GIS-based visualization of integrated highway maintenance and construction planning: a case study of Fort Worth, Texas

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Abstract

Background: This paper reports on a case study of the use of visualization of geospatial data that is distributed across data sets and requires integration over time and space to aid decision makers. Like many State Highway Agencies (SHAs) in the United States, the Texas Department of Transportation (TxDOT) is organized along the traditional functional lines of planning, design, construction, maintenance, and operations. It has historically relied on experience and longevity of its staff to efficiently and effectively plan its construction and maintenance projects. Although functional boundaries of maintenance and construction are fairly clearly defined, there tends to be some overlap in projects that can be executed by either of the functional groups. The department currently does not have a robust integrated information system for identifying potential planning conflicts between its construction and maintenance projects. This has led to suboptimal use of resources, including overlapping plans for maintenance and mobility enhancement projects.

Case description: With over 650 highway projects assigned across two functional groups within the district's (TxDOT Fort Worth district) boundary, it is a challenging task to assemble a coherent plan for managing these projects over a multi-year planning period that is subject to external stakeholder input as well as shifting funding constraints. Temporal and spatial data needed for integrated planning resides in specialized information systems developed for the needs of individual functional groups. To address this challenge, this district decided to integrate and visualize data from individual information systems in a Geographic Information System (GIS). A GIS-based tool was developed to integrate, visualize, and analyze projects data from multiple information systems.

Discussion and evaluation: This paper documents the benefits associated with visualization and integration of projects data in a GIS to address planning challenges facing a typical highway agency. Among the lessons learned are the potential uses of GIS, which include detecting spatially and temporally overlapping projects, supporting integrated planning, and improving communication among functional groups within a state highway agency.

Conclusion: The study demonstrates that such spatial-temporal representations of project data can lead to early identification of potential overlaps during the planning phase. In a broader context, such geospatial visualization efforts can also form the basis for eliciting practitioners' perspectives and knowledge input in the development of spatial decision support systems.

Keywords: Geographic information systems (GIS), Data integration, Construction, Data visualization, Maintenance and rehabilitation (M&R), Highway planning

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Introduction

Successful highway infrastructure planning and maintenance requires significant investments in terms of time, human resources, and money. Every year, billions of dollars are spent on maintaining highway infrastructure via new construction projects, road maintenance, and rehabilitation activities (Lee et al. 1996; Zhang et al. 2001). Increasing urbanization has led to a growing demand for highway infrastructure resulting in transportation systems becoming more complex in response to the demand (O'Brien et al. 2012; Podgorski and Kockelman 2006). Consequently, the need to optimally allocate limited resources to maintain and improve the state of transportation infrastructure cannot be overemphasized. These factors among others, significantly affect public funds expenditure on highway infrastructure development, thus drawing increased public scrutiny to budget planning and funds allocation for highway infrastructure (Sanchez 2006).

Today, the critical focus on and the need for efficient management practices in transportation planning and policy are underscored by key federal laws passed in the last three decades. These include the Surface Transportation and Uniform Relocation Assistance Act of 1987, the 'Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA),' and the recent 'Moving Ahead for Progress in the 21st century Act (MAP-21).' These laws have exhibited an increasing emphasis on integrated management practices and efficient use of federal funds. They also highlighted the need to invest in transportation systems by looking at the issue from the perspective of economic, socio-cultural, technological, and sustainable systems. Central to these considerations, is a push towards the use of data to drive highway agencies in making more informed decisions concerning highway planning and management (Thill 2000).

Such advancement notwithstanding, the transportation planning process is a continuous and arduous task involving data, models, and users. As part of the planning process, decision-makers need to use a vast collection of data and information to address a number of substantial issues like traffic management, construction scheduling, Right of Way (ROW) acquisition, public communication, and others (Nobrega and O'Hara 2011; Sankaran et al. 2016a; Woldesenbet et al. 2015). Highway agencies often collect a plethora of data and information about the nation's network of highways. The sources of such data vary widely and their forms range from drawings, pictures, maps, tables, text descriptions, to accounts of personal experience (Flintsch et al. 2004). However, highway agencies usually have to deal with fragmented databases, multiple incompatible models, redundant data acquisition efforts, and sub-optimal coordination between the various agencies or departments operating on the same highway facilities (Chi et al. 2013; Ziliaskopoulos and Waller 2000). To compound this problem, multiple independent legacy information systems usually co-exist within the same agency (Chi et al. 2013; Thill 2000).

In spite of huge investments in data collection and archiving efforts, the amount of information and knowledge generated from data repositories are minimal and less supportive of informed decision making. Additionally, both practitioners and researchers have questioned the efficiency of data programs in meeting the needs of users for highway infrastructure planning purposes (Flintsch and Bryant 2006; Woldesenbet et al. 2015). Transportation professionals still face the onerous task of organizing highway data into suitable forms to support decisions concerning highway maintenance, rehabilitation, traffic control, highway monitoring, and projects prioritization. These issues have given rise to a surge in the demand for effective practices and tools that can integrate, manage, and analyze highway data (Parida and Aggarwal 2005).

Over the past two decades, many State Departments of Transportation (DOTs) have explored the use of digital information systems for highway management decision support (Kang et al. 2008; Lee et al. 1996). Accordingly, TxDOT relies on several information systems; these include but are not limited to the Pavement Management Information System (PMIS), a Maintenance Management Information System (MMIS) referred to as COMPASS, and the Design and Construction Information System (DCIS). The challenges associated with accessing and leveraging data from multiple information sources highlights the need for an integrated system that can fuse projects data and support applications to aid Maintenance and Rehabilitation (M&R) planning. While TxDOT has made progress to integrate some highway data, there is a lack of an automated process to visualize and integrate data from the individual information systems to better support highway project planning decisions.

The need for such a system has grown for metropolitan districts since they have significantly more lane-miles of on-system highways under their responsibility and consequently more projects in various phases of development and delivery at any given time. The funding mechanism for maintaining, rehabilitating and upgrading the existing system is complex. It has become further complicated since TxDOT's funding is dependent on revenue from multiple sources with different permissible uses. Moreover, the planning process is fiscally-constrained at the category level; the amount of funding available determines the number of projects that can be planned within specific categories. Metropolitan planning organizations' (MPO) policy boards have responsibility for certain funding

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categories requiring concurrence from TxDOT. In addition, at any given time, several projects are in various phases of construction. The actual cost of construction can vary from the budgeted costs that affect category funds available going forward. Construction costs can vary from budgeted costs at the time of bidding or throughout the construction phase owing to change orders, unexpected conflicts needing additional right-of-way, costs to relocated existing utilities, and many others. Furthermore, there are instances when existing roadways that were not expected to be rehabilitated within the planning horizon, have to be rehabilitated owing to faster deterioration in condition. This leads to reactive maintenance to maintain safety and pushing lesser priority projects down the list. The combined effect of these factors (and many more) creates a need for an integrated planning process leveraging modern visualization tools which will allow the integration of temporal and spatial data which can be viewed, reviewed, and updated in a dynamic setting.

The rest of the paper is organized as follows. The next section describes the general challenges in performing highway planning tasks and how GIS has been previously used to address some of the identified challenges. In the "Objective and Methodology" section, a research framework based on a case study is presented. Following this, the "Case Study" section points out district-specific barriers to planning tasks and how a GIS-based tool was developed to integrate data from multiple information systems used by the district. A formalized presentation of the benefits of GIS integration and visualization to M&R planning follows. Finally, the paper ends with conclusions on the findings of this study and the directions for future work in the "Conclusions" section.

Background review

Planning is a complex and multidimensional process which requires re-thinking of traditional approaches (Dragićević and Balram 2004). Planning involves procedures to identify future transportation needs and recommending solutions in the long- to midterm timeframes. This includes developing transportation strategies which consider transportation investments and addresses strategicissues at the local, state and network level (Systematics 2006). State Highway Agencies (SHAs) need to make the most efficient choices in the planning and allocation of inadequate highway funds to keep highway infrastructure physically robust and functionally efficient. In addition to rising costs to maintain the aging transportation network, the Texas transportation system is also strained by traffic congestion and infrastructure deterioration (Podgorski and Kockelman 2006). This problem is exacerbated by highway spending shortfalls due to insufficient state "gas tax" revenues which constitute a major component of highway funding sources

especially in states like Texas. Consequently, highway planning and projects prioritization have become even more laborious for decision-makers. The following challenges identified in these research studies (Caldas et al. 2011; Podgorski and Kockelman 2006; Waddell 2011) further highlight additional issues that highway planners generally need to contend with:

- Agency Goals: Multiple stakeholders including Metropolitan Planning Organization (MPOs), state and district agencies, and private institutions all have different mandates and pursue unique individual goals. Consequently, due to the competing interests of agencies and functional groups within highway agencies, the planning process often yields results that are sub-optimal for individual agencies or functional groups within the same agency.
- Uncertainty: Uncertainties in ROW acquisition, environmental review, public acceptance, and political approval greatly affects an already complex highway planning process.
- Knowledge Acquisition Approaches: Divergent epistemologies also create a major problem for integrated highway planning. More often than not, different approaches to knowledge extraction result in different conclusions about highway issues which affect the interventions that different agencies or functional groups would like to take.
- Transparency: Highway agencies continue to struggle in employing multiple communication modes to make highway plans available while implementing decision models that have a satisfactory degree of transparency.
- Limited Resources: SHAs usually do not have enough resources (human, cost, and time) to perform other relevant M&R functions. This includes effectively performing audits on integrated highway development plans and tracking highway project allocations on different pavement sections over the long term.
- Data Availability and Quality: The increasing complexity of the application of information technology sometimes complicates the planning process. However, the crucial concern is that the tools developed to extract useful information for modeling and decision support are far from addressing the needs of users.

