Modeling Investments in County and Local Roads to Support Agricultural Logistics

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Investments in local roads in North Dakota to support agricultural logistics are estimated with a detailed model that predicts flows from 1,406 crop-producing zones to 317 elevators and plants, and forecasts improvements and maintenance costs for paved and unpaved roads. The study finds that (1) the average farm-to-market trip distance has increased from 12 miles in 1980 to 26 miles in 2009, (2) the estimated resurfacing cost per mile for agricultural distribution routes is 40% greater than for non-agricultural routes, and (3) the estimated cost to maintain acceptable service levels on county and local roads is roughly double historical funding levels.

INTRODUCTION

According to the National Agricultural Statistics Service (NASS 2010), North Dakota leads the United States in the production of spring wheat, durum wheat, sunflower, barley, dry edible beans, canola, and flaxseed. In 2009, the total market value of agricultural goods produced in the state exceeded $5.5 billion (NASS 2009a). The top three commodities by value are wheat ($1,822 million), soybeans ($1,074 million), and corn ($708 million) (NASS 2009a).

Given the importance of agriculture to North Dakota's economy, industry and state officials have grown increasingly concerned about the capabilities of local roads to support agricultural logistics in the face of increased traffic loads and rising construction costs. The purpose of this study is to quantify the investment and maintenance needs of county and local roads that serve as agricultural logistics routes. To this end, an integrated system of models has been developed to predict crop production, distribution, truck movements, and roadway investment and maintenance needs for individual road segments. These details are necessary for legislators to allocate scarce funding to areas of greatest need. While this study focuses on North Dakota, the modeling process can be replicated in other states.

The study benefits significantly from previous work that has focused on the prediction of agricultural traffic flows and the impacts of heavy trucks on rural roads. Purnell, Yoder, and Sinha (1978) developed a methodology for analyzing the effects of increased traffic on rural highways from rail-line abandonment using pavement/traffic equations developed by the Association of State Highway and Transportation Officials (AASHTO). Tolliver (1989) integrated spatial interaction and pavements models to predict grain flows within a system of elevators and to quantify the impacts of large subterminals on rural highways. Russell, Babcock, and Mauler (1996) developed road damage equations that were used to estimate the highway costs of truck movements from farms to elevators and from elevators to final destinations. Prozzi, Harrison, and Prozzi (2003) analyzed the changing needs of individual agricultural sectors in Texas and developed methodologies for quantifying the effects of increased truck traffic on rural pavements. Babcock, Bunch, Sanderson, and Witt (2003) estimated damage functions for highways in Kansas and quantified the increased costs of potential railroad abandonments.

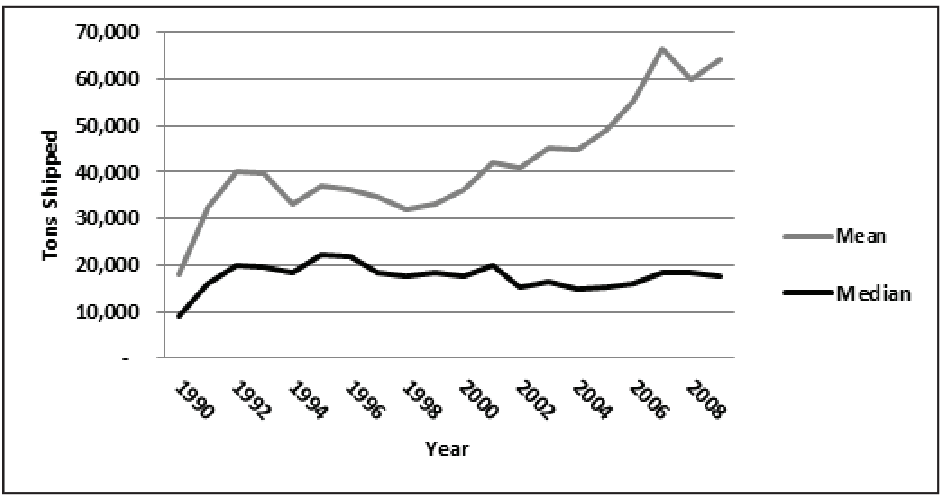
In addition to providing a statewide analysis of road investment needs, this paper introduces a geographically specific modeling technique based on Geographic Information Systems (GIS) resources (including GIS crop layers and local road networks) that have only recently become available. In addition, this paper utilizes transshipment models to predict flows from elevators to processing plants, including ethanol production facilities, and quantifies the effects of shifts in crop production (e.g., from wheat to corn) that result in greater crop densities and more truck movements from a given area of land. The paper begins with a description of key trends and factors that have motivated this study.

