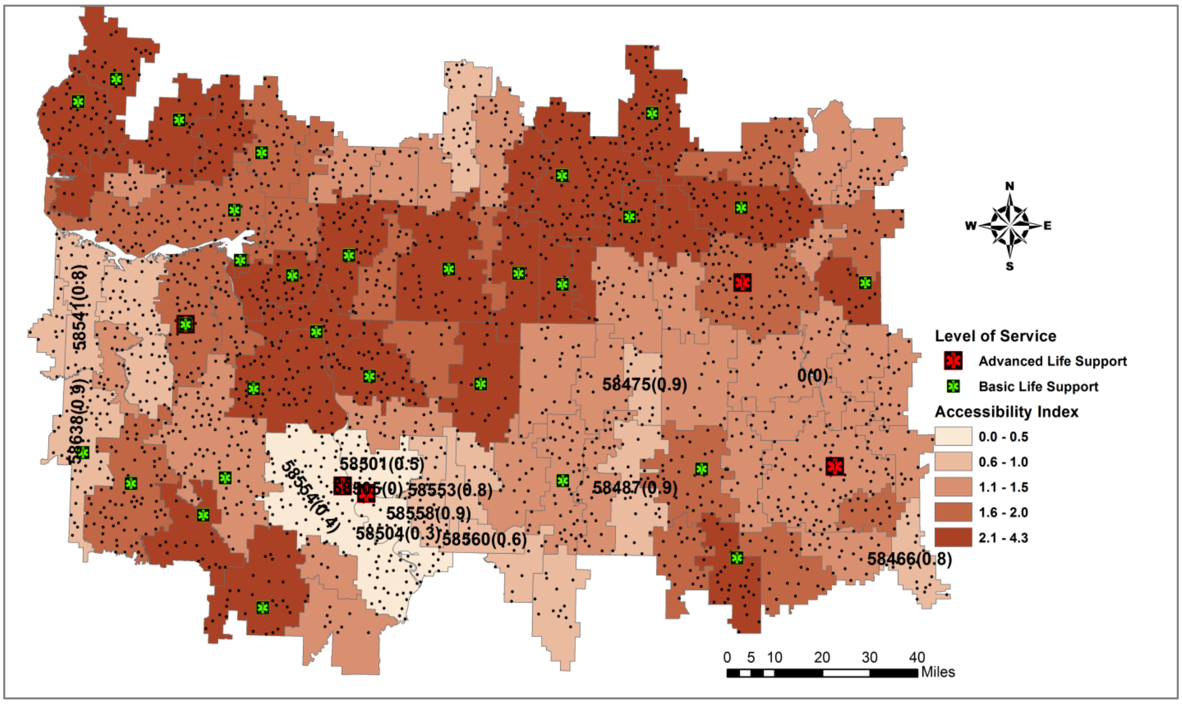
Of 91 ZIP codes, 75 indicate high accessibility. However, about 17.5% (16 of 91) of ZIP codes are under-covered. Once the ambulances practice an in-motion strategy for services in small urban areas, the accessibility will be doubled as shown in Table 1 and demand-covered-ratio will increase as well.

Accessibility (A_z) for a ZIP code is visualized in Figure 4. ZIP codes 58504, 58554, 58501, and 58560 show poor accessibility. The poor accessibility indicates slow response times by the closest ambulance services. Two major reasons for the poor service are service boundaries and shorter designated response times in urban and suburban areas. Frontier areas enjoy relatively fast service with higher accessibility because of the 30 min designated response time.

Table 1. Accessibility and coverage rate for zone improvement plan (ZIP) codes to ambulance locations.

