SAMOHODNI MODULARNI TRANSPORTERI U UBRZANOJ IZGRADNJI MOSTOVA (DIO DRUGI): PROJEKAT PUTANJE

Mihailo Ostojić[1] Miloš Knežević[2]

Rezime: Nadovezujući se na osnovni pregled predstavljen u prethodnom radu, ova studija se bavi kritičnim aspektom dizajna putanje putovanja za samohodne modularne transportere u ubrzanoj izgradnji mostova. Efikasan transport teških komponenti mosta se u velikoj meri oslanja na precizno planiranje putanje kretanja, što obezbeđuje sigurnost, stabilnost i ekonomičnost tokom rada. Ovaj rad predstavlja koncept projektovanja putanje, identifikujući ključne parametre koji utiču na njegovo planiranje, uključujući geotehnička razmatranja, karakteristike terena, dimenzije opterećenja i faktore životne sredine. Analizirani su stvarni podaci o opterećenjima od mostova koji su transportovani u Sjedinjenim Američkim Državama, zajedno sa dimenzijama mostova, nudeći praktičan uvid u zahtjeve dizajna. Takođe su razmatrani bezbjednosni standardi i ekonomska opravdanja za projektovanje putanja, naglašavajući njihovu ulogu u obezbjeđivanju uspješnog sprovođenja projekta. Ova studija pruža sveobuhvatan okvir za inženjere u svrsi optimizacije putanja, minimiziranju troškova i poboljšaju efikasnost rada samohodnih modularnih transportera u složenim građevinskim okruženjima.

Ključne reči: projekat putanje kretanja, samohodni modularni transporteri, ubrzana konstrukcija mostova

SELF-PROPELLED MODULAR TRANSPORTERS IN ACCELERATED BRIDGE CONSTRUCTION (PART SECOND): TRAVEL PATH DESIGN

Abstract: Building on the foundational overview presented in the first paper, this study delves into the critical aspect of Travel Path design for Self-Propelled Modular Transporters in Accelerated Bridge Construction. The efficient transportation of heavy bridge components relies heavily on precise travel path planning, which ensures safety, stability and cost-effectiveness during operations. This paper defines the concept of Travel Path Design, identifying key parameters that influence it's planning, including geotechnical considerations, terrain characteristics, load dimensions and environmental factors. Real-world data on bridge loads transported via those transporters in the United States are analyzed, alongside dimensions of completed bridge projects, offering practical insights into design requirements. Safety standards and economic considerations for Travel Path design are also discussed, emphasizing their role in ensuring successful project execution. This study provides a comprehensive framework for engineers to optimize travel paths, minimize costs and enhance the efficiency of Self-Propelled Modular Transporter operations in complex construction environments.

Key words: Travel Path Design; Self-Propelled Modular Transporters; Accelerated Bridge Construction

1. INTRODUCTION

A Self-Propelled Modular Transporter (SPMT) is a computer-controlled platform vehicle that can move bridges or other structure weighing up to several thousand tons with precision. The prefabrication of bridges off-site under controlled conditions followed by installation on-site can achieve high-quality assembly and installation with traffic impacts of few hours compared to months that are typically required for conventional on-site bridge construction (Khudeira, S., 2023) [1]. Accelerated Bridge Construction (ABC) is a paradigm shift in bridge delivery, where reducing interruption to traffic and safety are given higher priorities (Azizinamini, A., 2020) [2].

The side-by-side box-beam bridge is the bridge of choice for short to medium span bridges due to ease of construction, favorable span-to-depth ratios, aesthetic appeal and high torsional stiffness. The bridge can be constructed in an accelerated fashion and classified among the systems that qualify accelerated bridge construction (Attanayake, U. & Aktan, H., 2015) [3]. ABC methods have been increasingly used for bridge rehabilitation and replacement projects in recent years. The main advantage of those methods over conventional staged construction is the reduced impact on traffic and

[1]Independent Researcher, email: mihailoo@t-com.me
[2]Civil Engineering Institute Founder, email: knezevicmilos@hotmail.com

mobility caused by on-site bridge construction, lane closures and detours (FHWA, 2011) [4]. ABC methods, on the other hand, often require a higher initial cost and the potential for more planning, design coordination and increased construction lead time (El-Rayes et.al., 2023) [5].