KEY FACTORS and TRENDS

Due to improvements in seed, production technologies, and management practices, crop yields in North Dakota have increased substantially during the past 20 years. In 1990, corn averaged 80 bushels per acre throughout the state (NASS 2010). However, corn yields rose to 115 bushels per acre in 2009, down from a high of 124 bushels per acre in 2008 (NASS 2010). The effects of yield gains have been intensified by changes in land use. In 1990, roughly 60% of the cropland in North Dakota was planted with wheat (NASS 2010). However, by 2009, wheat's share of cultivated acres had dropped to 45% (NASS 2010). Over the same period, corn acres increased from 5% to 10% of cropland (NASS 2010). The shift from wheat to corn production has effectively increased truck volumes because the relative yield of corn is more than double that of wheat.

While corn acreage and yields have been increasing, the number of elevators shipping grains or oilseeds has decreased from 458 in 1990 to 311 in 2009 (North Dakota Public Service (NDPSC) 2010). Although the number of elevators has declined, the amount of grain handled by these facilities has increased. The average tonnage shipped from elevators in North Dakota increased from roughly 18,000 tons in 1990 to 64,000 tons in 2009 (Figure 1). In contrast, median elevator throughput has remained relatively constant for the past 20 years. (NDPSC 2010)

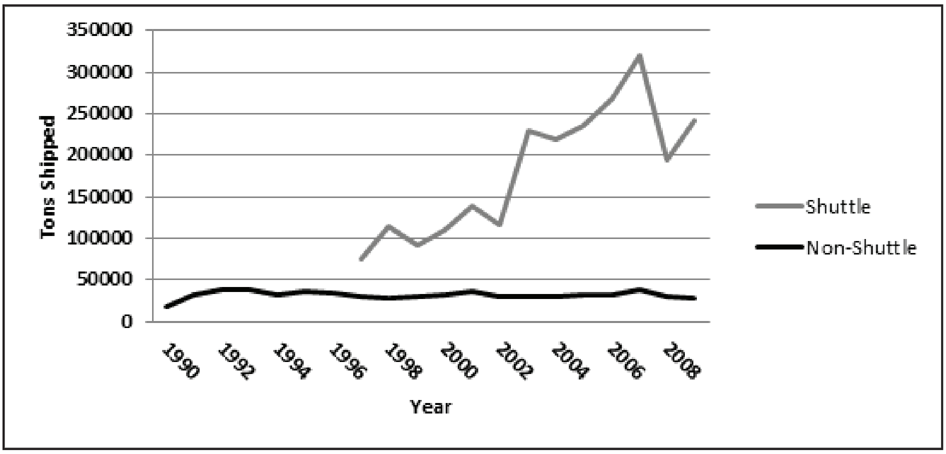
Figure 1: Mean and Median Tons Shipped by North Dakota Elevators (1990-2009)



Source: North Dakota Public Service Commission Grain Movement Database

In the 1990s, shuttle-train programs were introduced wherein an elevator may receive a substantially reduced rail rate if it is able to meet certain conditions and satisfy minimum grain shipment volumes designated by the railroads. Figure 2 shows the average tons shipped from shuttle and non-shuttle elevators in North Dakota. Prior to the shuttle-train program, elevator throughput statewide averaged less than 32,000 tons. This volume has remained relatively unchanged for traditional (non-shuttle) elevators through the last decade. However, for shuttle elevators, average throughput volume has increased from 74,600 tons in 1997 to 240,640 tons in 2009. (NDPSC 2010)

Figure 2: Mean Tons Shipped from Shuttle and Non-Shuttle Elevators (1990-2009)



Source: North Dakota Public Service Commission Grain Movement Database

As the previous discussion suggests, increasing yields and changes in crop mix have resulted in greater densities of production and more crop movements from a given area of land. At the same time, the number of grain elevators has decreased and shipments have become more concentrated at fewer elevators, resulting in fewer delivery options for farmers and longer farm-to-elevator hauls. More grains are being transshipped from smaller to larger elevators. These elevator-to-elevator transshipments, coupled with the growing demands of in-state processors, have resulted in more intrastate truck (as opposed to interstate rail) movements at a time when construction prices for asphalt and gravel roads have been dramatically increasing. With this background, the paper turns to a description of the primary data and methods used to predict agricultural traffic flows and roadway investment needs.

OVERVIEW OF MODELING METHODS AND DATA

The estimation of agricultural tonnage and investment needs for individual road segments requires an integrated system of models, including (1) a crop production and location model; (2) a crop distribution model, in which movements or flows are predicted from crop-producing zones to elevators and processing plants; (3) a traffic model in which predicted flows are converted to trucks and assigned to individual road segments; and (4) a road investment model, in which truck traffic and road characteristics are used to estimate investment needs.