ZIP code	Required service time (t_o^Z)	# of Random events	# of events within t_o^Z	Travel Distance (miles)			Response Time (minutes)			Accessibility (A_Z)	Demand–Covered-Ratio (C_Z)
				Mean	Min	Max	Mean	Min	Max		
58504	9	26	4	18.2	2	37.7	20	2.2	46.7	0.4	15.38%
58554	9	97	17	15.4	0.9	35.5	17	0.9	36.1	0.5	17.53%
58501	9	28	5	12.4	0.8	19.7	13.6	0.8	22.3	0.7	17.86%
58560	20	7	4	30.8	25.1	36.1	31	26.6	38.8	0.6	57.14%
58541	30	24	6	40.1	24.3	51.4	44.2	26.5	52.3	0.8	25.00%
58466	30	20	3	37.2	25.5	47.9	36.8	24.4	48	0.8	15.00%
58553	20	6	1	25.9	14.4	35.7	26.3	12.1	38.4	0.8	16.67%
58625	30	13	2	38.4	33	48.3	46.4	40.5	50.4	0.9	15.38%
58475	30	11	5	29.2	20.9	38.9	32.5	25.1	42.1	0.9	45.45%
58638	20	55	28	17	2.9	44.9	22.9	3.2	58.9	0.9	50.91%
58487	20	23	9	21.3	13.6	30.1	22.8	12.7	33.8	0.9	39.13%
58558	20	26	8	21	13	27.9	22.6	13.6	33.2	0.9	30.77%
58535	30	31	31	10.4	1.3	21.6	12.2	1.5	23.2	2.5	100.00%
58575	30	48	48	10	1.3	19.6	12.2	2.7	24	2.5	100.00%
58356	30	55	55	10.6	0.6	22.9	12	0.6	24.7	2.5	100.00%
58341	30	82	82	10.4	0.7	17.7	11.5	0.8	23.1	2.6	100.00%
58442	30	31	31	9.4	1.5	18	11.2	1.8	19.8	2.7	100.00%
58530	30	61	60	9.6	0.6	23.4	11.1	0.7	36	2.7	98.36%
58348	30	50	50	9.5	2.1	19	10.7	2.1	23.8	2.8	100.00%
58771	30	26	26	9	1.9	24	10.7	2.1	26.6	2.8	100.00%
58770	30	41	40	8.8	1.9	21.7	10.4	1.9	31	2.9	97.56%
58443	30	14	14	8.3	2.7	12.9	10.1	4.7	15.3	3	100.00%
58444	30	19	19	8.3	1.4	17	9.9	1.6	21.2	3	100.00%
58451	30	11	11	7.1	1.7	10.6	8.7	1.8	16.8	3.4	100.00%
58438	30	27	27	6.3	2.4	11.2	6.9	2.4	12.5	4.3	100.00%

Figure 4. Accessibility with respect to the average response time following the North Dakota (ND) emergency medical service (EMS) response time rules.

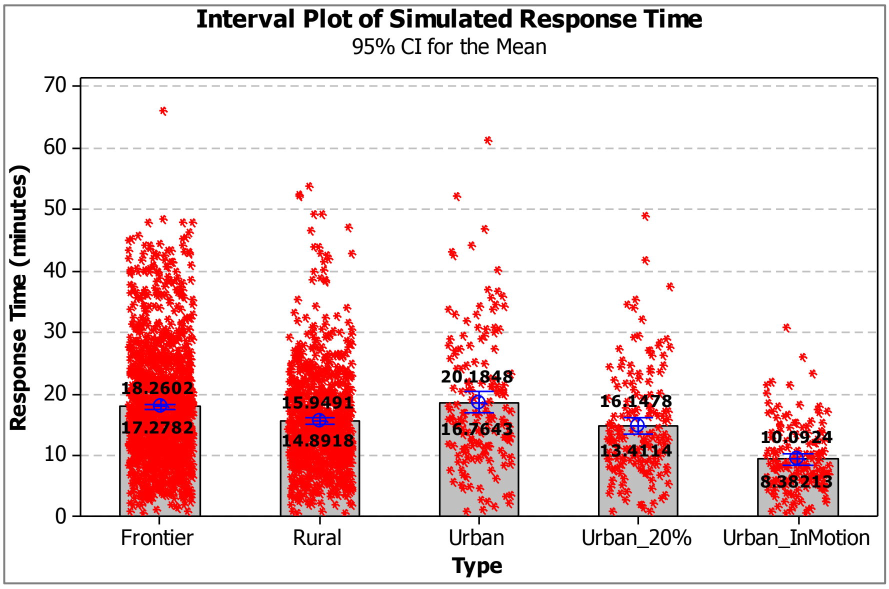


The results indicate that the coverage area and response time rules are critical to accessibility. Similarly, ZIP codes with wider service areas have relatively slow response times because the average travel time for a ZIP code varies by distance from ambulance service facilities to the locations of the hypothetical incidents distributed in a ZIP code area. Thus, the accessibility can be explained with the demand-covered-ratio (C_z) to estimate how many incidents are covered within the required service response time.