2. TRAVEL PATH DEFINITION

The Travel Path (TP) refers to the carefully designed route connecting the Staging Area (SA) of the bridge to the Construction Site (CS), along which SPMTs transport bridge elements. The design of the TP is a critical component of the overall project, as it directly impacts safety, cost and the efficiency of operations (Ostojic, M. & Aktan, H., 2014) [6].

Several factors must be considered during the TP design process, including ground improvements, load calculations, clearances, utility relocations, protective measures for structures being crossed, barriers and ensuring the shortest possible path with minimal turns. Additionally, the route must prioritize safety for both surrounding objects and workers. A well-designed TP strikes a balance between cost-effectiveness, safety and quality of work, while accounting for alternative traffic routes to minimize disruption (Ostojic, M. & Aktan, H. 2014) [6].

The TP design also significantly influences the SPMT platform's travel height. Geotechnical engineers play a crucial role in evaluating ground conditions and recommending reinforcements or improvements to enhance ground bearing capacity under temporary shoring bents, if required. Common solutions include preloading temporary shoring bents, using rigid construction mats, or employing dynamic compaction techniques.

Structural engineers contribute by performing necessary calculations related to boundary conditions and ensuring the structural stability of carriers for continuous superstructure transportation. Their input ensures that the TP can accommodate the load safely and without compromising the integrity of surrounding infrastructure.

3. PARAMETERS THAT INFLUENCE TRAVEL PATHS' DESIGN

The design of the TP for SPMTs requires careful consideration of multiple parameters that impact the safety, cost and efficiency of the transportation process. Each parameter plays a critical role in ensuring that the SPMT can transport heavy bridge components without compromising the integrity of the load or the surrounding infrastructure. The key parameters are outlined below.

3.1. Position of the Bridge Staging Area

Bridge Staging Area (BSA) is the site where the bridge superstructure is constructed before being transported to the Bridge Construction Site (BCS). It serves as a vital hub for construction activities and must be appropriately prepared to support the SPMT's operations.

Key factors related to BSA that influence TP design include:

- *Site Preparation*: The contractor is responsible for ensuring that the BSA is properly prepared, which includes excavation, clearing, grubbing, drainage, filling, soil support for equipment and temporary supports. Proper preparation is essential to create a stable foundation for the SPMT to operate effectively.
- *Geotechnical Assessment*: A detailed geotechnical investigation of the BSA is crucial to identify underground conditions, assess soil stability and determine the need for ground improvements or soft soil mitigation. The geotechnical project is typically submitted along with project drawings to ensure transparency and accountability.
- *Path Design Implications*: The position of the BSA directly impacts the design of the SPMT's travel path. The path must connect the BSA to the BCS while considering traffic, ground

conditions, physical barriers and other site-specific constraints. A suboptimal BSA location can lead to more complex and costly TP designs.

3.2. Bearing Capacity of the Soil

Soil bearing capacity at the BSA, BCS and TP locations plays a crucial role in ensuring that the ground can support the combined weight of the SPMT and the transported bridge superstructure. If the bearing capacity is inadequate, it may result in soil settlement, instability, or failure, posing risks to both the cargo and the project timeline.

Key considerations for soil bearing capacity include:

- *Minimum Requirements*: The soil must have a bearing capacity of at least 72kN/m² to safely support the weight of the SPMT and its load. In specific cases, stricter requirements may apply depending on site-specific conditions and project needs.
- *Safety Factor*: A 15% safety factor is typically added to the calculated dead load to account for the effects of uneven terrain and load shifts during movement.
- *Geotechnical Report*: The geotechnical report confirms whether the required bearing capacity is met and outlines any necessary ground improvements. If the soil does not meet the required bearing capacity, several solutions can be applied, including:
- *Use of Timber Mats or Steel Plates*: Placed along the TP to distribute load and prevent soil compression.
- *Excavation and Soil Replacement*: Removing soft or weak soil layers and replacing them with compacted material that meets bearing capacity requirements.
- *Soil Compaction*: Use of dynamic compaction or preloading techniques to improve the soil's load-bearing capacity.
- *Ground Improvements*: In cases where the natural soil conditions are not sufficient, ground reinforcement methods may be required, as detailed in the section on geotechnical recommendations. These reinforcements ensure that the ground can safely accommodate the weight of both the SPMT and its cargo.