Crop Production Estimates

In this study, crop production estimates are generated for 1,406 county subdivisions in North Dakota using USDA's 2009 Cropland Data Layer (NASS 2009b). In counties that have organized townships, the subdivision is defined as the township, which is approximately 36 square miles (on average). Eighty-five percent of townships have areas greater than 30 square miles, but less than 40 square miles. In counties without organized townships, the subdivision is the county itself. In the analysis process, the land area devoted to the production of each crop in each county subdivision is estimated using GIS procedures that allow the extraction of vector data (which are in the form of points and lines) that are geometrically and mathematically associated with satellite raster images (which are in the form of individual pixels) and geographically calculate crop land area.[1] To increase the precision of these estimates, the predicted areas devoted to crop production in each subdivision are adjusted based on the 2009 county production values (NASS 2010). In this adjustment, the predicted production of each crop in each subdivision is apportioned based on its share of cultivated land area within the county. The crop land area and production information is shown in Table 1. The average crop production per subdivision is 20,490 tons.

Table 1: Crop Area and Production

Crop	Crop Area (Thousands of Acres)	Percentage of Area	Area Production (Thousands of Tons)
Spring Wheat	6,300	38.51%	8,694
Soy Beans	3,870	21.4%	3,483
Corns	1,740	10.9%	5,603
Durum Wheat	1,570	7.68%	1,837
Canola	725	4.31%	667
Sunflower	868	4.16%	659
Dry Beans	580	2.73%	4
Barley	1,130	2.63%	1,898
Winter Wheat	545	2.46%	785
Dry Peas	480	2.19%	6
Flaxseed	293	1.1%	197
Sugar Beats	218	0.98%	4,796
Lentils	163	0.79%	1
Oats	165	0.54%	180
All Crops	18,647	100%	28,809

Crop Destinations

In this study, the final or interim destinations for crops are in-state processing plants or elevators that ship crops out of state to various domestic and export locations. The throughput at elevators (in annual tons) is computed from monthly reports submitted to the North Dakota Public Service Commission by outbound mode and destination. The annual grain demand at ethanol plants are derived from several sources, including (1) reported shipments from North Dakota elevators to in-state processors, (2) the stated productive capacities of the plants, and (3) confidential survey information that describes the percentages of corn acquired from the local drawing areas around the plants and expected production volumes.

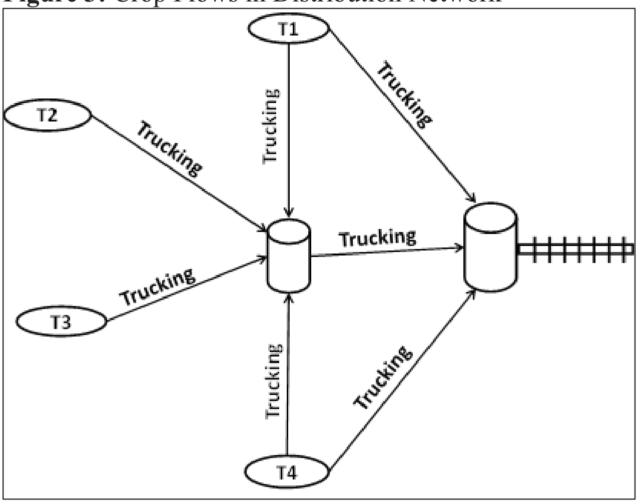
Model Components and Structure

The crop distribution model is comprised of a set of nodes, links, and paths. A path (such as one leading from a crop-producing subdivision to an elevator) is typically comprised of many individual links or road segments. For example, a subdivision-to-elevator path may include local gravel roads, paved county major collectors, and state arterial highways. Each segment (or link) is demarcated by two intersections or junctions in the road network. In many instances, two or more paths may be combined to form a trip chain. For example, a trip chain may include a path from a crop-producing subdivision to an elevator, and a path from that elevator to a processing plant.

The nodes consist of three types: origin, intermediate, and destination. The origin nodes are represented as centroids (i.e., central traffic loading points) situated near the centers of crop-producing subdivisions. The elevators and in-state processing plants are destination nodes. However, elevators may also serve as intermediate nodes. As an intermediate or transshipment node, an elevator may receive shipments directly from subdivisions or from other elevators. Subdivisions may ship directly to in-state markets (e.g., ethanol plants) or elevators. Links represent road segments including highways, county and urban roads, and paved and unpaved roads.

A simplified grain distribution system is depicted in Figure 3. As the figure shows, farm producers from various subdivisions or townships may ship directly to a shuttle-train elevator, or to a smaller elevator located closer to the subdivision. The smaller elevator, in turn, may transship some of the grain it procures to the shuttle-train facility; the shuttle-train facility, in turn, ships large quantities by rail to markets located out of state. A similar network for movements to in-state processors can be drawn by substituting a processing plant for the shuttle-train elevator. In this case, the primary outbound product will be ethanol, vegetable oil, malt, or flour.[2] The grain distribution network consists of 305 elevators (44 of which are shuttle-train facilities), six ethanol plants, a malt plant, and five flour mills. Altogether, the network consists of 1,406 origins and 317 destinations.

