Optimising the configuration of a double-decker sleeping car from Germany to the Mediterranean – squaring the circle

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ABSTRACT

The revitalisation of night train services aims to offer a sustainable alternative to air travel on routes between 500 and 2000 km. However, high operating costs make ticket prices uncompetitive compared to low-cost airlines and high-speed day trains, resulting in the discontinuation of several services in Europe over the past 15 years. Challenges persist, including limited passenger capacity, large space requirements per passenger, and lack of seat turnover. Furthermore, the constraints of the G1 gauge limit international services, putting night trains in central Europe at a disadvantage compared to the American Superliner or the Finnish VR Ny, as well as other modes of transportation. This paper explores early-stage design strategies to improve the economic viability and efficiency of double-decker sleeping cars. Findings from Project "AliSa" identify critical design trade-offs and technical constraints. Desk research and CAD analyses reveal that accommodating two double cabins on both the upper and lower decks within the G1-profile is not feasible, as seen with the Superliner model. One alternative is to emphasise reclining armchair seating, which is less affected by height restrictions and offers greater flexibility. Norske tog's survey indicates positive passenger attitudes towards this option, particularly when paired with private cabins to enhance privacy. Additionally, shorter but wider carriages improve spatial efficiency and comfort. A novel configuration is proposed to maximise capacity while adapting to demand variations. Some armchairs are reserved for the entire journey, while

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others allow seat turnover. This setup incorporates adaptive lighting and modular partitions to balance privacy with occupancy efficiency. A linear programming simulation using demand scenarios and different ticket prices optimises the upper deck configuration, combining two-person cabins, overnight armchairs, and turnover armchairs. Results indicate that turnover armchairs are more profitable in high-demand scenarios, while night armchairs gain relevance in lower-demand situations.

1. INTRODUCTION

The revival of night train services offers a low-carbon alternative for mid-range travel. However, high operating costs and limited passenger capacity often make them less competitive compared to air travel and high-speed day trains (HST). This paper presents evaluation and early-stage design insights from the AliSa project (from the German *Angebotsdifferenzierter, leichter und innovativer Schlafwagen* – “offer-differentiated, lightweight and innovative sleeping car concept”), funded by the Federal Ministry for Economic Affairs and Energy of the Federal Republic of Germany. This project aims to improve the economic viability, operational efficiency and affordability of night train services across all social groups.

Previous studies and surveys have identified key factors influencing passengers’ choices for night train services - namely travel time, cost and comfort, with the latter closely linked to privacy considerations (Kantelaar et al., 2022). These factors strongly shape passenger preferences and often deter them from choosing rail over other modes of transport (Rüger & Mailer, 2020). A TU Dresden study found that 80% of participants prefer a lying position, and 50% prioritize privacy (Bellmann & Bauer, 2019). Furthermore, passengers also emphasise the need for adequate luggage space and the importance of maintaining visual contact with it (Rüger, 2021). Nonetheless, most existing research primarily relies on feedback from current night train users, resulting in a somewhat biased sample and providing limited insight into the broader potential market. Recent research work by Ramboll (2024), which confirms the lack of demand data for night trains, helps address this gap by estimating modal shift potential from air and car travel under various demand scenarios. Additionally, the literature points to an inherent disadvantage in the productivity of current sleeping and couchette carriages which, while essential for overnight services, remain unused during the day, reducing productivity. Troche et al. (2007) suggest that enabling day and night use could more than double their economic efficiency. Concepts such as the

EuroDayNiter (Manthei, 2005) and the TANA project (Rüger et al., 2024), designed for full day/night operation, provide potential solutions to this challenge. However, no vehicle has yet reached full realization in this area.

Combining literature data, CAD analysis, and a simulation model, this study proposes an innovative strategy to optimise space while maintaining a sufficient degree of passenger comfort and adapt to fluctuating demand. It also addresses design constraints and trade-offs. The paper proceeds in two main phases: first, an **evaluation** of current and former night train services is conducted to define benchmarks, requirements and early-stage design decisions for the AliSa concept, with a focus on economic viability. The upper deck is identified as a key area for revenue generation, due to its potential capacity and homogeneity. In the second phase, a linear programming model is used for the **optimisation** of the proposed upper deck configuration, aiming to maximise profit through the allocation of night and turnover armchairs, while keeping a small number of fixed private cabins.