NCHRP studies (Neumann 1997; Systematics 2006) also reiterated the presence of these problems across many DOTs in the nation. According to NCHRP Report 798 (D'Ignazio et al. 2015), planners need to project long-term transportation needs, identify funding strategies and sources, and optimize resources available to attain the best value for highway investments. In conducting lifecycle planning for transportation assets, they also need to incorporate maintenance operations while

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planning for new capital construction projects. This process involves having functional groups within the same highway agency working across silos to comprehend and integrate agency-wide thinking; the key to this process being information flow.

Highway infrastructure problems in many cases involve spatial relationships between objects and events. Accordingly, visualization of highway data has been expedited by current advances in information technology and data collection technologies (Khattak and Shamayleh 2005). Given the spatial characteristics of road network data, the rational way to store and use such data should be via a consistent spatial referencing system such as a GIS (Medina et al. 1999). GIS is primarily used for storing, querying, analyzing, visualizing, and interpreting geographic data. It helps to reveal patterns and trends of objects that relate to one another in space and time (Ford et al. 2012).

With GIS, a user can integrate information from various sources and spatially connect that information to study aspects of an infrastructure system that was hitherto unapparent. By leveraging the capabilities of GIS, many highway agencies today are integrating highway data to improve highway operations and planning tasks (Flintsch et al. 2004). Transportation agencies are using GIS tools to collect data, communicate information about asset condition and needs, select and prioritize treatments, plan and manage work, and aid with disaster recovery (Rasdorf et al. 2003). In most cases, however, these applications are limited to collecting and displaying data and involves limited use of targeted spatial analysis functions (Hall 2015). Over the past two decades, several research efforts have demonstrated the applicability and value-added impact of GIS to highway pavement management and highway planning (Flintsch et al. 2004; Hall 2015; Sanchez 2006). Many other research efforts have explored this area, emphasizing the integration of decision-support tools and methods (Beiler and Treat 2014; Parida and Aggarwal 2005; Zhang et al. 1994; Zhou et al. 2009).

Previous applications of GIS for project planning by DOTs
Today, many DOTs use GIS to visualize previous, active and planned construction projects in their respective states. With an increasing emphasis on transparency with the public, SHAs also tend to provide online versions of such visualization efforts via GIS server platforms. Most of the SHAs discussed below were recognized by the Federal Highway Administration (FHWA) for their data integration and geo-visualization efforts using GIS for highway project planning and communication.

Washington State Department of Transportation (WSDOT) created an integrated database that utilized pavement condition data, traffic data, pavement preservation planning data, and capital project planning data. This was used for projects prioritization of preservation and improvement projects. The maintenance data were also fused with pavement condition data to determine routine inspections and repairs on the state's highway facilities (Rydholm et al. 2015).

Highway agencies, Colorado State DOT (CDOT), North Dakota DOT (NDDOT) and TxDOT have all created online interactive maps that visualize construction projects (usually capital construction projects) scheduled to take place in their respective states. Most of these maps give users the option to query the map for easier extraction of relevant information (Colorado Department of Transportation 2016; North Dakota Department of Transportation 2016; Texas Department of Transportation 2016a). In the case of TxDOT, however, projects are visualized by the different phases of project development and long term versus short term planned projects.

Michigan DOT has multiple online maps that document road and bridge projects for their 5-years transportation program. MDOT also created an online map for the different public agencies responsible for the maintenance of road segments throughout the state. Using their in-house developed tool (Transportation Management System), agency staff use GIS for spatial analysis of road condition data, asset inventory, and budget decisions for project planning (Federal Highway Administration FHWA 2012).

The Transportation Information Mapping System (TIMS) of Ohio DOT is one of the most robust and extensive GIS-based systems used by DOTs. It contains data on all their transportation infrastructure assets, safety, roadway information, environmental issues, and alternate modes of transportation in the state. It provides users with the ability to visualize capital highway projects scheduled for the next 4 fiscal years as well as projects completed in the previous 4 fiscal years on highway assets. Additionally, it has the capability to integrate external spatial data in multiple interoperable formats (including shapefiles, Google Earth files, latitude/longitude coordinates, among others).

However, in most of these endeavors, data integration, and visualization efforts have focused on using GIS to support either capital planning or highway maintenance operations—rarely integrating both. One of the few cases of such an endeavor is from Connecticut DOT (ConnDOT). ConnDOT were reported to have mapped candidate projects and planned work for maintenance and capital construction projects. It was estimated that this could lead to increased coordination between the construction and maintenance functional groups within the highway agency (Hall 2015).

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This notwithstanding, the extant literature still lacks a formalized approach to integrating projects data from the "capital construction planning" and "maintenance" functional groups to support integrated decision making. To address this gap in practice and research, the aim of this study includes presenting a data integration framework for fusing projects data using GIS. Furthermore, this study provides a repeatable data integration process; providing highway agency staff with custom spatial functions to extract useful information from an integrated database, and links these functions to practical benefits that improve the highway planning process.

Objective and methodology

There are two components to the objective of this paper. The first involves documenting the existing M&R project planning procedures and identifying planning challenges that exist within districts. The second involves integrating projects data from disparate sources in a GIS environment to address information needs of highway planners and other functional groups within the district.

Given the objective and exploratory nature of this research, the research team chose the case study approach (Eisenhardt 1989). The case study method draws on actual events to investigate modern procedures and phenomena that have a general impact on the state of practice in an otherwise unalterable environment (Yin 2013). Researchers chose a case study involving the development and use of a GIS-based tool to support integrated highway maintenance and construction planning. Figure 1 shows an overview of the research approach followed in this study.

The initial part of the study involves an extensive literature review and input from highway agency staff on the planning challenges that they face. The agency staff who contributed to this phase included highway professionals who have worked in the construction and maintenance planning roles for at least a decade. After identifying the challenges faced, the research team focused on addressing a technological challenge that could aid in also addressing some of the organizational challenges. A data integration approach was proposed and a GIS-based tool was built to demonstrate the practicality of the framework. Finally, based on input from agency staff, researchers identified the practical benefits of this tool to M&R project planning.

Case description

The Fort Worth District is responsible for nine (9) counties and approximately 9,000 highway lane miles within its boundary. The district oversees nearly $4 billion investment in construction projects and over $100 million annual expenditure on preventative, routine, and rehabilitative maintenance operations (Texas Department of Transportation 2016b). Given the scope of operations of this district, the need for seamless integration of individual information systems is evident. Figure 2 displays an overview of the entire 'on-system' highway network of the Fort Worth area and the user interface of the GIS-based tool that was developed.

The 'on-system' highway network excludes county roads, local city streets, and functionally classified city streets, which the district office is usually not responsible for. While there are instances where the district collaborates with city agencies to maintain city streets, the projects involved usually remain under the purview of the city's planning agency. Also, the user interface mainly includes a "Quick Access" toolbar, "Custom
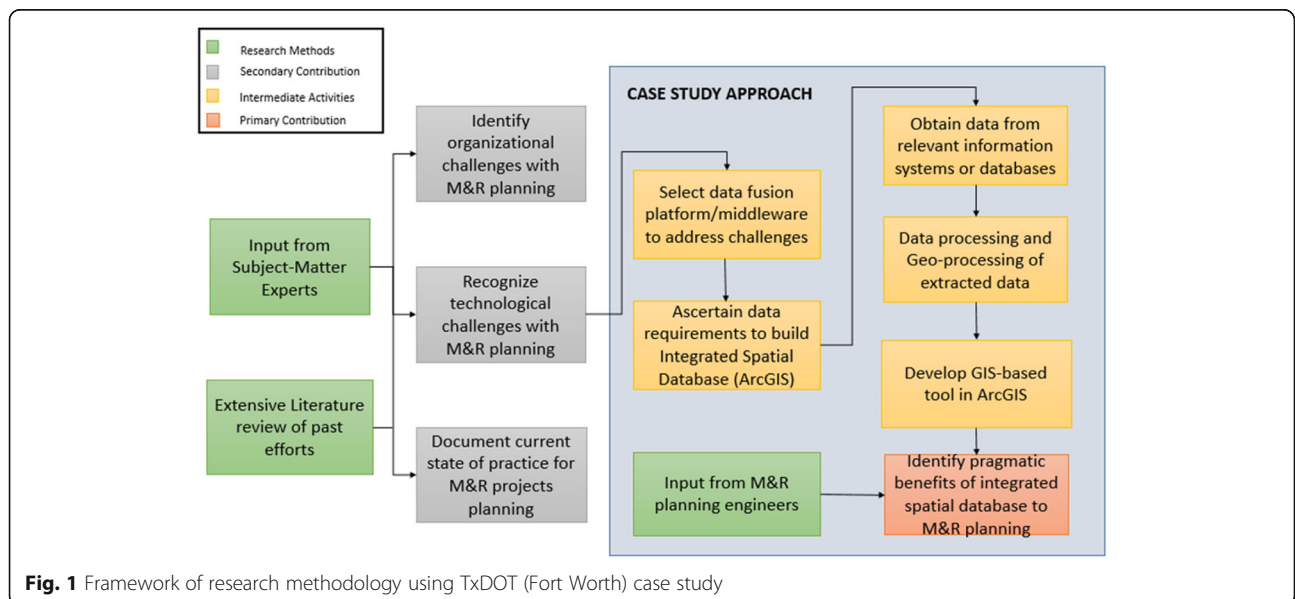