Figure 3: Crop Flows in Distribution Network



Objective Function and Constraints

The objective of the crop distribution model (Equation 1) is to minimize the total distance of moving all agricultural commodities to plants or final elevators, from where they are shipped out of state, subject to the following constraints: (1) the demands at the elevators and ethanol plants (which represent the tons of each crop handled or utilized per year) must be met (Equation 2), (2) the sum of all shipments of a particular crop from a county subdivision to all elevators and plants cannot exceed the predicted supply in the subdivision (Equation 3), (3) conservation of flow must be maintained at the elevator nodes—i.e., the inbound flows to an elevator must be equal to the elevator's reported throughput plus the outbound flows from the elevator to other elevators or ethanol plants, and (4) the predicted tons traversing a path must be greater than or equal to zero.

(1) $Min \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{o} d_{ij} * x_{ijk} + \sum_{i=1}^{m} \sum_{q=1}^{p} \sum_{k=1}^{o} d_{iq} * x_{iqk} + \sum_{q=1}^{p} \sum_{j=1}^{n} \sum_{k=1}^{o} d_{qj} * x_{qjk}$

Subject to:

(2) $\sum_{i=1}^{m} \sum_{k=1}^{o} (x_{ijk} \times NT_k) + \sum_{q=1}^{p} \sum_{k=1}^{o} (x_{qjk} \times NT_k) = D_j \quad \forall j \in \{1, \dots, n\}$

(3) $\sum_{j=1}^{n} (x_{ijk} \times NT_k) + \sum_{q=1}^{p} (x_{iqk} \times NT_k) \leq S_{ik} \quad \forall j \in \{1, \dots, n\} \cup \forall k \in \{1, \dots, o\}$

(4) $\sum_{i=0}^{m} \sum_{k=1}^{o} x_{iqk} = \sum_{j=0}^{n} \sum_{k=1}^{o} x_{qjk} \quad \forall q \in \{1, \dots, p\}$

(5) x_{kji}, x_{iqk}, and x_{qjk} are non-negative integers for all i, j, and k

Where

i = Index for subdivision

j = Index for plant or final elevator

q = Index for transitional (transshipment) elevator

d_{ij} = Distance between i and j

d_{iq} = Distance between i and q

d_{qj} = Distance between q and j

x_{ijk} = truckloads of commodity k transported between i and j

x_{iqk} = truckloads of commodity k transported between i and q

x_{qjk} = truckloads of commodity k transported between q and j

NT_k = Net load in tons for commodity k

D_j = Demand at destination j in annual tons

S_{ik} = Supply at origin subdivision i in annual tons

GIS Network and Shortest Path Algorithm

The GIS part of the overall model was constructed through a multistep process. (1) The geographic coordinates of all elevators and plants were used to create points in the GIS network that represent facilities. (2) A centroid (or central loading point) was generated for each crop production zone at the weighted center of the zone. The attributes of each zone (e.g., production and land area) were assigned to the appropriate zonal centroid. (3) An integrated highway network was created that includes all state, county, township, and other local roads. In this network, roads of different jurisdictions were connected so that crops could be routed over any combination of roads. (4) Beginning and ending mile point references were generated for each road segment using geographic coordinates. Then, the distance of each segment was computed using these beginning and ending mile points. In addition to the distance of the segment, the following roadway attributes were identified and stored with each segment: (1) surface type (paved versus unpaved), (2) functional classification, and (3) route name.

Once the aforementioned steps were completed, the optimal routes between origins and destinations were identified. The routing procedures embedded in the GIS software are based on Dijkstra's algorithm for finding the shortest path. This algorithm can be used to minimize distance, time, or cost. As described in Winston (1993), Dijkstra's algorithm is a graph search procedure that solves the single-source shortest path problem for a network with non-negative path costs, producing a shortest path tree. To find a shortest path from a starting location *i* to a destination location *j*, Dijkstra's algorithm maintains a set of nodes, P, whose final shortest path from *i* have already been computed. The algorithm labels the origin node (e.g., the centroid) with a permanent label, and then labels each node *i* that is connected to the origin node by a single arc with a "temporary" label equal to the length of the arc joining the origin node to *i*. Next, the node with the smallest temporary label is chosen and the node's label is made permanent. The algorithm then finds another permanent node and updates the shortest path of all neighbors of this node that are not already included in the set of permanent nodes. This process is repeated until the destination node is added to the permanent set. At this point, the shortest path through the network has been found.

The distribution model identifies an optimal or logistically efficient set of truck movements. Shorter trip distances minimize fuel consumption and use-related vehicle depreciation. Because trucking cost is typically measured on a per-mile basis, minimizing the distance of agricultural goods movements to elevators and plants is parallel to minimizing farm-to-market trucking cost on a systemwide basis. Note that the model minimizes the total or chained trip distance, including transshipments from one elevator to another or from an elevator to an in-state processing plant. Transshipments occur when production in the primary draw area is not sufficient to meet an elevator's demand. In such cases, the trip chain extends from the township to the shuttle-train elevator via a smaller elevator en route.