2. METHODOLOGY

During the evaluation phase, existing and discontinued sleeper car concepts from various regions (Europe, America, Asia) were explored to derive insights relevant to the AliSa concept. Thereafter, an optimization of the upper-deck was conducted. The research was structured as follows:

1. **Evaluation of existing and former night train services:**
   - **Literature review and data collection:** A total of 18 sleeping car concepts were surveyed, spanning various regions, and characterised based on the following criteria: general and operational features, service routes, wagon type and length, passenger capacity, amount and layout of seating / couchette and sleeping cars, cabin quality levels, presence of WC and PRM-cabins where applicable, etc. Additionally, 10 related vehicle concepts were documented, which were either already represented by one of the previously surveyed models or lacked sufficient data for inclusion in the broader analysis.
   - **Benchmarking:** A structured benchmarking approach was applied to systematically compare the surveyed night train concepts. This involved the development of a matrix-based tool to evaluate key parameters such as spatial efficiency, modularity, passenger comfort features, and suitability for day/night use. By analysing these criteria across the mentioned concepts, common patterns, best practices as

well as critical trade-offs between comfort, capacity and flexibility were identified.

- **Early design decisions:** Based on the benchmarking results, a set of requirements was iteratively formulated through a qualitative synthesis approach: key findings from the literature and benchmarking were evaluated for their relevance to improving capacity, modularity and cost-efficiency within the constraints of different loading gauge profiles. The latter were identified and discussed through a detailed CAD analysis.

2. **Linear programming simulation**: The optimization of the upper deck configuration was carried out using a linear programming model developed with Python's PuLP library (Mitchell, 2004). The model aims to **maximise profit** while dynamically adjusting the allocation between night recliners (NRA) and turnover recliners (TRA) in response to pricing and demand constraints. NRA are intended for full-route bookings, whereas TRA, similar to first-class quiet zone seats with dimmed lighting, are available for shorter segments (approximately one-third of the route). This novel, flexible configuration scheme improves occupancy efficiency by better aligning with varying demand. It also facilitates the day/night use of the reclining armchairs and incorporates adaptive lighting and adjustable cabin dividers to balance privacy with occupancy efficiency.

FORMULATION OF THE OPTIMIZATION PROBLEM

For the simulation, reference values were initially defined for key parameters, which can later be varied. Initial simulations revealed a model tendency to select TRA, so a business rule requiring a minimum of 4 NRA in high demand was introduced. In high demand scenarios, base demand is set at 40 for TRA and 15 for NRA. In low demand scenarios, the base demand is set at 15 for TRA and 5 for NRA. These demand levels are dynamically adjusted based on ticket price elasticity. The model uses a base price of €85 for TRA – reflecting an average fare of 5-hour 1st-class ICE routes – and €130 for NRA, based on full-night fares of upper-segment night trains in Central Europe, with elasticity factors (*elast*) of 0.6 and 0.2 respectively, reflecting differing demand sensitivities.

$$\text{max}_{TRA} = \max(0, \text{base\_demand}_{TRA} - \text{elast}_{TRA} \times (\text{t\_price}_{TRA} - 85)) \quad (1)$$

$$\text{max}_{NRA} = \max(0, \text{base\_demand}_{NRA} - \text{elast}_{NRA} \times (\text{t\_price}_{NRA} - 130)) \quad (2)$$

The objective function maximises profit by balancing revenues from each type of booking against costs, where the total seats constraint is: TRA + NRA = fixed_total_seats = 23. The $revenue_{NRA}$ is t_price_{NRA}, while it is assumed that the TRA is booked in two thirds of the route, so that the $revenue_{TRA}$ = 2 x t_price_{TRA}. Cabins are considered fixed with two units with two berths each, and an occupancy fixed at 75%. The fixed costs of the entire waggon are estimated at approximately €4,000, with an additionally €10 in operating costs applied per occupied seat. The profit calculation of the upper deck is evaluated in relation to the total costs of the waggon:

$$\text{maxProfit} = (\text{revenue}_{TRA} \times \text{TRA}) + (\text{revenue}_{NRA} \times \text{NRA}) + (\text{revenue}_{cabin} \times \text{fixed\_cabins}) - ((\text{operating\_cost} \times (\text{TRA} + \text{NRA} + \text{fixed\_cabins})) + \text{fixed\_cost}) \quad (3)$$

3. RESULTS

3.1 RESULTS OF THE EVALUATION AND PROPOSED ALISA CONCEPT

The following **findings** emerged from the literature review:

- Following the financial and debt crisis and the emergence of low-cost airlines, there was a **wave of major discontinuations** of night train services in Europe between 2015 and 2021 (see Figure 1). This highlights that the economic viability of some night trains remains uncertain and vulnerable to external economic pressures, even after the proliferation of new concepts post-Corona.

