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TRANSPORT SYSTEM RESILIENCE IN EMERGENCIES

A.A. Feofilova [1], L. Hu [2]
[1] Don state technical university, Rostov on Don, Russia, afeofilova@donstu.ru
[2] Don state technical university, Rostov on Don, Russia, 1534202112@qq.com

Abstract. The present paper employs a performance-based framework to analyse transport network resilience, quantifying system response to disruptions. The study employs a structured assessment methodology to evaluate key resilience metrics, including absorption capacity, recovery speed, and adaptive capability. The findings of the study identified critical vulnerabilities in restoration processes despite strong ultimate recovery performance.

Keywords: emergency, traffic management; transport system resilience

УСТОЙЧИВОСТЬ ТРАНСПОРТНОЙ СИСТЕМЫ В ЧРЕЗВЫЧАЙНЫХ СИТУАЦИЯХ

А.А. Феофилова [1], Л. Ху [2]
[1] Донской государственный технический университет, Ростов-на-Дону, Россия, afeofilova@donstu.ru
[2] Донской государственный технический университет, Ростов-на-Дону, Россия, 1534202112@qq.com

Urban transport infrastructures are pivotal components of modern societies, playing a central role in urban functioning, especially when facing increasing threats from various disasters. Their critical role necessitates a robust understanding and evaluation of their resilience, particularly in the context of emergency management . This understanding is crucial for developing effective strategies to mitigate the impacts of natural and man-made disasters on these vital systems [1]. This paper, therefore, aims to identify and summarize existing indicators of transport infrastructure resilience, offering insights into current approaches and potential future studies. Specifically, resilience in this context refers to the capacity of multimodal and integrated transportation systems to prepare for, resist, absorb, adapt to, and recover from disruptions while maintaining or restoring normal service levels [2]. Such resilience is characterized by a system's ability to continuously adapt to achieve operational goals, recovering effectively from disruptive events and shocks to regain its initial state [3]. This comprehensive perspective on resilience, encompassing preparation, absorption, and recovery, aligns with the evolving scholarly focus on urban integrated transportation networks.

Recent studies propose quantitative and probabilistic frameworks for assessing resilience under specific hazards. For instance, in [4] authors developed a probabilistic model to evaluate seismic resilience in emergency medical response systems, focusing on total social losses and restoration time. Similarly, in [5] authors introduced optimization-based methods to measure and maximize evacuation performance in disrupted transport networks.

A broader theoretical perspective is provided in [6]. Authors emphasize the relationship between risk, vulnerability, and resilience in transportation, arguing that resilience is not only the system’s robustness but also its adaptability in dynamic environments.

From a transport systems science perspective, resilience research has evolved towards a more integrated and multidimensional understanding of how networks respond to and recover from disruption. Scholars advocate incorporating resilience principles throughout the disaster management process, from pre-event mitigation and preparedness to post-event recovery and adaptation. This perspective highlights that resilience is not a static property, but rather a dynamic system behaviour influenced by design, policy and operational flexibility.

Building on this foundation in [7] a network-based resilience assessment framework for highway systems is introduced, emphasising the identification of critical nodes and links that sustain safety and functionality during emergencies. Similarly in [8] a simulation-based resilience evaluation to urban bus networks is applied, providing quantitative insights into network redundancy, recovery trajectories and service continuity under disruptive scenarios.

A common method used to visualize and quantify how a transport system (or any critical infrastructure system) responds to and recovers from disruptions over time is the conceptual resilience curve framework (fig.1). Figure 1 presents a conceptual depiction of the methodology framework, designed to more precisely quantify resilience across various system phases. The vertical axis represents the system performance level P, whilst the horizontal axis denotes time. The plotted curve—commonly termed the resilience curve—illustrates the evolution of system performance over time following a disturbance. At time point t_d, the system encounters an external shock leading to a decline in performance, which begins to recover at time point t_r. The system continues to improve until it reaches a new equilibrium state at time point t_{ns}. Based on these key temporal markers, the system's evolution can be divided into four distinct phases.