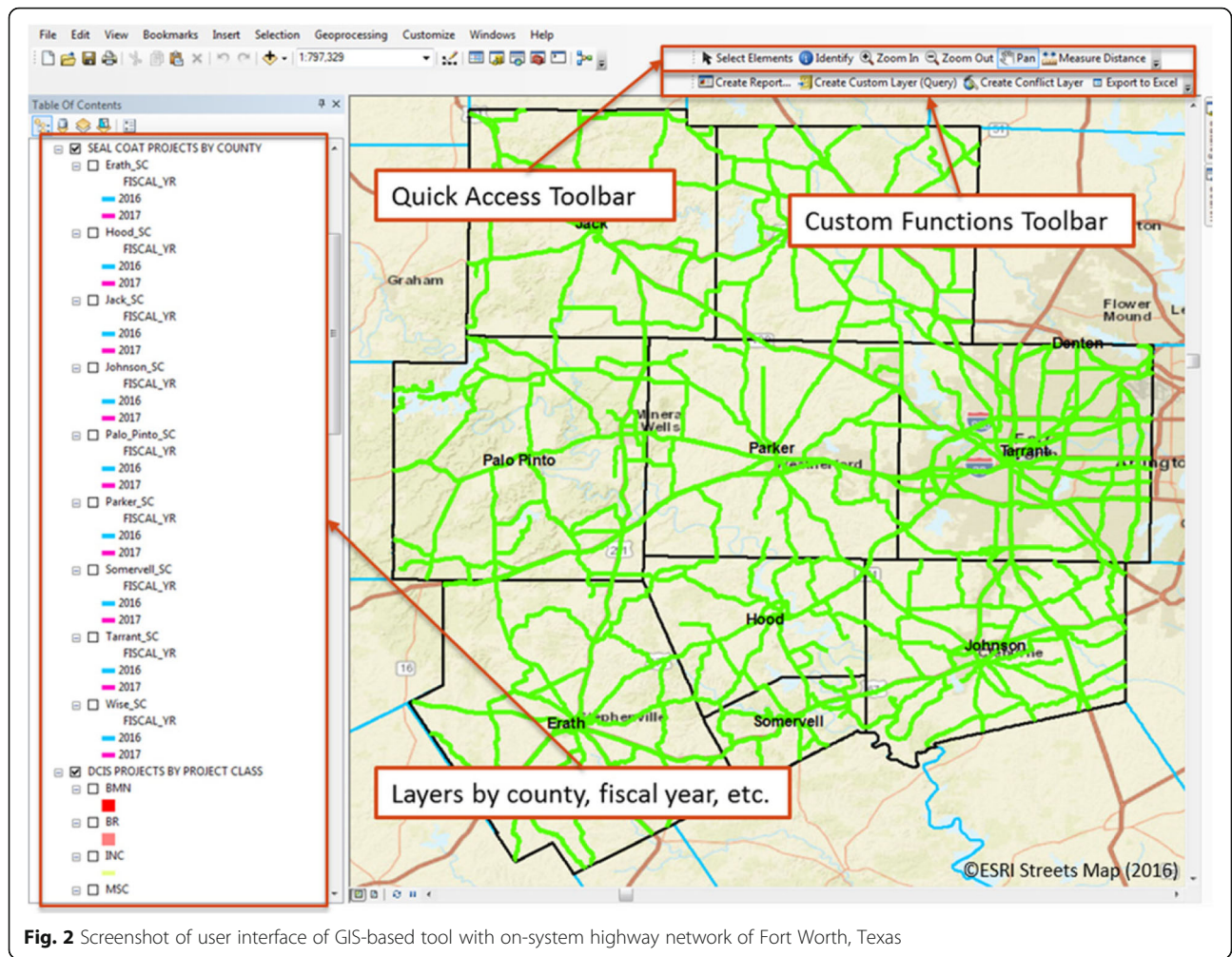**Fig. 1** Framework of research methodology using TxDOT (Fort Worth) case study

Fig. 2 Screenshot of user interface of GIS-based tool with on-system highway network of Fort Worth, Texas

Functions" toolbar, and feature layers displayed to the left of the screen (default in ArcMap application of ESRI's ArcGIS Software).

Transportation plans (TxDOT)

The state law requires TxDOT to provide the Legislative Budget Board (LBB) and the Governor with a district-specific analysis plan for the use of highway funds. The plan should include pavement score targets and the performance impact of the proposed maintenance spending on the state of the highway infrastructure network (Liu et al. 2012). Consequently, TxDOT prepares the 4-years Pavement Management Plan (PMP) which includes financial constraints for all categories of highway M&R funding (new, preventive, and routine maintenance projects). The PMP is usually a part of a more extensive plan for the entire transportation network of the state of Texas. Figure 3 shows the 10-years Unified Transportation Program (UTP), the 4-years State Transportation Improvement Plan (STIP), and the 2-years letting schedule by TxDOT. This case study examined the 4-years
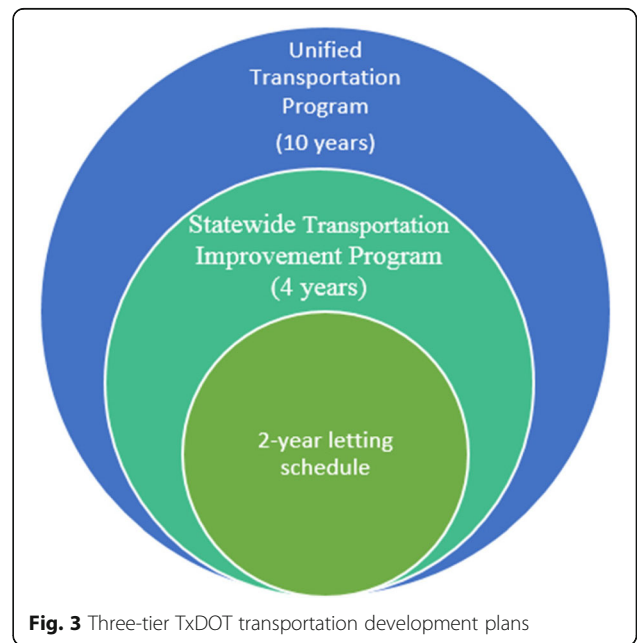
Fig. 3 Three-tier TxDOT transportation development plans

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plan (STIP) focusing on the highway projects scheduled for those fiscal years.

Current state of practice (TxDOT)
Two of TxDOT's stated goals and objectives consist of "*delivering the right projects by implementing effective planning and forecasting processes to deliver the right projects on time, and on budget*, and *preserving its assets through preventive maintenance of the system and capital assets*"(Texas Department of Transportation 2016b). In order to meet these and additional goals, TxDOT's complex portfolio of projects consists of maintenance, rehabilitation, safety, bridge, widening, capacity-addition, and several other project types delivered by its district offices responsible for multi-county geographical regions of Texas. The simpler maintenance projects can either be done with in-house workforce or through contractors with very short turnaround times. Maintenance projects can cover both roadway and roadside maintenance tasks. Normally these projects are handled by the maintenance functional group of a district office. These projects are programmed in the aforementioned COMPASS system and can have very short planning time associated with them. Additional maintenance projects can be cyclical in nature. However, several M&R projects require planning and design effort with associated lead time and a formal process of letting to achieve cost-efficiencies. These projects are planned, programmed, and generally developed by the transportation planning and development (TPD) group of a district. They are managed within the DCIS information system which is the department's primary system of record for design and construction projects. On the farther end, there are capacity addition and reconstruction projects managed by the TPD that take years to plan, design, and fund for construction.

Developing plans consisting of projects that undergo "starts" and "stops" during their varied development phases is a continual challenge faced by the district staff. The district's maintenance and TPD functional groups have different challenges and processes for planning, design, funding, and delivery. This is primarily due to the type of projects within their purview and the associated expectations and funding constraints. In order to gain synergy between the plans of these functional groups, the district leadership depends on effective communication and collaboration among multiple stakeholders (Sankaran et al. 2016b). However, the above-described processes can benefit from emerging tools and techniques to save time and enhance effectiveness.