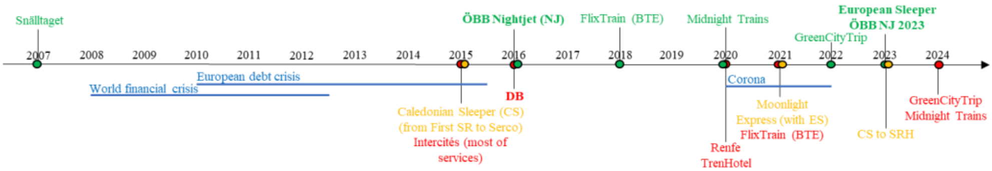

Figure 1: Timeline of the start and discontinuation of night train services in Europe from 2007 to 2024: green for starts, orange for mergers, red for discontinuations, and blue for external events.

- Up until recently, night train services were national initiatives. New developments by ÖBB and European Sleeper (ES) reflect a new trend in the **international positioning** of operators.
- A **variety of sleeper wagon concepts** have emerged across different market segments. These concepts vary significantly in terms of service and design quality (see Table 1).

Table 1: Spectrum of identified train concepts and their corresponding market segments.

Segments	Examples	Defining attributes
Budget	PKP, ČD, ES, TransSib	Older or refurbished 2nd- and 3rd-class rolling stock with limited comfort and sleep quality; often not price competitive with HST or low-cost airlines.
Mid-to-Upper	ÖBB NJ, CS, VR, SJ, FLEX	Upgraded wagons facing strong competition from HST and air travel; some heavily subsidized (e.g. CS), others discontinued (e.g. Renfe TrenHotel).
High-Density	Škoda (2024), Luna Rail	New double-decker concepts with high passenger density and modular layouts. Luna Rail's (Dubrau, 2024) concept allows for day/night use.
Premium	TANA, Luxon	High-end sleeper prototypes seeking greater comfort and exclusivity.
Non-EU	Amtrak, CRRC	Fewer constraints on loading gauge and interoperability.

- Despite the variety of night train concepts, **no lightweight design** is on the market yet.
- Nearly all of the characterised concepts incorporate at least one **modular solution**, such as interconnected compartments, folding couches that convert into seats, folding table tops that cover washbasins, or folding backrests transforming into small tables. The modular design of the **Amtrak Superliner Roomettes** (National Railroad Passenger Corporation, n.d.) serves as a benchmark for the AliSa project due to its high passenger density - up to 4 passengers every 2 meters of deck length – enabled by the vehicle width accommodating two parallel Roomettes and sufficient height for its duplication across both decks. Each Roomette consists of two wide seats facing each other during

the day, which convert into a long couchette at night, in addition to an overhead couchette folded up during the day.

- **Reclining armchairs are gaining popularity**, being included in both the TANA project and in Norske tog's new order (successor to the Norwegian national railways (NSB) for rolling stock) for night trains entering service in 2028 for the Norwegian operator Vy. Following a survey by Norske tog and a study of its sleeper train service, the new Type 79 (**Stadler FLEX)** night trains will have carriages with recliners, alongside others offering seats and convertible berths. However, Norske tog is not waiting for 2028 and has already decided to refurbish its current night trains with reclining armchairs (Railway Public s.r.o., 2023).

The following relevant implications and **requirements** were derived for the AliSa concept:

- **Dimensional optimisation and modularity**: The car body should be as wide as technically and legally possible to accommodate larger modules and improve sleep comfort. Vehicles like Amtrak's Superliner, the Finnish VR Ny and Stadler FLEX exploit larger loading gauges in their networks and serve as benchmarks for AliSa. Despite more restrictive Central European loading gauges, the project aims for an optimized width by designing shorter, wider wagons: a formation of two 14.900 m end wagons and a 14.500 m middle wagon, all with single-axle bogies is proposed (see Figure). This results in approximately 90% the length of the usual 2 x 25 m wagons, but 2.960 m width, about 10% wider than conventional concepts like the Nightjet or ES.