The distinction between paths and segments is important in describing the purpose of this model and how it differs from typical supply chain or industry distribution models. In an industry distribution model, only the path distances or travel times are considered, because the predicted optimal flows and shipping costs are the end objectives. In this analysis, the predicted flows are an interim step to estimating road investment needs. The analysis is complicated by the fact that an individual road segment may be included in many distribution paths. To estimate road investment and maintenance needs, each path must be decomposed into its constituent segments and all the predicted flows traversing a segment must be summed to yield the agricultural traffic load. Moreover, the flows must be converted to truck trips and axle weights. The results of an unpublished statewide survey are used for this purpose. The survey indicates that roughly 62% of the crop volume destined for North Dakota elevators is transported in combination tractor-trailer trucks, predominantly in five-axle tractor-semitrailers, which represent 90% of combination truck volume. Another 38% is transported in single-unit trucks consisting of tri-axle and tandem trucks.

PREDICTED FLOWS

Approximately 21.89 million tons of grains and oilseeds are analyzed in this study. The tonnage of each crop is shown in Table 2, as well as the weighted-average length of haul, which reflects the movement from farm to first elevator or plant, as well as any subsequent movement from the first elevator to another facility. The oilseed category in Table 2 includes sunflowers and canola, while the other crop category includes dry edible beans, oats, and other specialty crops.

Table 2: Predicted Tons of Agricultural Freight and Average Trip Lengths

Crop	Annual Tons	Average Trip Distance (mi.)*
Barley	1,681,418	87.8
Corn	5,102,252	21.1
Oilseeds	578,929	26.6
Other	547,028	39.7
Soybeans	4,144,969	23.1
Beans	562,124	30.8
Wheat	9,268,699	18.1
All Crops	21,885,419	26.2

* Average trip distance obtained by summing the ton-miles from the distribution model and dividing by tons for each commodity.

In 1980, the average farm-to-elevator trip distance in North Dakota was 12 miles (Griffin, Wilson, and Casavant 1984). In comparison, the total predicted distance of all crop movements in 2009-2010 (including transshipment distances) was 26 miles. However, there are significant variations among crops. The average trip distance for barley reflects a spatial disconnect between supply and demand. Much of the barley grown in 2009 was cultivated in the north-central part of the state, while the major demand sources are the malting plant and elevators located in eastern North Dakota, resulting in lengthy truck trips.

The predicted ton-miles of agricultural goods are shown in Tables 3 and 4. In Table 3, the predicted ton-miles are listed by type of pavement. As this table shows, agricultural goods required roughly 566 million ton-miles of transportation during crop year 2009-2010. More than half of these ton-miles occurred on principal arterial highways, most of which are owned and maintained by the North Dakota Department of Transportation (Table 4). The next greatest concentration of flows was on county major collectors, approximately 132 million ton-miles (Table 4). Sixty-five percent of these ton-miles can be traced to paved county major collector (CMC) roads (Table 5).

Table 3: Predicted Ton-Miles of Agricultural Freight in North Dakota by Road Type

Surface Type	Ton Miles	Percent
Paved High-Type (State)	319,449,945	56.4%
Paved (County and Local)	99,563,913	17.6%
Graded & Drained	2,807,777	0.5%
Gravel	141,222,015	25.0%
Trail	2,233,471	0.4%
Unimproved	720,330	0.1%
All Roads	565,997,453	100.0%

Table 4: Predicted Ton-Miles of Agricultural Freight in North Dakota by Roadway Class

Functional Class	Ton-Miles	Percent
Principal Arterial	319,871,952	57%
Minor Arterial	3,804,845	1%
Major Collector	132,333,047	23%
Minor Collector	621,758	0%
Local	109,365,851	19%
All Roads	565,997,453	100%

Table 5: Predicted Distribution of Agricultural Ton-Miles Among Paved and Graveled County Major Collector Roads in North Dakota

Surface Type	Ton-Miles	Percent of Ton-Miles
Gravel	46,866,136	35.4%
Paved	85,459,102	64.6%
Trail	7,808	0.0%

ROAD ANALYSIS PROCEDURES

Both paved and unpaved roads are analyzed in this study. In addition to traffic levels, the key factors in estimating gravel road investment and maintenance costs are the frequency of gravel applications, the thickness of the gravel overlay, blading frequency, and the cost of gravel. The gravel overlay thickness reflects the depth and quality of the road surface as well as its condition. The gravel interval represents the quality of the gravel surface as well as the roadway condition and maintenance practices, while the blading interval is representative of the counties' maintenance activities in general.

Responses from an unpublished 2009 survey of county road managers were used to develop input costs and frequencies for the unpaved road cost model. The survey responses indicate that the statewide average gravel thickness in North Dakota is 932 cubic yards per mile and the statewide average graveling interval is six years, with five years being the most frequent interval. The statewide average cost of gravel is $6.54 per cubic yard. However, gravel costs range $3.00 to $14.00 per cubic yard across the state. Moreover, there are substantial variations in gravel intervals and overlay thicknesses from one part of the state to another. Gravel loss factors, such as weather conditions, traffic volume, and traffic speed, in addition to gravel cost and availability, are the most likely reasons for variations.