Prior to engaging in extensive visualization efforts, it is important to work with agency staff to understand the extant work practice, issues with the existing system, and identifying areas for improvement. As such, the use

and potential benefits of integrating multiple data sources and technologies should be explored within this context. More importantly, this allows tacit and explicit knowledge gained to be better incorporated in the development of later versions of information systems (Tsai and Lai 2002). Thus, the planning challenges associated with the current highway planning process in this district are discussed below.

Planning challenges in fort worth district
In carrying planning tasks, TxDOT districts rely on individual functional groups within its organization. These groups collaborate throughout the planning process for highway infrastructure planning and development. However, due to disparities in information systems, unique functional group funding processes, and planning requirements; agency staff is continually challenged to attain a wholly integrated planning process (D'Ignazio et al. 2015).

Different information systems and data access
TxDOT's functional groups currently use architecturally different information systems to support the project-planning process that each group undertakes. Furthermore, expertise needed for utilizing information in these systems is limited to specific functional group staff. Both systems do allow users to capture project information with multiple location attributes including linear references; nevertheless, each functional group has a preferred primary location attribute, which leads to an asymmetry of information about location attributes. Accordingly, planners for construction-let projects (in DCIS) tend to use, as their primary location attribute, qualitative descriptions like intersections (limits) that a project will expand to and from. On the other hand, staff in the Maintenance functional group often uses the Texas Reference Marker System (a type of a Linear Referencing System). This reduces the ease of information flow between these two departments and points to the need for a more integrated system that can visualize these projects obviating the need to be familiar with the other department's preferred spatial referencing system.

Project scheduling periods
The project scheduling periods for the TPD and Maintenance functional groups are usually 10 years (UTP) and 4 years (PMP) respectively. As a result of this disparity in the planning horizons, it becomes difficult to track some of the DCIS projects that need to be programmed with corresponding maintenance activities in the COMPASS database. Staff from both functional groups needs to ensure that complementary projects are scheduled in a consistent manner. For example, "Level up" projects that usually complement "Seal Coat"

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projects need to be programmed together for every fiscal year. This process of tracking complementary projects and the dynamic changes that occur due to annual complexities in project priorities can benefit immensely from an integrated database of M&R projects.

Funding sources

Similarly, the funding sources often vary for projects residing in different information systems. Multiple stakeholders are involved in the selection of these projects, which call for stronger justification to the public, local agencies, and federal institutions. While, projects in COMPASS are simpler and consequently require simpler decision-making process as compared to the DCIS projects, the overlap in funding sources between the projects in the different systems further challenges the complexity in developing a funding strategy and consequently, planning for projects.

These issues make it difficult for such individual functional groups to develop maintenance plans while giving full consideration to upcoming construction projects by other divisions. Staff from different functional groups within the district would clearly benefit from data integration and visualization, as this would lead to improved information flow, better collaboration, and effective integrated planning.

Developing GIS-based tool for visualization

In view of the planning challenges identified above, the district decided to address the disparities in information systems and data access barriers. This was done via the development of an integrated GIS-based tool to fuse all the projects' information from the TPD and Maintenance functional groups of the district. Thus, the team went through the following stages.

Stage 1: extraction of input data

The first step was to identify the relevant data sources and data types required for developing the GIS-based tool. The sources used could be broadly grouped as GIS shapefiles, highway inventory data, DCIS projects data, and COMPASS projects data. The GIS data were accessed primarily from the Transportation Planning and Programming (TPP) division of TxDOT and the Texas Natural Resources Information System (TNRIS). Table 1 shows the different data sources, formats, attributes, and a brief description of each database or shapefile.

Additionally, Table 2 shows a breakdown of projects by data source and project classification. The projects data extracted and displayed in Table 2 were obtained in February 2016. Hence, some of the projects may have changed since then. With over 650 projects under the purview of the TPD and Maintenance functional groups

of the Fort Worth district, the complexity involved in managing all these projects over multi-year cycles is evident. Furthermore, the overlaps in inter-connected highway projects that reside in different databases are not apparent in traditional database systems due to the absence of a visual component.

After identifying and obtaining the required data sources, the next step of this project was to process the data to ensure that all the records contained accurate spatial attribute values in a GIS-compatible format. Figure 4 displays a conceptual flowchart that documents data processing (data cleaning, validation, etc.), geoprocessing, and visualization in the GIS-based tool. The succeeding sub-section provides more in-depth information about the data processing and geoprocessing tasks followed in developing this tool. The framework includes 3 major components; data extraction from the database systems, a middleware —processing platform, and the output in the form of active maps and reports.

Stage 2: data/geo-processing

The processing took place in two steps—data processing and geoprocessing using GIS. The first step involved data processing in a spreadsheet environment for the extracted projects data. This comprised data cleaning, data validation, and sorting. Data cleaning is concerned with identifying and removing errors and inconsistencies from data in order to enhance the quality of data (Rahm and Do 2000). Most of the data-processing tasks involved data cleaning. A new field was also created to query the highway inventory database for GIS-compatible linear reference values for project records. This was done by cross referencing the other location referencing systems to a central and comprehensive linear referencing system known as the "Distance from Origin (DFO) system. The PMIS of TxDOT contains three different linear referencing systems for each discretized pavement section for the entire highway network. Accordingly, after the DFO system was selected as the main LRS for integration purposes, all the other referencing systems were converted to the DFO system. Given that all the referencing systems are linear, intermediate values were interpolated. In a few instances (less than 5%) where only qualitative location descriptions were given, the authors used the "Statewide Planning Map" (Texas Department of Transportation 2016a) developed by TxDOT to extract the DFO values of project limits.

The projects' data were also validated using a "set of validation rules" to ensure that attribute and spatial data were consistent across all records in the databases. An example of a consistency rule is that the sum of the beginning TRM number (DFO equivalent) of a project and its displacement should be equal to the DFO value for

Table 1 Projects data source, relevant attributes and description

Database (Format)	Relevant Attributes	Description
DCIS (Comma Separated Values - CSV)	• Project description • Spatial (county, highway, reference markers, DFO) • Temporal (fiscal year and letting dates) • Cost (construction cost estimate)	This is a statewide automated information system which allows all district offices of TxDOT to manage projects data in a consistent common format. It mostly contains highway projects funded by all the 12 categories of funding by TxDOT.
COMPASS (Hypertext markup language - Html)	• Activity description • Spatial (county, highway) • Temporal (fiscal year and letting dates) • Cost (construction, equipment, labor, materials estimate)	The COMPASS system is the Maintenance Management Information System (MMIS) of TxDOT that allows districts to manage maintenance activities that are more routine and are usually of a smaller scope.
Highway Inventory Data - PMIS (Excel spreadsheet - xls*)	• Spatial (county, highway, reference markers, DFO) • Road condition data (distress, ride, skid, and condition scores) • Pavement roadbed information (main lanes or frontage roads, single or divided roadbeds) • Traffic data (AADT, etc.)	PMIS is a comprehensive database on the entire network of the state-maintained highway system. It contains extensive information for each pavement section in the entire network.
On-system Highway Network (Shapefile - shp)	• Spatial (county, highway, reference markers, DFO) • Pavement roadbed information (main lanes or frontage roads, single or divided roadbeds)	This is a "polyline" shapefile which was used as the "route event" feature dataset on which events/projects were visualized. It contains all the relevant spatial attributes and features to visualize projects in GIS.
Auxiliary: County Boundaries and Reference Markers (Shapefile - shp)	• Spatial (county, reference markers, DFO) • County polygons	These are "polygon" and "point" shapefiles that contain the county delineations and linear reference markers respectively.

the starting point of a project. The same applies for the ending point of a project limit. Table 3 gives examples of the value range restrictions and valid data formats that were used to ensure that the value entries for the spatial attributes in the projects database were consistent and accurate.

For the complementary attribute field, the highway number had to be exactly the same format across the different project data sources. As such, the original fields were formatted to be consistent with the valid value range and data format. For example, first, the entry "IH

Table 2 Projects breakdown by information system source in TxDOT (Fort Worth)

Source	Number of Projects	Source	Number of Projects
DCIS		COMPASS	
HMA Overlay	37	Routine Maintenance	229
Seal Coat	37	Preventive Maintenance	34
Safety	63	Light Rehabilitation	10
Bridge	26	Medium Rehabilitation	17
Others (Miscellaneous, etc.)	206	Heavy Rehabilitation	3
Total	369	Total	293
Grand Total Number of Projects			662

Others also include among others, Right-of-Way (ROW), Landscape enhancement, and Preliminary engineering project classifications

20" had to be formatted to "IH0020." Secondly, to indicate whether the road was a left or right main lane, left or right frontage road, or one undivided roadbed, a 2-letter appendix ("-?G") was added. This naming convention is consistent with TxDOT's official highway name designations for main lanes and frontage roads.

The second step involved data fusion in a geospatial environment. Route event layers were created using the highway network shapefile and the processed projects data. ESRI's ArcGIS software was used for geospatial operations because that was the default GIS application used by TxDOT at the time of the tool's development. Figure 5 shows a systematic flow of the data processing and geoprocessing tasks followed in developing the GIS-based tool.