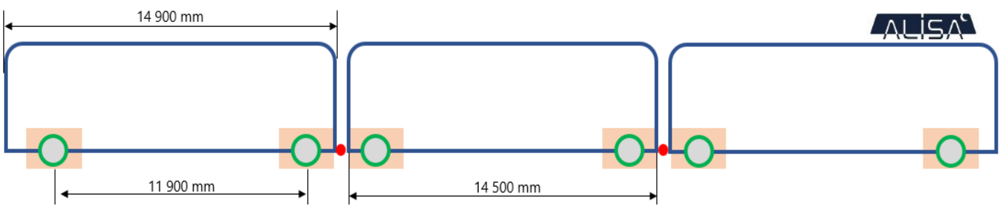

Figure 2: Sketch of the AliSa three-wagon formation of shorter but wider wagons.

- **Interoperability**: A double-deck design is confirmed, that should be capable of travelling across multiple European countries. Initially, a **G1-profile** was considered for interoperability on routes from

Germany to the Mediterranean, including France and Italy. However, it was found out, that this low gauge severely limits passenger density, impacting economic viability, and prevents the intended double gangway on both the upper and lower decks. As a result, a decision was made to adopt the larger **GC-profile**, which is closer to the Amtrak benchmark and is intended to be available for high-speed tracks connecting European capitals by 2030. This profile also enables a double gangway between the carriages of the AliSa three-car formation (see Figure 3)

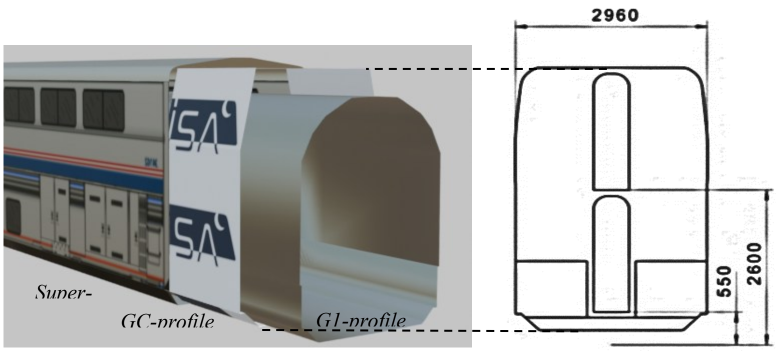

Figure 3: Left: AliSa cross-section with GC profile (4.650 m height) between a G1 profile (4.310 m) and the projected Superliner (4.930 m) for reference. Right: Final AliSa GC profile with its double gangway and optimised width (2.960 m). *Source of Superliner illustration: trainweb.org*

- **Ticket price and space efficiency**: It was found out that concepts with premium sleeping compartments typically charge three times the price of a seat for them, while long-haul aircraft "First Class" fares are around eight to ten times the price of a standard seat. The relatively low willingness to pay for a premium bed in a sleeping compartment does not justify the space it occupies in an optimised concept. The AliSa concept will include space-optimised compartments.
- **Economic efficiency and passenger density**: The AliSa concept will feature an optimised arrangement of sleeping berths and sanitary facilities, along with a PRM cabin and technical space on the lower deck. To improve economic viability, enhancing seat turnover and allowing for day/night use is essential. In response, a novel upper-deck configuration has been proposed, incorporating **dual-use reclining armchairs**, addressing both sleeping arrangements and seating turnover, while moderately impacting privacy.

Table 2: Comparison of key dimensional features of representative night trains and positioning of the AliSa system after the optimization.