The unpaved road cost model simulates typical practices at various levels of traffic. As traffic levels increase, the amount and/or frequency of gravel applications and blading typically increase to preserve surface condition. In this study, costs were developed for three accelerated graveling cycles: five-year, four-year, and three-year intervals. The graveling intervals correspond to classifications of average daily traffic (ADT) — i.e., 0-50, 50-100, 100-150, and 150-200 ADT.

Due to the heterogeneity of survey responses at the county level, an individual county scenario was constructed to reflect reported maintenance practices. One such scenario is presented below. The assumptions reflect actual gravel road maintenance activities as reported in county surveys. The scenario is based on a baseline gravel overlay of 930 cubic yards per mile (e.g., a 2-inch overlay on a 28-foot wide roadway) at an interval of five years. The gravel cost is $5.80 per cubic yard, to which a transportation cost of $0.24 per cubic yard per mile and $1,800 per mile of gravel application costs are added. Blading cost is estimated to be $18.75 per mile per event.

Table 6 presents the costs associated with increases in gravel road maintenance for this scenario. For low traffic roadways, the estimated cost for gravel road maintenance is roughly $3,900 per mile per year. For roads with 50-100 ADT, the gravel interval remains constant, but the blading interval decreases by 50% to twice per month, representing a doubling of blading frequency. For roads in the 100-150 ADT category, the gravel interval is decreased to four years and the annual cost exceeds $4,800 per mile. For the highest volume roads, the gravel interval is three years, the blading frequency is increased to weekly, and the cost per mile rises to $6,623.

Table 6: Unpaved Roadway Maintenance Scenario Estimates

ADT	Gravel Interval	Blade Interval	Cost Per Mile
0-50	5 Years	1 per Month	$3,913
50-100	5 Years	2 per Month	$4,213
100-150	4 Years	2 per Month	$4,817
150-200	3 Years	4 per Month	$6,623

Source: unpublished 2009 survey of North Dakota county road managers

The key factors in the paved road analysis are (1) the number of trucks that travel the road segment, (2) the types of trucks and axle configurations used to haul agricultural commodities, (3) the structural characteristics of the roads in agricultural logistics routes, (4) the widths of the roads, and (5) the current surface conditions. The methods used in this study are derived from Tolliver (1989) and Babcock, Bunch, Sanderson, and Witt (2003). In this approach, the pavement design equations of the American Association of State Highway and Transportation Officials (AASHTO 1993) are used to analyze axle load impacts. The equations are expressed in equivalent single-axle loads (ESALs). In this metric, the weights of various axle configurations (e.g., single, tandem, and tridem axles) are converted to a uniform measure of pavement impact. An ESAL factor for a specific axle represents the impact of that axle in comparison to an 18,000-pound single axle. The effects are nonlinear. For example, an increase in a single-axle load from 18,000 to 22,000 pounds more than doubles the pavement impact, increasing the ESAL factor from 1.0 to 2.44.

The calculation of ESAL factors is illustrated for a tractor-semitrailer weighing 80,000 pounds with a weight distribution of 12,000 pounds on the front (steering) axle and 34,000 pounds on each of the tandem axles. The ESAL factor for a 34,000-pound tandem axle is 1.07, which suggests that its impact is only marginally greater than the impact of an 18,000-pound single axle. The ESAL factor for the 12,000-pound single axle is 0.177 and the overall ESAL factor for the truck is 0.177 + 1.07 × 2 = 2.32. This means that for every loaded mile the truck travels, it consumes a small part of a pavement's life, as measured by 2.32 units or ESALs. A similar calculation for a 50,000-pound single-unit three-axle truck (with a tandem rear axle) yields an ESAL factor of 1.68—i.e., 0.61 + 1.07.

The capability of a paved road to accommodate heavy truck traffic is reflected in its structural rating, which is measured through the structural number (SN). The structural number is a function of the thickness of the surface and base layers and the materials of these layers. The surface layer of a county or local road is typically composed of asphalt while the base layer is composed of aggregate material. The amount of cracking and deterioration of the surface layer is considered in the structural number of an aging pavement. Moreover, the conditions of base layers and underlying soils are important considerations when assessing seasonal load limits and the year-round capabilities of roads. The average thicknesses of pavement layers in county and local paved roads in North Dakota are shown in Table 7. These values represent weighted means derived from a 2009 unpublished survey.