Stage 3: visualization output (layers)

Projects data were visualized as feature layers according to the county, project type, and fiscal year. Figure 6 shows a visual of the 4-years PMP for the district according to the fiscal year as displayed in the tool. It also includes some projects from the 10-years UTP from the long-term plan for highway construction projects in DCIS. In addition to this, intra-database and inter-database analyses were also performed and added as layers to the tool.

Intra-database analysis refers to the identification of sections of highway pavement that are scheduled to receive annual or biennial projects in the same database (DCIS or COMPASS). Included within this category, for example, would be a road pavement with a rehabilitation project scheduled to take place continuously for 3 consecutive

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Fig. 4 Conceptual framework for a GIS-based tool developed for Case Study
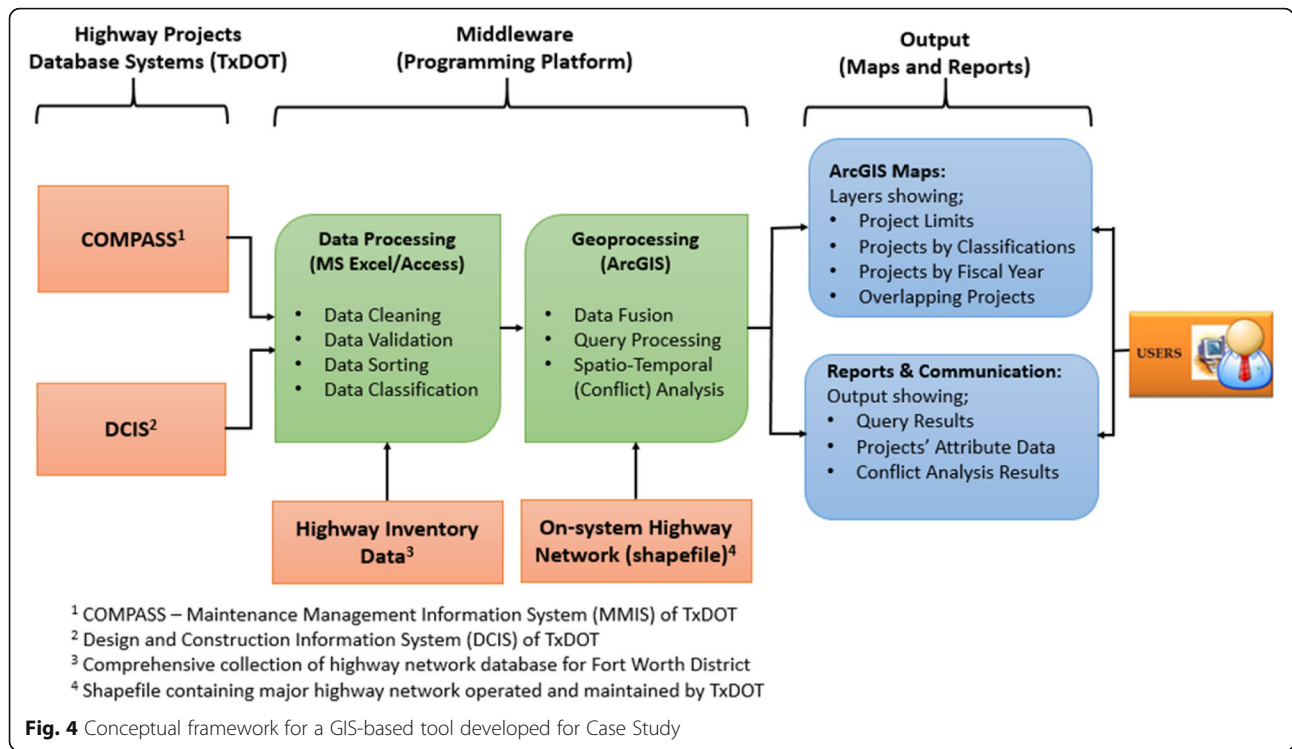
fiscal years. On the other hand, inter-database analysis refers to the identification of pavements that have both construction and maintenance projects scheduled to take place in the same fiscal year—for example, a road section that has a "light rehabilitation" project (COMPASS) and a "Seal Coat" project (DCIS) scheduled within the same fiscal year. Figures 7 and 8 show visual examples of conflicting project layers for projects across databases and road sections receiving repetitive annual M&R treatments respectively.

Table 3 Validation rules implemented on spatial data quality fields (based on PMIS data)

Reference System	Spatial Data Attribute	Valid Value Range	Valid format
Texas Reference Marker System	Beginning Reference Marker Number	0– 668	Integer
	Ending Reference Marker Number	0– 668	Integer
	Beginning Reference Marker Displacement	0.00 – 0.99	Decimal
	Ending Reference Marker Displacement	0.00 – 0.99	Decimal
Mile Point Reference System	Beginning Mile Point	0.00 – 50.00	Decimal
	Ending Mile Point	0.00 – 50.00	Decimal
Distance From Origin (DFO)	*Beginning DFO	0.00 – 454.50	Decimal
	*Ending DFO	0.00 – 454.50	Decimal
Complementary	*Highway Number	"??????-?G"	String

*GIS-compatible data attributes

Stage 4: custom functions

Thematic maps are not the end-products in GIS, but are a means to store and represent information that is vital for analysis and decision-making (Rasdorf et al. 2003). Beyond thematic maps, other functions like reporting, querying, and other custom functions can be added to a GIS to make it more valuable to the planning process. In this case study, planners were provided with 2 custom functions to aid in information extraction from the spatial database. The first function allows planners to execute spatial-temporal queries from the integrated database. For spatial-temporal queries, highway planners can query the integrated spatial database for answers to questions in the form;

> *"What are the construction or maintenance (DCIS or COMPASS) projects in County A, of project type B that cost C dollars, which are scheduled to take place in D fiscal year?"*

This query function allows planners to query by database source for 4 major attributes including county, project/work type, estimated construction cost, and planned fiscal year of execution. The advantage of a GIS-based system over traditional database system in executing this query is demonstrated by the visualization of an output layer which is the response to the query. For example, Fig. 9 shows the result of the "spatial-temporal" function query for DCIS construction projects in all the districts,
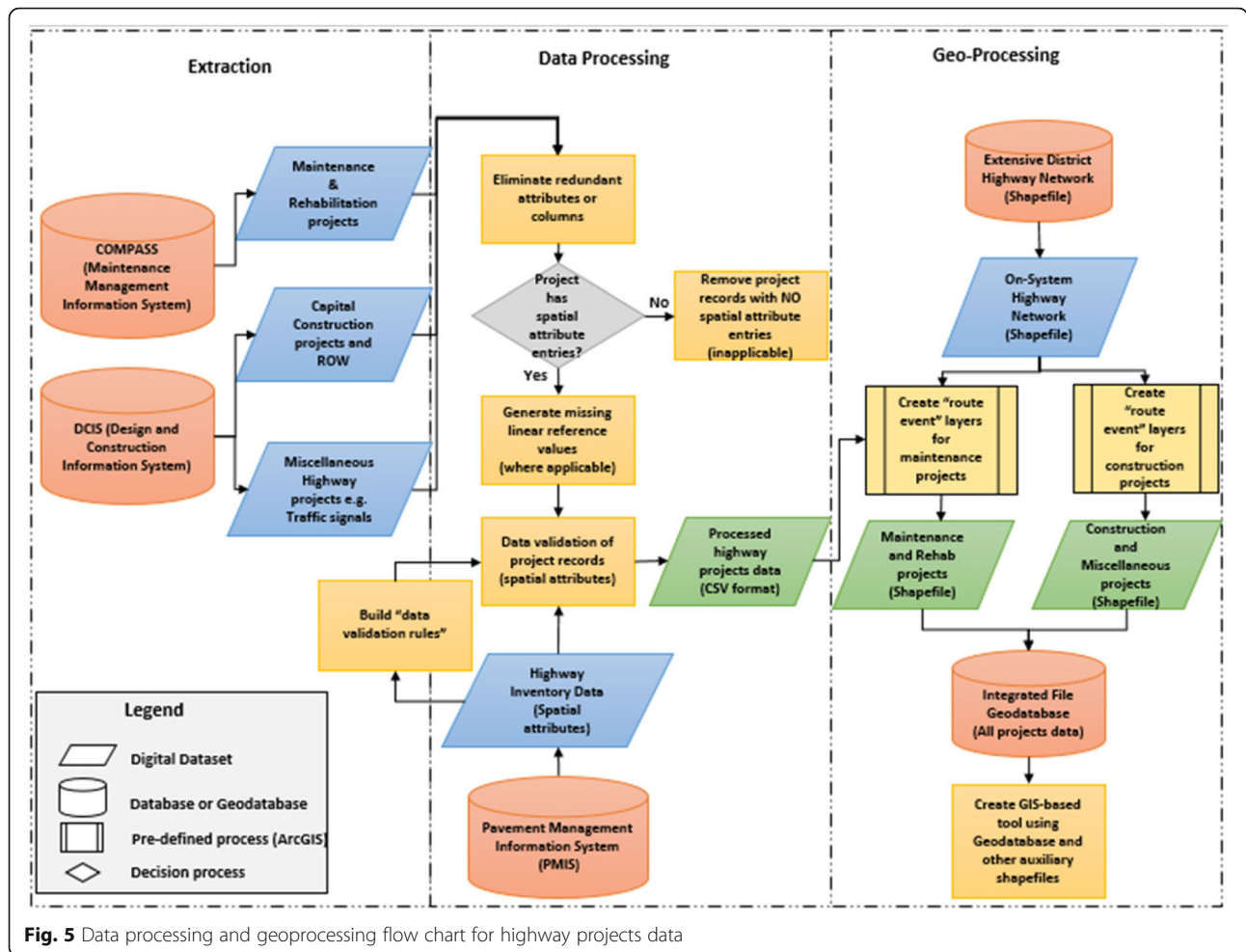
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Fig. 5 Data processing and geoprocessing flow chart for highway projects data

of project type "Seal Coat" that cost more than $100,000 in the fiscal year, 2017.