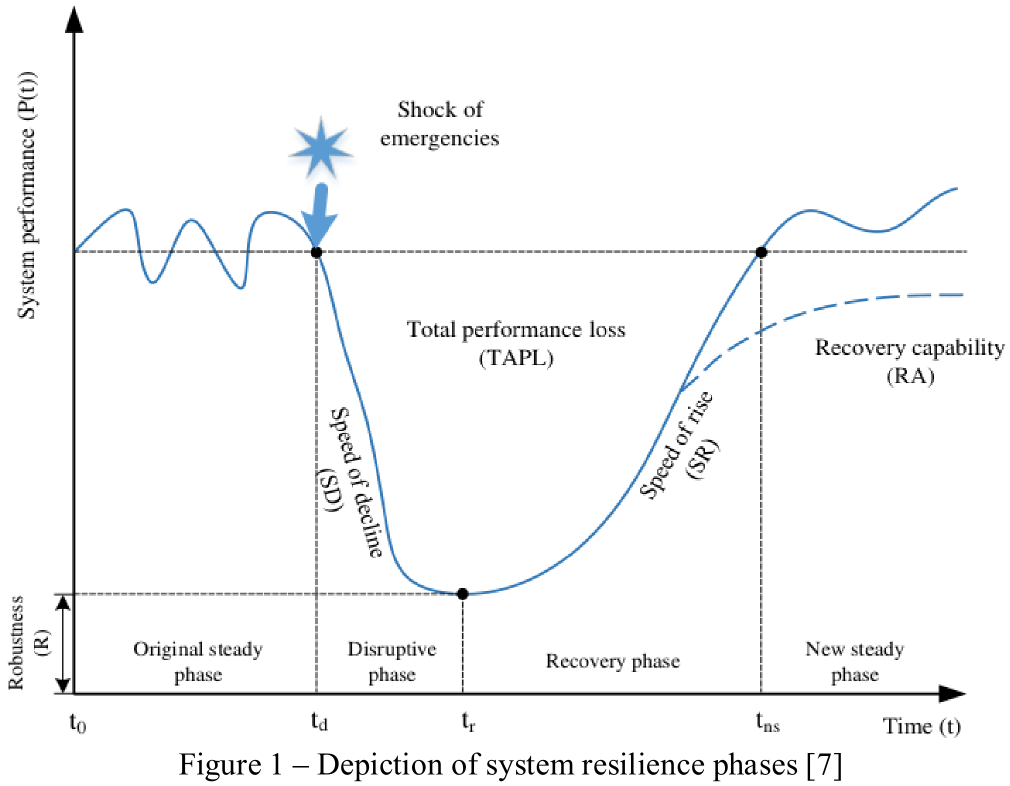

Figure 1 – Depiction of system resilience phases [7]

Рисунок 1 – Описание этапов повышения устойчивости системы [7]

Detailed breakdown of the **four stages** based on the time points t_d, t_r, and t_{ns} is:

1) the **first stage**, known as the *initial stability stage* ($t<t_d$), represents the period before the system experiences any disturbance. During this phase, the system operates under normal conditions, and its performance level is typically considered the **target or reference value**. The **average performance** during this stage can thus be used as the baseline for comparison.

2) the **second stage**, or *disturbance stage* ($t_d<t<t_r$), begins once the system is subjected to an external shock. During this period, the system absorbs the disturbance, leading to a decline in performance until it reaches its minimum level. The system's **robustness (R)** characterizes its **ability to withstand and absorb** the adverse impacts of the disturbance.

3) the third stage, designated the *recovery stage* ($t_r<t<t_{ns}$), signifies the period during which the system's performance is known to improve following a disturbance. During this phase, the system adapts and restores its functionality, progressively moving towards stability. The system's adaptive and recovery capabilities can be measured by evaluating the rate of recovery. **(SR)**—indicating how rapidly performance is restored—and the **performance loss recovery proportion (PLRP)**, which measures the extent of regained performance relative to the loss incurred.