Model	Wagon width	Wagon height	Wagon length	Volume comparison (Superliner 100%)	Max. passenger density (pax/m) in couchette / recliners wagon
ÖBB NJ (2023)	2.825 m	4.050 m	26.500 m	ca. 74%	ca. 2
ES (Schmid, n.d.)	2.825 m	4.050 m	26.000 m	ca. 74%	ca. 2.5 (5 persons compartment considered)
Caledonian Sleeper (n.d.)	2.750 m	ca. 4.000 m	22.200 m	ca. 71%	ca. 1.5
Norske tog Type 79	3.200 m	4.360 m	ca. 26.000 m	ca. 91%	ca. 1.8
Amtrak Superliner	3.100 m	4.930 m (double decker)	25.900 m	100%	4 (4 pax. every 2 m per deck)
AliSa (GC-profile)	2.960 m	4.650 m (double decker)	14.500 / 14.900 m	ca. 88%	ca. 3 2.1 alone at upper deck

3.2 RESULTS AND DISCUSSION OF THE UPPER DECK OPTIMISATION

The AliSa concept aims to integrate various types of cabins and seats within a modular architecture. Each upper-deck consists of five 2.550 m segments (excluding staircase space), enabling multiple layouts. One such configuration is the object of this optimisation study: Based on an initial configuration of the upper deck with 2 double cabins and 23 reclining armchairs (RA) within an available inner surface of 14.025 m length and 2.860 m width (Figure 4), the linear optimisation problem was formulated as described in chapter 2.1.

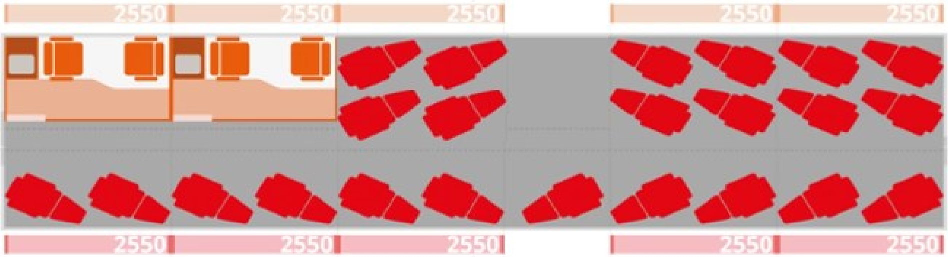

Figure 4: Upper deck layout with two fixed double cabins (upper left) and 23 dual-use recliner armchairs prior to their allocation as either turnover or night recliners (TRA-NRA).

4. OPTIMISATION RESULTS AND DISCUSSION

The optimisation results from the linear programming model for both high and low demand scenarios with varying price points are shown in Table 3. The profit values shall be taken just as an orientation, since they are based on the previously mentioned parameters and a rough cost estimation.

Table 3: Optimisation results allocation of TRA and NRA for different scenarios.

Demand scenario	t_price_{TRA} (€)	t_price_{NRA} (€)	TRA	NRA	Estimated profit (€)
1 - High demand	85	130	**19**	**4**	200
2 - High demand	95	150	**19**	**4**	760
3 - High demand	105	170	**19**	**4**	1320
4 - Low demand	85	130	**15**	**5**	-320
5 - Low demand	95	150	**9**	**1**	-1460
6 - Low demand	105	170	**3**	**0**	-2520

In high demand scenarios, the model consistently selects the minimum required number of NRA (4), favouring TRA due to their higher revenue potential, as they are assumed to be booked twice per night.

In contrast, **low demand scenarios** exhibit a different pattern: At moderate prices, the model still manages to fill most of the available seats, favouring TRA to optimise seat usage within the limited demand. However, as ticket prices increase, the demand sensitivity leads to a noticeable drop in seat allocation, specially of TRA (see Table 3 and Figure 5). NRA seem to fit better in a scenario with low demand and moderate ticket prices.

Overall, this adaptive upper deck configuration demonstrates its potential to cover the full cost of the wagon in all high demand cases, with Scenarios 1 and 4 representing near break-even points for high and low demand, respectively. In low demand situations, however, profitability cannot be guaranteed with the upper-deck alone, and a precise configuration strategy is required to minimise possible losses.