The left image in Fig. 9 shows the projects on pavement sections that satisfy the query that was constructed for the system. Similarly, the right image shows a snapshot of the attribute table of the resulting layer created to demonstrate the accuracy of the query results and the information that a typical user(s) can access. The highway names are in the standardized format used by TxDOT and the project classification "SC" represents "Seal Coat." Also, the roadbed type designation "ML" represents "Main Lanes."

The second custom function is used to conduct spatial-temporal conflict analyses on any number of layers to investigate potential project-scheduling errors in both project databases. Conflicting projects are defined in this context as a number (2 or more) of projects which reside in different information systems but are scheduled to be executed on the same pavement section within the same time frame. In the context of this case study, an example will be if a "medium rehabilitation" project (residing in COMPASS) is scheduled to take

place the same time (month/year) as an "Asphalt Overlay" project (residing in DCIS). The process of identifying these conflicting projects is what has been referred to in this study as a "spatio-temporal conflict analysis." Highway planners can therefore ask questions in the form;

"Are there any conflicting projects on Highway A in County B, of project type(s) C scheduled for the fiscal year, D?"

Figure 10 shows a snapshot of the simplified representation (left) and user interface (right) of the 2 custom functions built to support the querying and conflicts analysis. The query function is a modification of the default "Make Feature Layer" tool in the "model Builder" environment of the ArcMap application (one of the ArcGIS suite of applications). The "input features" and SQL "expressions" were parametrized and customized according to the attributes of the feature layers in the tool. Similarly, the conflict analysis tool is a modification of the default "Intersect" tool of ArcMap. Here again, for
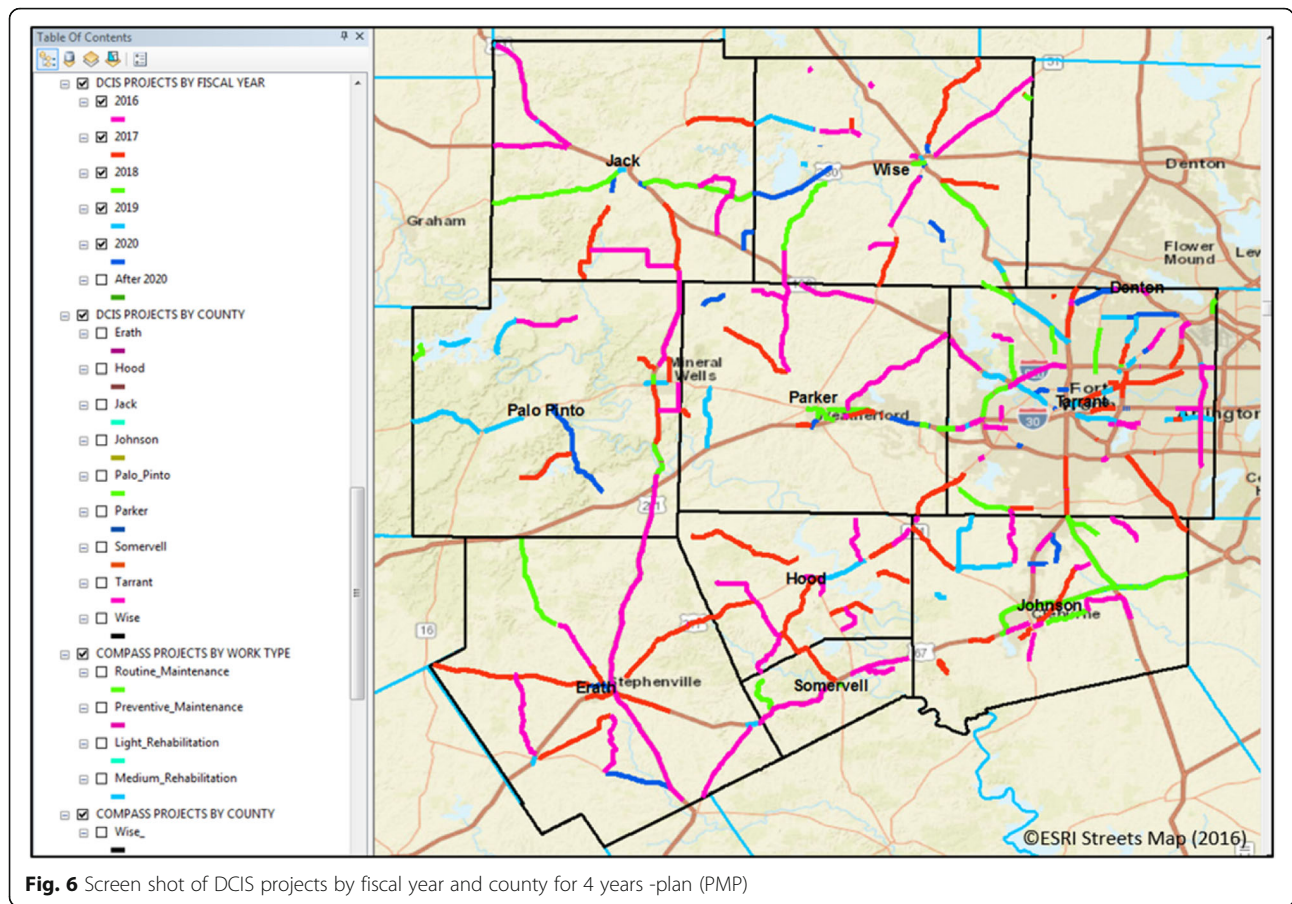
Fig. 6 Screen shot of DCIS projects by fiscal year and county for 4 years -plan (PMP)

the purposes of automation and general applicability, the "input features" and the "output feature" name were parametrized. This allows users to run these analyses on any number of feature layers (default or generated) present in the GIS-based tool.

These custom functions provided users with advanced capabilities of extracting useful information about projects across databases (DCIS and COMPASS) to support highway-planning decisions. The next section will throw more light on the practical ways in which this GIS-based tool can be used to enhance the project planning process for maintenance and construction projects.

Discussion and evaluation

This case study highlights how GIS technology can improve, through visualization, the decision-making process for planning highway projects. The primary functions of GIS in this regard include among others, the ability to integrate data from heterogeneous highway data sources and visually displaying projects in a way which is more useful for agency staff. GIS also affords highway agencies the opportunity to execute both spatial queries and conflict analyses that would, hitherto, have been difficult to achieve in a solely database environment. The benefits

enumerated below present ways in which GIS was, and can be used to support highway project planning.