3.3. Load (Cargo & SPMT)

The combined load of the SPMT and its cargo is one of the most influential factors in TP design. The weight of bridge components being transported and the SPMT itself affects not only the soil bearing capacity but also the load distribution and stress on temporary supports.

Key considerations for load include:

- *Load Distribution*: The load must be uniformly distributed along the TP to avoid excessive pressure points on the soil. The load distribution is assessed as part of the geotechnical analysis to ensure the ground can withstand the imposed forces.
- *Temporary Foundations*: If the bearing capacity of the soil is insufficient, temporary foundations may be installed. These foundations are designed to limit settlement to a maximum of 2.5cm and a differential settlement of 1.75cm.
- *Time-Dependent Settlement*: The settlement is calculated over a 2-year time frame to account for long-term soil movement. This ensures that the soil has sufficient capacity to support the load over time without risk of collapse or instability.
- *Temporary Support Design*: Temporary supports must be designed to withstand lateral forces equivalent to 10% of the dead load to ensure stability in case of sudden movements or load shifts. These supports are inspected regularly, with inspections recommended every three days to maintain safety and prevent deformation.

- *Vertical Tolerance*: The vertical tolerance for temporary support beams is limited to 0.3cm, ensuring that the elevation criteria for bridge substructures are met. This strict requirement guarantees a level surface for bridge placement, reducing the likelihood of misalignment.

Data on Bridge Loads Transported by SPMTs in the USA:

1. Graves Avenue over I-4 in Volusia County northeast of the city of Orlando in Central Florida, 2006: *individual span roll-in, 1,300-ton self-weight per span*;
2. LA 3249 (Well Road), a rural major collector, over I-20 in Ouachita Parish in northern Louisiana, 2011: *superstructure roll-in, 215-ton maximum span self-weight*;
3. MA Route 2 / US 202 over MA Route 2A (State Road) in the town of Phillipston in Worcester County, 2010: *245-ton self-weight*;
4. Cedar Street (urban minor arterial) over Route 9 in the town of Wellesley in Norfolk County, 2011: *530-ton self-weight*;
5. Willis Avenue over the Harlem River linking Upper Manhattan and the South Bronx in New York City, 2010: *steel through-truss swing span of 2,400-ton weight*;
6. Bridge over the Multnomah Channel of the Columbia River to Sauvie Island near the city of Portland in Multnomah County in Oregon, 2007: *1,250-ton main span vertical lift*;
7. On Sam White Lane over I-15 in the city of American Fork in Utah County, 30 miles south of Salt Lake City, 2011: *1,910-ton self-weight*;
8. Pioneer Crossing over I-15 in American Fork, south of Salt Lake City, 2010: *2,300-ton self-weight (the heaviest multi-girder spans moved with SPMTs in the US to date)*;
9. 4500 South (SR-266) over I-215 in Salt Lake City, 2007: *1,600-ton self-weight.* (USDOT) [7]

Real-world data from ABC projects in the U. S. provide valuable insight into the types of bridge loads transported using SPMTs. These case studies offer essential benchmarks for load requirements and ground preparation techniques.

Key insights from U.S. bridge projects include:

- *Range of Loads*: Bridge components transported by SPMTs typically range from 160 tons to over 3,600 tons, depending on the bridge type and construction approach. The load can consist of full superstructure segments or modular bridge elements that are combined later on-site.
- *Variation by Project Type*: Different projects exhibit varying load requirements. For instance, single-span modular bridges involve transporting large prefabricated sections, whereas multi-span bridges require the transportation of smaller components for assembly at the site.
- *Impact on TP Design*: The load type and weight influence the design of the TP in terms of required bearing capacity, temporary supports and ground improvements. Heavier loads require stronger soil reinforcement and more precise support placements to prevent settlement or collapse.
- *Practical Experience*: Studies of past ABC projects in the United States show that proper TP design can lead to significant cost savings by reducing the risk of settlement, load misalignment and cargo instability. Data from real-world applications inform best practices for future projects.