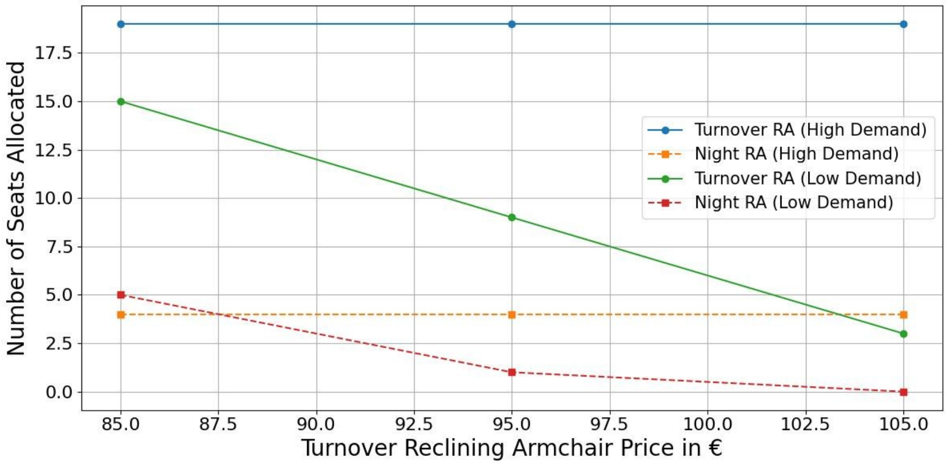

Figure 5: TRA and NRA allocation vs TRA price for different demand scenarios.

The physical separation between night and turnover areas is achieved using cabin dividers, similar to those found in commercial aircrafts, mounted on guides along the walls in longitudinal direction. This allows cabin dividers to be shifted row by row, enabling flexible proportions of TRA and NRA based on demand. However, the row-wise adjustment makes a direct translation of the optimisation results only approximately feasible, as each row contains either one or three recliners, which must be entirely assigned to either TRA or NRA (see Figure 6).

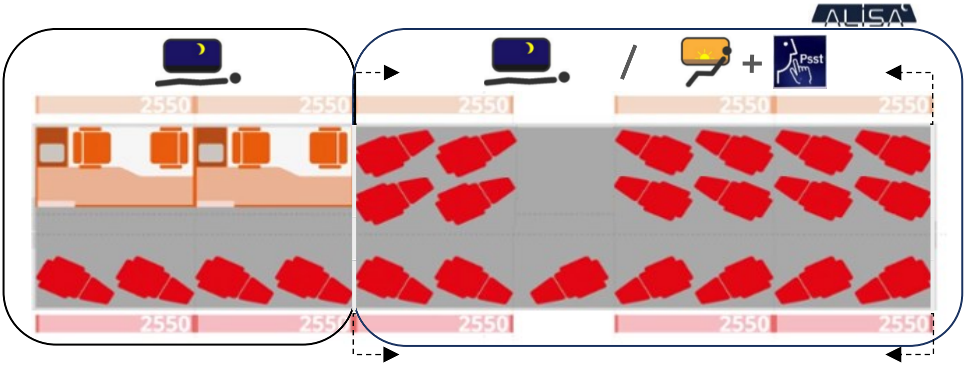

Figure 6: Proposed upper-deck configuration for high demand scenarios (1, 2, 3) and scenario 4 (low demand, moderate ticket price). The left cluster groups the cabins and NRA, while the right cluster is reserved for TRA. The left cabin divider is positioned between rows 4 and 5 but can be shifted rightward. The right divider remains in its default position. *Quiet area logo source: DB AG.*

5. CONCLUSION

This study has explored the potential of flexible configurations to improve the economic viability of night train services. By combining insights from the evaluation of current and discontinued sleeping cars, CAD-based design constraints and linear programming optimization, the early AliSa concept was developed with optimised geometrical features and a flexible, modular seating layout based on dual-use reclining armchairs. This layout supports both day and night use, with turnover recliners designed to be booked multiple times along a single night train journey.

The upper-deck optimization results show that, in high demand scenarios, profit-positive configurations are achievable, especially when turnover recliners are prioritised due to their higher revenue per seat. In low demand scenarios, however, targeted configuration adjustments are necessary to mitigate financial losses. Although the simulation is based on simplified cost assumptions, it provides a foundation for more detailed future planning. Further optimisation effort should focus on integrating the lower-deck layout and validating the results against broader passenger market data. In the coming months, the AliSa project will focus on optimizing structural lightweight design, achieving full vehicle integration, and developing a comprehensive cost model.

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AI was utilized as a programming tool during the optimisation process and for language polishing in the preparation of this paper.

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