A low coverage rate indicates that many incidents are not covered within the required response time. For example, ZIP code 58487 has a poor demand-covered-ratio of 39.13%. In other words, only 39.13% of the incidents in ZIP code 58487 would have an ambulance arriving within 20 min (also see Table 1). It is necessary to investigate other cases with reasonable accessibility and low demand-covered-ratios. ZIP code 58770, for instance, has an accessibility of 2.9 and a demand-covered-ratio of 97.56%. The response time range of the 58770 ZIP code area is 10.4 min, ranging from 1.9 min to 31.0 min, which is a wide range of service times. The area is located along I-94. Incidents occurring near the I-94 corridor have quick response times, while incidents occurring at a greater distance from major highways have slower response times.

The response time has a stochastic nature because of geographic distribution and travel time over a continuous space. In rural areas, the response time is likely to be between 14.8 min and 17.2 min, and in frontier regions, the response time is likely to be between 15.9 min and 18.2 min, based on a 95% confidence interval (Figure 5). In contrast, the response time of ambulances in urban areas is likely to be between 16.7 min and 20.1 min as simulated under normal situations. Thus, this study simulated two other scenarios: a 20% increase in travel speed from 45 to 55 mph in urban areas and an in-motion response strategy. The in-motion response strategy resulted in a 50% increase in travel response times (Figure 5).

Figure 5. Interval plots of travel time in minutes for three regional types for ambulance response times (95% confidence interval for the average travel time). *Urban_20%* presents a scenario by increasing the travel speed in urban areas by 20% and *Urban_InMotion* reduces travel time by 50% under the ambulance's in-motion response strategy.



The 20% increase in travel speed shows that the response time is likely to be between 13.4 min and 16.1 min based on a 95% confidence interval, which is still longer than the actual response times measured in the urban areas. The urban areas indicate that the spatial boundary is larger than in general rural areas, and the ambulance locations are concentrated in the center of the urban areas (*i.e.*, metropolitan areas and interstate highways). If we assume that ambulances in urban areas are in motion, the vehicles would arrive at the scenes in half of the simulated response time, between 8.3 min and 10.0 min.

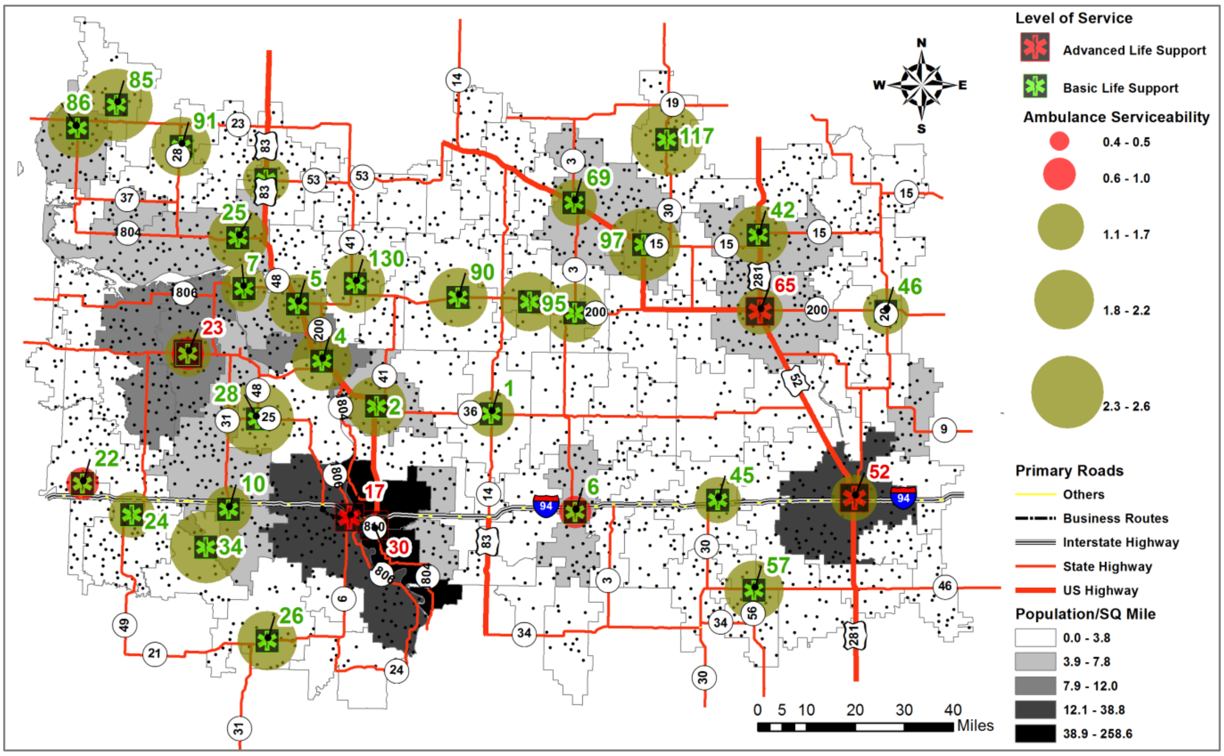
While stakeholders in a ZIP code area might consider accessibility (A_Z) and demand-covered-ratio (C_Z), the ambulance service considers the serviceability (S_j) regarding response to emergency calls and ambulance-covering-ratio (C_j). ND EMS rules require that ambulances respond to 90% of emergency calls in the required response time. When a neighboring ambulance is closer to the scene of the event than others, the neighboring ambulance serves the demands.