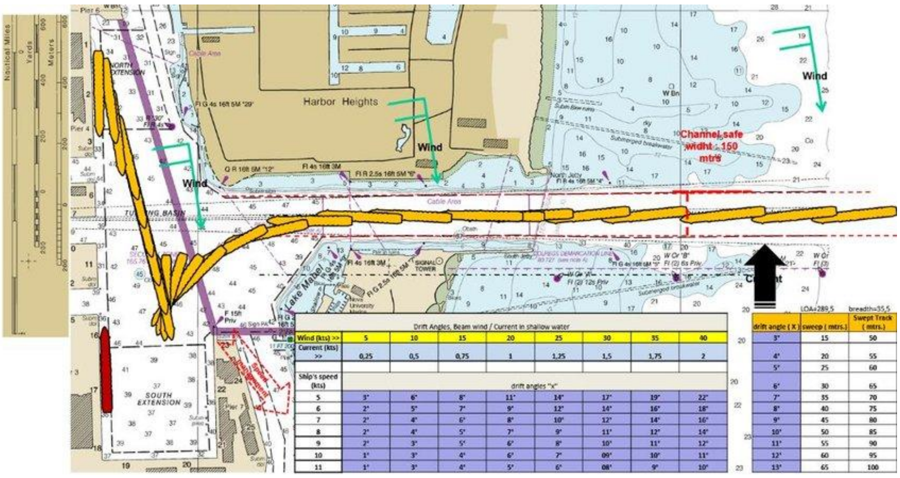

Figure 1: TP Design Plan between BSA and BCS, with drawing details and route explanation, maneuvers, recommended soil bearing capacity improvements, etc. (UDOT) [8]

3.4. **Utilities (Underground & Overhead)**

The presence of utilities, both underground and overhead, is a crucial factor in TP design. Utility conflicts can delay construction, increase costs and pose safety risks. Identifying, protecting, or temporarily relocating these utilities before construction begins is essential.

Key considerations include:

- *Underground Installations*: Utility lines such as electricity, water, gas and telecommunications often run beneath construction sites. It is critical to assess their position relative to the TP and ensure they are adequately protected from the load of the SPMT and the bridge superstructure. If the pressure from the SPMT exceeds the design limits of these utilities, reinforcements may be required, which could involve protective casings, additional soil coverage, or the use of support structures.
- *Overhead Installations*: Overhead power lines, telecommunication cables and other suspended installations can interfere with SPMT operations. Overhead clearance must be calculated to ensure sufficient space for the height of the bridge superstructure and SPMT platform. In some cases, utilities can be temporarily removed and reinstalled after transportation.
- *Conflict Resolution*: Prior to the construction of the TP, a utility conflict analysis must be conducted to determine if utilities can be relocated, protected, or left in place. The analysis is typically documented in the Geotechnical Report along with reinforcement recommendations.

3.5. **Cargo Dimensions & SPMT**

The dimensions of the bridge components being transported, along with the size of the SPMT, significantly influence TP design. Larger components increase the complexity of transportation, particularly in areas with limited space, tight turns, or height restrictions.

Key considerations include:

- *Size and Shape of Bridge Components*: The shape and dimensions of the bridge component directly impact TP design. Larger components require more clearance, wider paths and reduced curvature in the route. Design optimization, such as reducing weight or modularizing bridge components, can simplify transportation.
- *SPMT Platform Dimensions*: The platform width, length and height affect the overall route design, especially when negotiating turns or passing through tight spaces. SPMTs typically

operate with a platform height of around 1.2 meters, but this can be influenced by factors such as tire compression, platform camber and ground conditions.

- *Route Adjustments*: If the cargo is oversized relative to the available clearance or turning radius, adjustments must be made to the TP, often requiring detours, embankments, or even temporary removal of obstacles.

In the further text are being presented data about dimensions of bridges and/or bridge components transported with the SPMTs in different ABC projects within the USA:

1. Graves Avenue over I-4 in Volusia County northeast of the city of Orlando in Central Florida, 2006: *87,2m-long and 18m-wide two-span full-width decked pre-stressed beam bridge (43m)*;
2. LA 3249 (Well Road), a rural major collector, over I-20 in Ouachita Parish in northern Louisiana, 2011: *80m-long and 9,2m-wide four-span (15,2 –26m–21,3m–16,7m) composite steel girder bridge*;
3. MA Route 2 / US 202 over MA Route 2A (State Road) in the town of Phillipston in Worcester County, 2010: *18,5m-long & 15.5m-wide out-to-out single-span steel girder bridge roll-in*;
4. Cedar Street (urban minor arterial) over Route 9 in the town of Wellesley in Norfolk County, 2011: *25.3m-long and 16.2m-wide two-span continuous steel girder bridge roll-in (12.7m–12.7m)*;
5. Willis Avenue over the Harlem River linking Upper Manhattan and the South Bronx in New York City, 2010: *106,7m-long, 23,5m-wide and 20m-high steel through-truss swing span of 613,3m-long 15-span mainline bridge over the Harlem River (span lengths ranging from 16,3m to 66,7m)*;
6. Bridge over the Multnomah Channel of the Columbia River to Sauvie Island near the city of Portland in Multnomah County in Oregon, 2007: *111,3m-long and 26m tall steel tied arch main span of the 359m-long and 20,2m-wide five-span bridge with post-tensioned box girder approach spans: 63m + 62,5m (126m C.I.P. Cont. P.T. Box Girder) + 111,5m steel tied arch span + 62,5m + 59,5m (122m C.I.P. Cont. P.T. Box Girder)*;
7. On Sam White Lane over I-15 in the city of American Fork in Utah County, 55*km* south of Salt Lake City, 2011: *108m long and 23,4m wide two-span continuous steel plate-girder bridge (54m – 54m) roll-in*;
8. Pioneer Crossing over I-15 in American Fork, south of Salt Lake City, 2010: *58m long and 21m wide single-span bridge roll-in (longest multi-girder spans moved with SPMTs in the US to date)*
9. 4500 South (SR-266) over I-215 in Salt Lake City, 2007: *52,5m long and 25m wide single-span bridge roll-in.* (USDOT) [7].

3.6. **Terrain Topography**

The natural topography of the terrain influences how the TP is designed and the SPMT's capacity to move along it. The SPMT's unique hydraulic system allows it to adapt to uneven terrain, but specific design considerations are still required.

Key considerations include:

- *Slope Analysis*: SPMTs can navigate slopes of up to 10 degrees from the horizontal, but it is recommended to limit slopes to 8 degrees when transporting maximum loads. Steeper slopes may require alternative solutions, such as additional support vehicles for traction or pre-leveling of the terrain.

- *Hydraulic Adaptability*: SPMTs are equipped with advanced hydraulic systems that allow each wheel to move independently, following the natural terrain. This system maintains load stability while traversing uneven ground.
- *Leveling the Terrain*: If the existing terrain slope exceeds the SPMT's capacity, it may be necessary to level the terrain using techniques like excavation, embankment construction, or temporary bridge installation. These actions ensure smooth movement of the SPMT and reduce stress on its hydraulic systems.

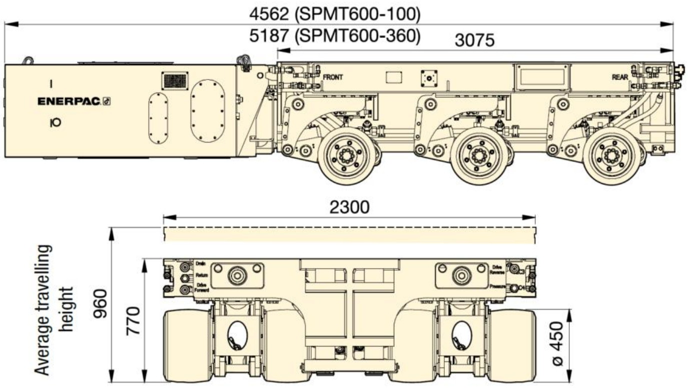

Figure 2: SPMT's hydraulic suspension for adoptability to bumpy terrain [9]

3.7. **Climate & Weather Conditions**

Weather plays an essential role in TP design and project planning. Adverse weather conditions, such as wind, rain and snow, can affect SPMT stability, cargo safety and soil conditions along the TP.