Table 7: Average Layer Thicknesses of County Collector and Local Roads in North Dakota

	County Major Collector	Local Road
Base layer thickness (inches)	5.1	3.9
Surface layer thickness (inches)	4.1	4.0

Source: unpublished 2009 survey of North Dakota county road managers

Two types of paved road improvements are analyzed: reconstruction and resurfacing. Reconstruction entails the replacement of a pavement in its entirety—i.e., the existing pavement is removed and replaced by one that is equivalent or superior. A road may be reconstructed because its pavement is too deteriorated to resurface, it has a degraded base that will provide little structural contribution to a resurfaced pavement, its roadbed is comprised of poor soils that are susceptible to moisture, or it is too narrow to accommodate thick overlays without widening. If a pavement is not too badly deteriorated and is of sufficient width, normal resurfacing is a cost-effective method of restoring the structural capacity of a road. In this improvement, a new asphalt layer is placed on top of the existing pavement surface in the depth needed to return the pavement to an acceptable level of serviceability and restore its structural strength. Without extensive truck traffic, a relatively thin overlay (e.g., 2 to 2.5 inches) can often be effectively applied. In comparison, reconstruction is very expensive, costing $1.25 million per mile. Thus, it can only be justified on roads with significant traffic volumes.

PREDICTED ROAD INVESTMENT NEEDS AND MAINTENANCE COSTS

Altogether, 10,286 miles of gravel roads in North Dakota are used for agricultural goods movements. In the unpaved road analysis, the predicted agricultural trips are added to the non-agricultural average daily traffic to obtain the total ADT for each impacted road segment. Using the predicted ADT volumes, the unpaved road segments in the agricultural logistics routes are classified by traffic volumes (0-50, 50-100, 100-150, and 150-200 ADT). Annualized costs are developed for each traffic classification based on the predicted gravel application intervals, blading frequencies, and cost of gravel. Using this procedure, a yearly improvement cost of $43.627 million is estimated for gravel surface agricultural hauling roads.

This study also found that 3,958 miles of paved county and local roads in North Dakota are significantly impacted by agricultural traffic. Of this total, 147 miles need reconstruction because of deficiencies in roadway width. The estimated annualized cost of these improvements is $9.2 million.

An additional 2,541 miles are expected to need resurfacing during the next 20 years at an estimated annualized cost of $31.2 million.

In the resurfacing analysis, a new structural number was computed for each road segment based on its projected ESAL demand, considering the effective structural number of the road's existing surface and base layer at the time of resurfacing. The additional inches of surface layer needed to return the segment to an expected 20-year life cycle were derived from the difference between the new and old structural numbers. For details on this procedure, see Purnell, Yoder, and Sinha (1978). The projected ESAL demand included both agricultural and non-agricultural traffic.

As shown in Table 8, the projected median overlay thickness needed on paved road segments in primary agricultural routes is four inches. In the resurfacing analysis, the cost of each segment is estimated from the inches of overlay needed and a projected 2011 unit cost of $70,000 per inch per mile, which is applicable to two-lane rural roads. With this unit cost, a 4-inch overlay costs $280,000 per mile. A 3-inch overlay costs $210,000 per mile, etc.

In addition to the $40.4 million of resurfacing and reconstruction improvements identified in this study, routine maintenance costs were estimated. Paved road maintenance programs include activities performed periodically (such as crack sealing, seal coats, and striping), as well as annual activities such as patching. The cost relationships in Table 9 were derived initially from the South Dakota Department of Transportation (2004), with the original cost factors updated to 2010 levels and annualized. Note that the annualized seal-coat cost in Table 9 allows for at least two applications during a typical 20-year life-cycle for roads with ADT of 200 or more.

Table 8: Estimated Surface Thicknesses for Major County Collector Segments in Agricultural Logistics Routes in North Dakota

Weighted Percentiles of Distribution	Inches of New Asphalt Surface Layer
90th	4.7
75th	4.0
50th	4.0
Mean	3.9
25th	3.7

A percentile in the table is the value of surface thickness below which a certain percent of the observations (i.e., road segments) fall. For example, the 90th percentile is the value of surface thickness below which 90% of the road segments lie.

Table 9: Routine Maintenance Cost Factors for Paved Roads by Traffic Level

ADT Traffic Range		**Annualized Cost of Road Maintenance Activities**			
Lower	Upper	Crack Sealing	Seal Coat	Striping	Patching
1	99	$540	$2,340	$75	$900
100	199	$540	$2,340	$115	$900
200	299	$720	$3,150	$125	$900
300	399	$720	$3,150	$125	$900
400	499	$720	$3,285	$140	$900

In this study, the estimated annual maintenance cost of road segments with agricultural truck traffic is $18.5 million per year. The total annualized cost of both maintaining and improving paved roads significantly impacted by agricultural traffic is $58.9 million. However, not all county and local roads in North Dakota have significant agricultural traffic. To provide a context for legislators, the costs of improving and maintaining non-agricultural roads were estimated as well. Because of lower truck traffic levels and fewer ESALs, these paved roads (exclusive of major oil routes) can be improved with thinner overlays. Moreover, the annualized maintenance cost of these routes is less. A comparison between agricultural and non-agricultural routes reveals that the estimated resurfacing cost of major agricultural distribution routes is 40% greater than the estimated resurfacing cost of non-agricultural routes on a per mile basis. Moreover, the estimated maintenance cost of agricultural distribution routes is 21% greater than the estimated maintenance costs of non-agricultural routes on a per mile basis.