When an ambulance responds to the demand calls within the designated time (t_0), the serviceability (S_j) is 1.0. The serviceability is predicted to be low in Locations 6, 17, 22, and 30, because the ambulance locations are responsible for larger coverage areas and operate with a lower level of transportation infrastructure in the frontier areas (Figure 6). Ambulance Locations 17 and 30 are designated to serve the catchment areas of Bismarck and Mandan within 9 min. However, maximum distance and maximum response time for the suburban areas near the cities are relatively longer because of the wider service coverage to meet the nine-minute requirement.

Ambulance Locations 22 and 23 in the western regions also show wider ranges of response distances and times. Note that the ambulances are required to provide coverage within 20 min, which is relatively longer than for urban areas. Ambulance Locations 6 and 45 serve wider areas along the I-94. Most of the random crashes along the I-94 would be served faster than the coverage provided by

Locations 95, 65, 45, and 6 because of the well-structured transportation infrastructure. Ambulance Location 6 covers 57.89% of the incident calls with an average serviceability of 1.0. Ambulance Location 52 might travel an average of 18.4 miles and a maximum 47.9 miles to provide service (Table 2).

Figure 6. Serviceability of ambulances based on average response time for the random incidents.



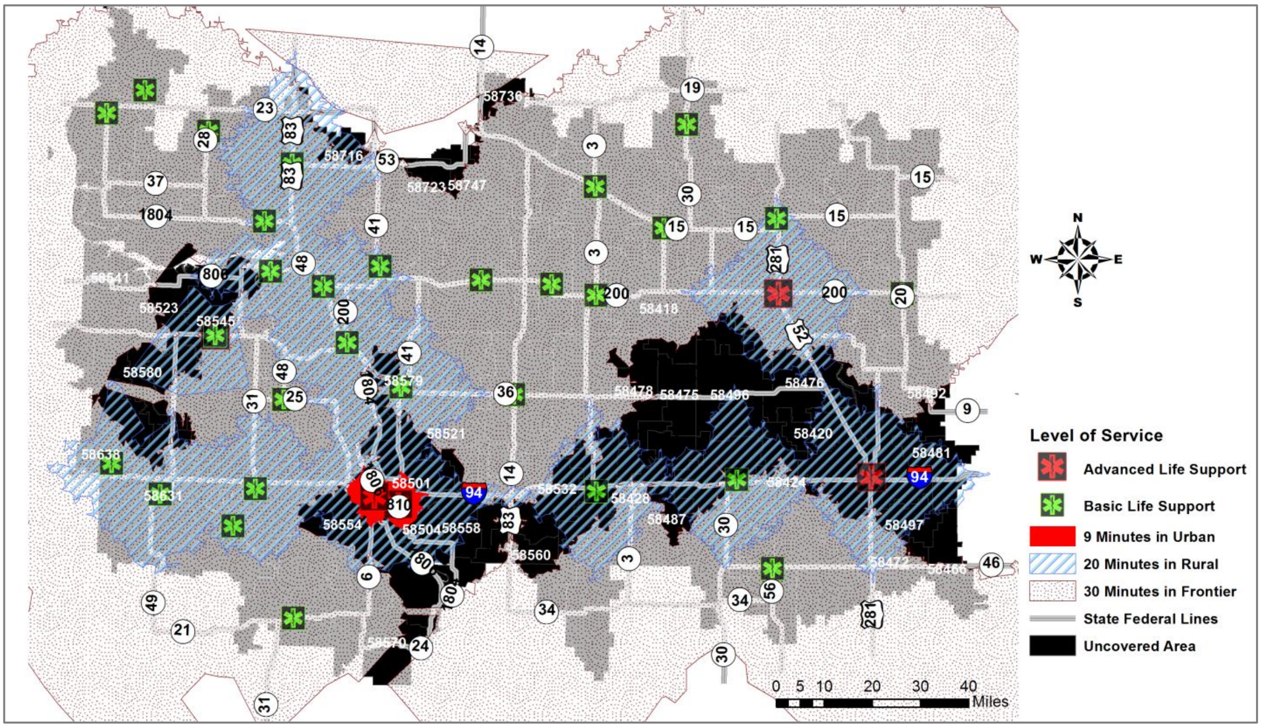
Ambulance 7 operates with an average response time of 11.9 min and an average travel distance of 9.6 miles, which indicates that 48 mph is the average speed for this smaller coverage area. Furthermore, ambulance Location 22 serves the areas with an average response time of 19.9 min and an average distance of 14.7 miles, resulting in an average speed of 44.3 mph. In contrast, ambulance Locations 6, 30, 42, 46, 52, 65, 69, 97, and 137 operate vehicles with an average speed greater than 55 mph on well-developed transportation infrastructures (Table 2). Among them, ambulance Location 52 indicates that it has an average speed as fast as 58.4 mph and serves a maximum distance of 47.9 miles.