Detecting redundant projects

The existing state of highway planning is at risk of scheduling projects whose scope of work may be covered or countered by overlapping M&R projects by a different functional group. The principal benefit of the GIS-based tool was its ability to synthesize all the overlapping projects inside and across different projects databases. Instances of redundant or unnecessary projects occur when the Maintenance functional group schedules a project that is within the scope of projects in the other (DCIS) database. It would be redundant, for instance, to schedule and allocate funds to install lane markings on a road section that is scheduled for a "Seal Coat" project a few months later. The seal coat project consists of a new surface treatment on the road and striping, thus calling for new pavement lane markings. By preventing such a project from going to the project development phase, district staff is able to save tax-payer dollars. Table 4 shows a list of the hitherto defined intra-database overlaps and inter-database conflicts.
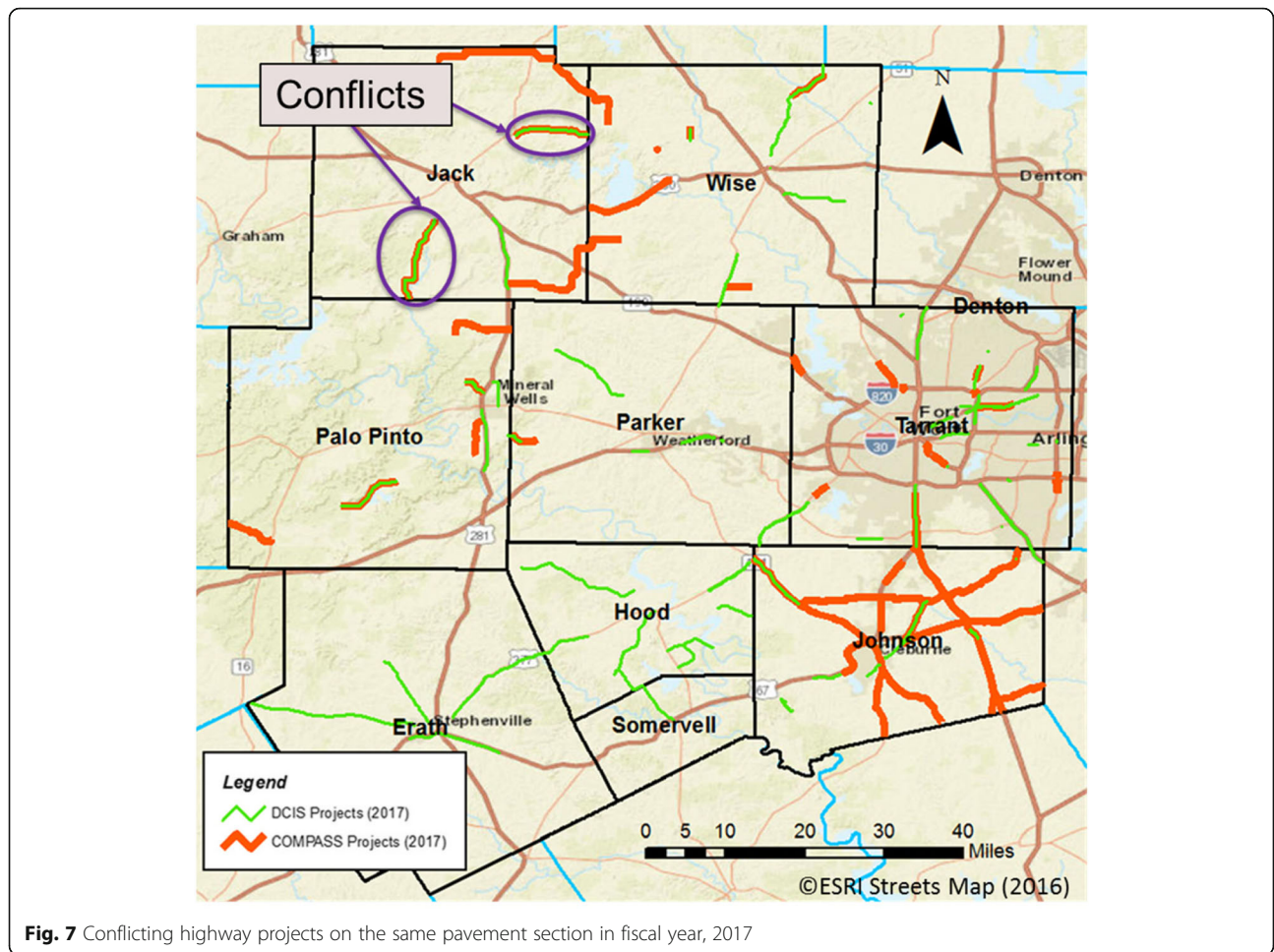
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Fig. 7 Conflicting highway projects on the same pavement section in fiscal year, 2017

The numbers (outside the brackets) in Table 4 represent the number of instances where conflicting or overlapping projects were identified on the same pavement section. It is evident from Table 4 that there is a significantly lower number of intra-database overlaps for pavement sections which can be attributed to the fact that construction projects in DCIS are more intermittent than maintenance operations projects. Furthermore, the maintenance projects database also includes more regular routine maintenance projects. This makes it more likely for the same pavement section to receive multiple instances of routine maintenance activities across different fiscal years.

Integrated planning and visualization

Within DOTs, there is a perennial challenge of integrating plans from different functional groups with individual goals and priorities, which is exacerbated by using different information systems. By leveraging GIS-based visualization of projects data, staff from different departments who are trying to make project planning decisions, can have access to and utilize useful information from other departments. Taking advantage of GIS' spatial contextualization of data would lead to access and consideration of scheduled M&R projects during capital project planning and vice versa. Consequently, agency staff in the Maintenance group can better plan for maintenance projects because they will be aware of current and future capital construction projects scheduled for the different pavement sections in the district.

Audit planned projects

Due to the complexities and constraints of financial sources that are used in funding projects, sometimes highway projects are split up into 2 smaller scope projects and put in the capital construction projects database and the maintenance projects database. Consequently, transportation planners occasionally schedule projects that are complementary but exist in different information systems or databases. Functions like spatial queries and conflict analyses in an integrated GIS environment allow highway engineers to audit and confirm the logic of spatial and temporal relationships between construction-let and maintenance projects scheduled for the same highway
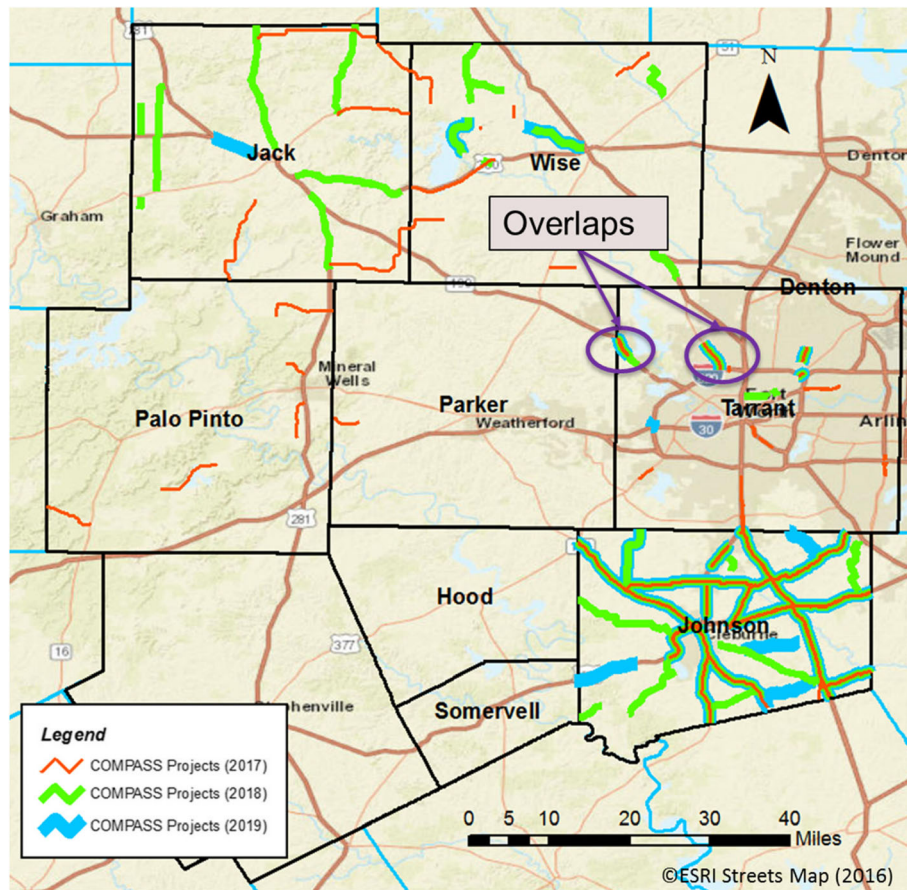
Fig. 8 Multi-year COMPASS projects that take place on the same pavement section
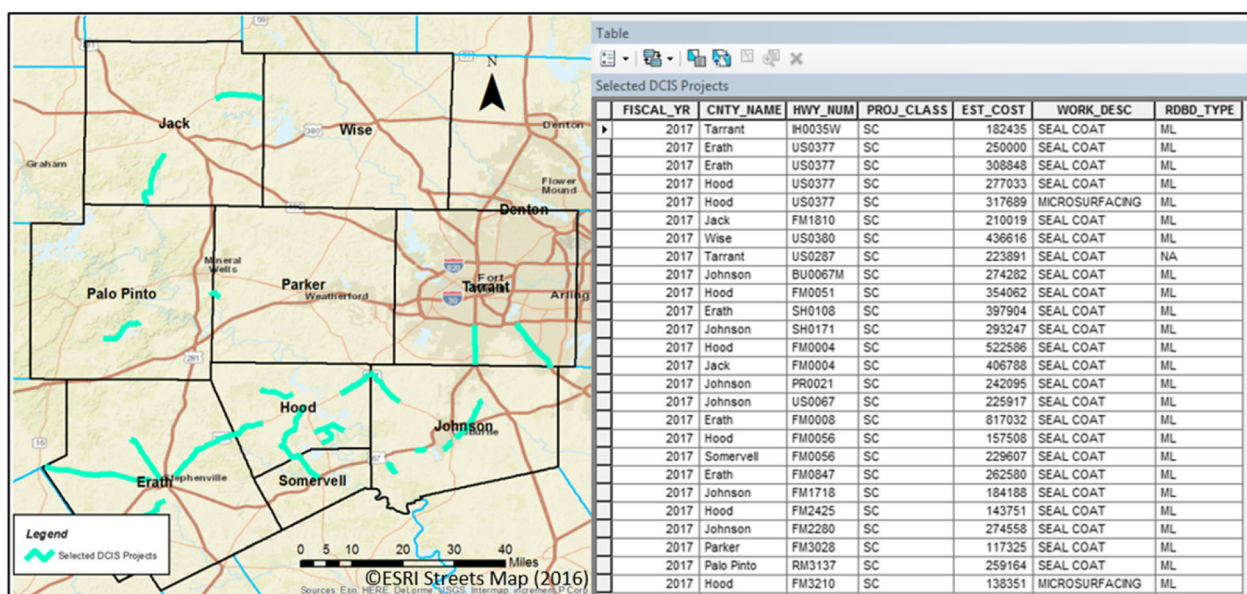