In total, the estimated investment and maintenance needs for paved county and local roads in North Dakota amounts to $100.5 million annually. Approximately $59 million (or 59%) of these needs are related to agricultural haul roads. The remainder corresponds to other county and local roads. The estimated investment and maintenance needs for unpaved county and local roads in North Dakota totals $110 million annually. Approximately $43.6 million of these needs are related to agricultural haul roads. In total, the estimated statewide investment and maintenance needs for all county and local roads in North Dakota is $211.5 million per year, including $100.5 million of paved road investment needs and $110.0 million of unpaved road investment needs. The estimated costs to maintain 20-year pavement life cycles and acceptable levels of service on county and local roads in North Dakota are roughly double the historical funding levels.

CONCLUSION

The purpose of this study was to quantify needed investments in local and county roads used for agricultural logistics and provide policy makers with detailed information on the locations and costs of high priority road segments. To accomplish these purposes, a detailed GIS model that predicts flows from 1,406 crop-producing zones to 311 elevators and six ethanol plants was integrated with a mathematical programming and roadway cost model. Some of the most important findings of this study are (1) the average farm-to-market trip distance in North Dakota has increased from 12 miles in 1980 to 26 miles in 2009; (2) the estimated resurfacing cost per mile on major agricultural distribution routes is 40% greater than the estimated resurfacing cost per mile on non-agricultural routes; (3) the average annual cost to resurface and maintain paved agricultural roads is $18,300 per mile, exclusive of any reconstruction or widening cost; (4) the average annual cost to maintain gravel surface agricultural roads ranges from approximately $3,900 per mile for roads with the lowest traffic levels to roughly $6,600 per mile for roads with 150 to 200 ADT; and (5) the estimated cost to maintain 20-year pavement life cycles and acceptable levels of service on county and local roads in North Dakota is roughly double the historical funding level. This study is the primary justification for the Rural Roads Funding Bill of 2011, which has been introduced in the North Dakota Legislature.

In conclusion, it is important to note the limitations of this study. One of these issues is the effect of spring load restrictions on farm producers, elevators, and processors. Highway load limits must sometimes be imposed during spring thaw when soils cannot effectively support heavy loads and the relative damage caused by axle weights increases substantially. As noted earlier, the tandem axles of an 80,000-pound tractor-semitrailer weigh 34,000 pounds each. However, under a 7-ton axle load restriction, each of the tandem axles of the truck is restricted to 28,000 pounds. This means that the truck must run with a reduced load of as much as 12,000 pounds. Under a 6-ton axle load restriction, each of the tandem axles is further restricted to 24,000 pounds, which means that the truck must run with a reduced load of as much as 20,000 pounds. This is an issue that should be revisited and the major county collectors in agricultural logistics routes should be evaluated individually to assess the need for and cost of potential reconstructions or thicker overlays. Moreover, because of the limited time frame for field investigation, it is possible that some of the roads targeted for resurfacing may have to be reconstructed because of advanced deterioration. In addition, due to the nature of the data, this study expressly considers roadway maintenance needs independent of actual funding levels, and does not consider potential low volume roadway abandonment that may occur as a result of limited funds in the long run.

In this study, flows are predicted to minimize the total distance of moving all crops to elevators and ethanol plants. The demands for specific crops at elevators and plants are known because of detailed surveys and a statutory requirement for licensed public elevators to report their monthly shipment volumes to the North Dakota Public Service Commission. If the elevator demands had not been known, the problem would have been formulated as a spatial price model. In this type of model, the prices offered at elevators would have been estimated from the prices offered at export and out-of-state markets, as well as the rail transportation costs of shipping grains and oilseeds from elevators to these distant markets. Such a model would have required detailed information about market and/or elevator bid prices. Nevertheless, it is important to note that the predicted flows from a net farm price optimization model may be different from the predicted flows generated from the cost/distance minimization criterion used in this paper.

The study uncovered a range of issues involved with detailed GIS modeling of county and local roads, most of which relate to the lack of a linear referencing system and uniform naming convention. On state highways, the precise location of an impacted segment can be envisioned using mile markers—e.g., the segment of I-94 bounded by mile markers 231 and 254. However, county and local road segments cannot be referenced in this manner. North Dakota and other states should follow the lead of the Iowa Department of Transportation and develop a linear referencing system and uniform naming convention for all roads, regardless of jurisdiction.

Endnotes

1. Vector data use X and Y coordinates to define the locations of points, lines, and areas, while raster data use a matrix of square areas to define where features are located. The squares are also called pixels, cells and grids.

2. The study did not estimate the impacts of ethanol byproducts shipments within the state. From discussions with ethanol producers and county officials, the impacts of ethanol byproduct shipments are primarily on the state highway system.

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