Ambulance users are interested in borderless service coverage. By including service and response coverage, service coverage can be estimated by travel time considering regional categories (urban, rural, and frontier services). Figure 7 shows the estimated service coverage by travel time performance. The ZIP codes along the I-94 are under-served by an average response time that is slower than 20 min. ZIP codes 58478, 58498, and 58476 between the I-94 and State Highway 200 could not meet the requirement without adding a new ambulance location. The ZIP codes areas along the Missouri River and Lake Sakakawea (see ZIP codes 58541 and 58523) are not covered at adequate levels as indicated by the 20-min and 30-min response times, respectively, because of natural barriers (Figure 7).

Table 2. Total travel distance from a service unit to scenes using the fastest path.

Ambulance Location	Required service time (t_o^j)	# of Random events	# of events within t_o^j	Travel Distance (miles)			Response Time (min)			Serviceability (S_j)	Ambulance-Covering-Ratio (C_j)
				Mean	Min	Max	Mean	Min	Max		
30	9	83	19	17.4	0.8	37.7	18.8	0.8	46.7	0.5	22.89%
17	9	93	29	15.6	0.9	35.5	17.1	0.9	36	0.5	31.18%
31	20	146	82	20.3	3.3	50.4	22.4	3.3	62.8	0.9	56.16%
22	20	45	28	14.7	2.9	33	19.9	3.2	47.1	1	62.22%
6	20	133	77	18.2	3.1	35.1	19.7	3.6	37.4	1	57.89%
52	20	175	143	18.4	0.7	47.9	18.9	0.7	48	1.1	81.71%
45	20	87	71	15.9	0.5	38.9	17.5	0.6	42.1	1.1	81.61%
24	20	89	66	13.7	0.7	34	16.5	0.7	52.4	1.2	74.16%
137	20	78	75	13.5	3.6	33.8	14.5	3.6	36.7	1.4	96.15%
23	20	15	15	12.1	2.2	17.6	14.4	2.2	23.9	1.4	100.00%
65	20	93	93	13.5	3.3	28.3	14.4	3.7	29.2	1.4	100.00%
1	30	73	54	18.2	1.2	38.1	20.6	1.2	38.8	1.5	73.97%
46	30	102	92	19.1	2.7	36.2	20.6	4.1	37.7	1.5	90.20%
10	20	63	47	11.5	0.3	23.6	12.9	0.3	24.6	1.5	74.60%
69	30	117	103	16.8	0.7	39.9	17.7	0.8	39.7	1.7	88.03%
7	20	16	16	9.6	0.9	13.6	11.9	0.9	17.6	1.7	100.00%
90	30	62	60	14.8	4	30.8	17.1	6.2	36.1	1.8	96.77%
2	20	53	50	10.2	2.7	23.3	11.4	2.6	26.7	1.8	94.34%
26	30	42	36	13.9	1.3	29.5	16	1.5	37.1	1.9	85.71%
42	30	117	112	14.8	0.6	37.2	15.9	0.6	36.6	1.9	95.73%
130	30	82	79	13.3	1.3	27.5	15.7	2.7	30.9	1.9	96.34%
57	30	86	78	13.9	1.5	30.1	15.6	1.8	32.6	1.9	90.70%
4	20	44	43	9.4	1.2	23.4	10.5	1.4	25.1	1.9	97.73%
25	30	75	73	13.7	2.7	28.6	15.3	2.9	40.8	2	97.33%
91	30	41	41	12.6	1.6	25.7	14.3	1.8	28.5	2.1	100.00%
86	30	58	56	13.1	1.9	30.5	14.3	1.9	31.2	2.1	96.55%
5	20	49	49	8.2	1.8	14.1	9.7	2	19.8	2.1	100.00%
100	30	30	29	11.6	1.7	29.7	13.6	1.8	34.1	2.2	96.67%
95	30	34	34	11.7	1.4	21.9	13.3	1.6	24.3	2.2	100.00%
34	30	20	20	11.1	3.6	18.6	13.3	5.1	21.7	2.3	100.00%
28	30	73	64	10.7	0.6	21.5	12.3	0.7	24.5	2.4	87.67%
97	30	75	73	11.5	2.4	34.5	12.3	2.4	38.8	2.4	97.33%
117	30	56	56	10.1	2.1	19	11.4	2.1	23.8	2.6	100.00%
85	30	29	29	9.6	1.9	24	11.4	2.1	26.6	2.6	100.00%