Fig. 9 Map (left) and attribute table (right) for query results of "Seal Coat (SC)" projects

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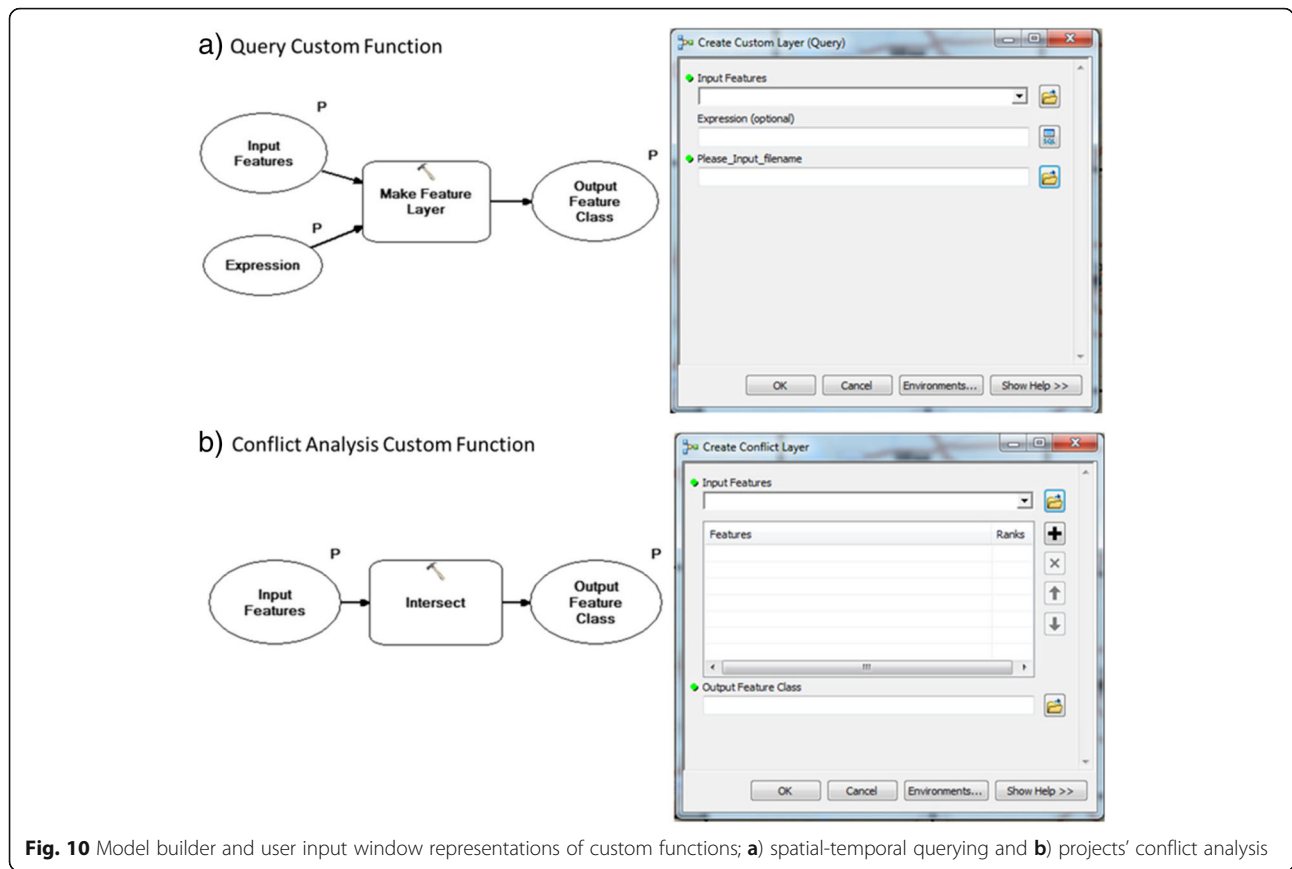
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Fig. 10 Model builder and user input window representations of custom functions; **a**) spatial-temporal querying and **b**) projects' conflict analysis

section. In this case study, spatial queries were used by highway planning engineers to detect the absence or otherwise of complementary M&R projects that were supposed to be in the 'other' highway projects database. This led to a review of that procedure and corrective action was taken to update the information system.

Re-design and improve workflows

In conversations about relationships between technology and work practices, there are usually two main schools

Table 4 Spatial Overlaps and Conflicts identified in DCIS and COMPASS

For Fiscal Years (2017–2019)			
Information system	Period	Intra-database Overlaps* (mileage)	Inter-database Conflicts (mileage)
DCIS	Annual (3 years continuous)	1 (0.48)	33 (57.7)
	Biennial	6 (3.59)	
COMPASS	Annual (3 years continuous)	38 (43.97)	
	Biennial	29 (53.91)	
	Sum Total	107 (159.65)	

*Excluding Routine maintenance projects that include tree removal and trimming, litter removal, and ROW mowing. Sum total of the mileage of the concerned road segments are in brackets

of thought. One is that technology should be used to support and make more efficient, the existing work practices of an entity. The other is that technological advancement needs to disrupt or redefine how workflows take place. For many highway agencies, the former is more likely to hold sway among decision makers. Accordingly, in the context of this case study, GIS-based visualization and data integration can be used to better support the project-planning process in the latter stages of project programming or be used to re-design some of the workflow processes for highway projects.

In this case study, conflict analyses were used to identify highway road sections that have been receiving a high frequency of rehabilitation projects over the planning horizon. As seen in Table 4, performing intra-database analysis affords highway planners the opportunity to review pavement sections that are receiving repetitive rehabilitation projects over the planning period. This can lead to the selection of a more elaborate long-term pavement treatment option. In this example, the proposed workflow incorporates lessons from the GIS-based system during the project-planning and -programming stage in lieu of using the system only to manage already scheduled projects. For instance, 14 out of the total 67 intra-database overlaps in the COMPASS database were sections of pavement with at least one

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incident of a light or medium rehabilitation project for 3 consecutive fiscal years. These pavement sections can, therefore, be reviewed for potential consideration of a major capital construction project or a heavy rehabilitation project that can have a more effective long-term impact on pavement performance.

Improved communication among decision-makers

Visualization of projects provides transportation agencies with a more "natural" way of presenting and viewing highway projects information. This leads to an ideal approach to support more intuitive and effective communication of scheduled projects with other decision makers and stakeholders in general. As pointed out by Jha et al. (2001), such geospatial efforts can lead to a wider participation of decision-makers at early stages of project planning while aiding in the anticipation of planning errors.

In the context of this case study, the GIS tool is currently available to agency staff in the Fort Worth district including all the area engineers in the district. Other stakeholders who also need access to the tool are granted access to support a more collaborative effort during project planning. The tool allows the district staff to better communicate with area offices about other projects "in the pipeline" which in turn, allows area supervisors to be more effective with the proposed list of candidate highway projects.

Conclusions

The maintenance and rehabilitation (M&R) planning process is complex; multiple sources of funding with restrictions, different planning periods, and multiple stakeholders within and outside the DOT. For many DOTs — particularly with rapidly growing urban and metro areas — the process is challenging to manage with existing toolsets and databases. This study reports on the use of a GIS tool to integrate disparate data sources into a single, visual interface. The visualization tool makes identification of problems and opportunities more straightforward by; shortening the planning time and increasing the agency's abilities to make better use of limited funding.

The merits of GIS include valuable visualization, contextualization of information, and integrated database management. This study has evaluated the benefits associated with integrating highway projects data with GIS. It indicates that such integration efforts could be used to better support construction and maintenance operations; improve the planning process; save time and resources, and ensure that accurate information is available to different functional groups within the department.

In this case study, the automation of data processing and geoprocessing of projects data was complicated by a myriad of data quality issues; including missing data, inaccurate data, asymmetric data granularity, and semantic interoperability issues. More work is needed to delineate practical data integration challenges with GIS and to propose recommendations for improved data management practices for the district. Additionally, future work may also include the integration of highway conditions data, accidents data, and traffic information to provide a central source of information for the district to aid in project planning.

The authors recognize that every DOT is different and the highway planning practices may differ from one agency to another. However, this paper presented practical issues that are familiar to most DOTs and highway agencies in the domain of highway project planning. The findings of this study highlight an opportunity for highway agency staff to take advantage of GIS to improve integrated planning of highway infrastructure. The key to this process is the need for DOTs to, first, identify existing challenges with their current planning process and, second, employ GIS where necessary to address data-related issues. As highlighted by this case study, the opportunities for improvement are substantial and warrant investment in new tools and supporting processes.

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