Key considerations include:

- *Wind and Snow Loads*: The bridge structure is exposed to wind and snow loads during transport. Project owners are responsible for specifying wind and snow load design values, which are calculated using probability factors for adverse weather occurrence.
- *Soil Conditions*: Rain, snow and freeze-thaw cycles impact soil strength and stability. Precipitation can weaken soil layers, leading to reduced bearing capacity. This is why geotechnical reports incorporate weather data to assess soil reinforcement needs.
- *Weather Monitoring*: It is essential to monitor weather forecasts before transport begins. If heavy rain or high winds are expected, transport should be delayed to avoid the risk of cargo instability, slippage, or ground failure [10].

3.8. **Potential Barriers & Obstructions**

Barriers and obstacles, such as existing structures, large rocks and steep inclines, must be addressed in TP design. These obstacles may force a change in route alignment or require additional design solutions.

Key considerations include:

- *Route Adjustments*: When obstacles cannot be removed, the route must be altered to avoid them. This could involve curve widening, bypass paths, or route extensions.
- *Temporary or Permanent Removal of Barriers*: Barriers like fences, signage, or smaller structures may be temporarily removed during transport and reinstalled afterward. Larger, immovable barriers may require custom construction solutions.

- *Environmental Considerations*: Care must be taken to minimize the environmental impact of TP design changes, particularly in sensitive areas. Any intervention should follow the recommendations outlined in the Protection Plan for Surrounding Facilities [11].

3.9. **Financial Factors**

The financial aspect of TP design influences all other parameters, as the budget dictates the extent of ground improvements, equipment usage and design complexity. Striking a balance between cost, constructability and safety is essential for successful project execution.

Key considerations include:

- *Budget Constraints*: Projects with strict budgets may be limited in their ability to implement optimal ground improvements, construct embankments, or remove barriers. Trade-offs must be carefully considered to avoid unnecessary cost increases.
- *Cost-Benefit Analysis*: Cost decisions must be made to balance efficiency and cost. For example, while pre-leveling the terrain may be expensive, it can reduce operational delays and lower the overall project cost.
- *Owner's Responsibility*: It is the owner's duty to provide sufficient funding to meet design and safety requirements. Financial factors are typically discussed in a dedicated section of the project's financial plan.

This comprehensive analysis of key design parameters highlights the complexity of TP design for SPMTs. Addressing these parameters ensures safer, more efficient and cost-effective transportation of bridge components.

4. CONCLUSION

The TP design for SPMTs is a critical aspect of successful ABC. This paper has explored the key parameters influencing TP design, including the positioning of staging areas, soil bearing capacity, cargo dimensions, terrain topography, weather conditions, utilities, potential barriers and financial considerations. By addressing these factors comprehensively, engineers can ensure safe, efficient and cost-effective transportation of heavy bridge components.

Real-world data from U.S. bridge projects have highlighted the importance of meticulous planning in achieving optimal results. The insights provided in this paper serve as a practical framework for construction professionals to navigate the complexities of TP design in diverse project environments.

Building on this foundation, the next phase of research will focus on verification and requirements for TP design. The third paper will examine methods for validating TP suitability, detailing safety standards, geotechnical reinforcement requirements and economic trade-offs to provide a holistic approach to TP implementation.

5. REFERENCES

[1] Khudeira, S. (2023). Truss Bridge Construction Using Self-Propelled Modular Transporters Compared to Traditional Bridge Building Methods. In Automation in Construction toward Resilience (pp. 157-186). CRC Press.

[2] Azizinamini, A. (2020). Accelerated bridge construction.

[3] Attanayake, U., & Aktan, H. (2015). First-generation ABC system, evolving design and half a century of performance: Michigan side-by-side box-beam bridges. Journal of Performance of Constructed Facilities, 29(3), 04014090.

[4] FHWA. (2011). Accelerated Bridge Construction. Report, 100, 1-347.

[5] El-Rayes, K., El-Gohary, N., Golparvar-Fard, M., Ignacio, E. J., & Helaly, H. (2023). Economical Impact of Full Closure for Accelerated Bridge Construction and Conventional Staged Construction. FHWA-ICT-23-009.

[6] Ostojic, M. & Aktan, H. "Designing SPMT's Travel Path for Accelerated Bridge Construction" Western Michigan University, MI – USA, 2014.

[7] U.S. Department of Transportation: www.transportation.gov

[8] https://www.researchgate.net

[9] blog.enerpac.com

[10] Utah Department of Transportation: www.udot.utah.gov

[11] US Department of Transportation, Federal Highway Administration: www.transportation.gov