Figure 7. Estiated ambulance service coverage based on the service response time requirements.



These inadequately covered areas show low population densities mirrored by a lack of ambulance locations. Suburban areas are also under-covered because of longer service distances from the urban centers and the requirement for a 9-min response time within urban areas. In-motion operations in urban areas would increase serviceability and ambulance-covering-ratio shown in Table 2.

Access and service coverage can be fully implemented by integrating transportation and facility locations [28]. The geographic regions, as defined by U.S. Census Bureau and state guidelines, and travel speed along the road networks vary in different states and areas; however, these factors can be applied to other regions by changing the regional travel speed. The model should appropriately reflect a variety of regional classifications, required response times, and average travel speeds through the networks.

6. Conclusions and Limitations

This paper introduces a new approach, which takes into account the response time and virtual incidents based on the Census households. The proposed methodology measures potential accessibility from the perspective of present residents in ZIP code areas and potential serviceability from the view of service providers. Both measures explain the demand-covered-ratio for ZIP codes and ambulance-covering-ratio for ambulance locations in light of the EMS response time rules for the three regional categories of urban, rural, and frontier services.

The fastest-path-based accessibility and serviceability with geospatial random events shows that the model is able to plan rational ambulance service coverage under consideration of households and travel time. The model provides an improved tool for efficient communication with stakeholders such as the public, policymakers, and public service planners. The model can be applied to statewide ambulance planning for service coverage and service location planning. The model is also transferable to other states. However, the model should be carefully revisited to consider metropolitan cities with large populations because those metropolitan cities have different characteristics with various external factors. As the model also represents space-time accessibility by including population and serviceability for service catchment, a practical application for the proposed model is to design the service coverage areas and estimate response times (*i.e.*, development of emergency service map books).

In addition, census blocks, which are the smallest geographic unit used by U.S. Census Bureau for population and household information, can replace the ZIP codes for calibration of the regional categories. Up-to-date census data is available from the U.S. Census Bureau to reflect service coverage rate and designate the urban, frontier, and rural areas distinctly for 2010. The dataset will allow the study to calibrate the model and will be applied to the statewide ambulance service planning in a timely manner for spatial restructuring of ambulance fleets and locations considering geographical, financial, and political boundaries. In many rural areas, demographic shifts result in rural residents moving to metropolitan areas. As a result, ambulance locations close and transportation distances for emergency services become longer. Thus, continuous improvement programs are essential and collaboration with state transportation departments plays a major role in mitigating various travel barriers and improving deteriorated infrastructure.

The continuous improvement program will mitigate the gap created by population migration, industry reorganization, aging, and transportation infrastructure. In addition, collaboration with the agency that is in charge of transportation networks enhances implementation. Even though the model was demonstrated in a regional case study, it can be generalized and applied to large-scale boundaries by adjusting the parameters. By doing so, planners can utilize multiple indicators such as serviceability, accessibility, demand-covered-ratio and ambulance-covering-ratio.

The model estimated the response time from the fixed locations of ambulances to the incidents. In rural areas, decreasing volunteerism and longer travel time from the first responders to the ambulance locations causes longer response times. In a future study, a first responder response model could improve the proposed model. While response time is typically measured for required service performance, the patient's condition should be considered in order to decrease mortality rates.

In addition, the road network should provide ambulance-based travel speeds, which reflect road condition and safety. The study can be separated into winter season and non-winter season to reflect road conditions due to seasonal impacts.

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Conflicts of Interest

The author declares no conflict of interest.

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