4) the **fourth stage**, or *new stable stage* ($t>t_{ns}$), occurs once the system's performance has reached a new equilibrium level, and that this level is being maintained. This new stable state may be equal to, higher than, or lower than the original stable level, depending on whether the system fully recovers, improves through adaptation, or experiences a lasting performance degradation.

Table 1 – Key measures for determining transport system's resilience [9]
Таблица 1 – Ключевые показатели для определения устойчивости транспортной системы [9]

Indicator's Symbol	Description	Formula
R	Minimum system performance during disruption	$R = \min\{P(t)\}, (t_d < t < t_r)$
SD	Speed of Decline	$SD = \frac{1}{2}[\frac{P(t_d) - P(a)}{a - t_d} + \frac{P(a) - P(t_r)}{t_r - a}]$
SR	Speed of Recovery	$SR = \frac{1}{2}[\frac{P(t_{ns}) - P(b)}{t_{ns} - b} + \frac{P(b) - P(t_r)}{b - t_r}]$
RA	Recovery Ability	$RA = \frac{P(t_{ns}) - P(t_r)}{P(t_0) - P(t_r)}$
TI	Time of Incident Impact	$TI = t_{ns} - t_d$
TPL	Total performance loss	$TPL = \int_{t_d}^{t_{ns}} P(t_0) - P(t)\,dt$
TAPL	Average performance loss	$TAPL = \frac{TPL}{TI}$
GR	Resilience Index	$GR = \frac{R * SR}{SD} * TAPL^{-1} * RA$

The following are examples of Resilience calculations for the scenario: A major accident involving damage to the road surface and temporary traffic restrictions occurred on a section of a four-lane motorway. The total impact period lasted approximately 48 hours, encompassing the initial emergency response, the clean-up operations, and the partial restoration of traffic flow. Subsequent to this, a period of normalisation lasting between one and two days was necessary for traffic patterns and driver behaviour to stabilise and return to normal parameters. The initial data and results of calculations using the formulas from table 1 are given in tables 2 and 3, respectively.

Table 2 – Initial data
Таблица 2 – Исходные данные

Time (hours)	Stage	System Performance P(t), [%]	Description
0	Normal operation	100	Normal traffic conditions before the incident
2	Disturbance onset (t_d)	80	Start of capacity reduction due to traffic accident
6	Minimum performance (t_r)	35	Peak congestion and network disruption
18	Recovery phase	70	Partial reopening of lanes and temporary repairs
30	New steady state (t_{ns})	97	Traffic conditions stabilized to near-normal level

Table 3 – Results
Таблица 3 – Результаты

Indicator	Formula	Result	Units / Meaning	Interpretation
R	R=min P(t)	35	%	Minimum performance level during disturbance
SD	(80−35)/(6−2)	11.25	% ,per hour	Rate of degradation following the incident
SR	(97−35)/(30−6)	2.58	%, per hour	Rate of recovery after minimum performance
RA	(97−35)/(100−35)	0.95	–	System restored 95% of its lost capacity
TI	(30−2)	28	Hours	Duration of the impact
TPL	trapezoidal integration	978	%,·h	Cumulative loss of performance
TAPL	(978/28)	34.9	% ,	Average performance loss during disturbance
GR	(R×SR/SD)×(1/TAPL)×RA	0.22	Dimensionless	Comprehensive resilience index

The resilience analysis of the transport system reveals a system with strong final recovery, but with critical speed issues. While it ultimately recovers 95% of lost performance (RA = 0.95), the initial collapse is severe (R = 35%) and rapid (SD = 11.25%/h). The main weakness is the slow recovery rate (SR = 2.58%/h), which is less than a quarter of the degradation speed. This results in prolonged impairment (TI = 28 hours) and substantial cumulative performance loss (TAPL = 32%).

The low comprehensive resilience index (GR = 0.24) primarily reflects this recovery speed deficit. Rather than improving the already adequate final recovery level further, resilience enhancement should prioritise accelerating the restoration process through better response protocols and redundant systems to reduce recovery time and the overall impact.

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