Safety, Security, and Efficiency Benefits of Technology in Highway Hazardous Materials Transportation Applications

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ABSTRACT

The Federal Motor Carrier Safety Administration recently undertook an ambitious project entitled the Hazardous Materials Safety and Security Technology Field Operational Test. The objective was to use existing technologies to demonstrate an approach to enhancing the safety and security of hazardous materials transportation by highway, with the goal of speeding up deployment by the trucking industry.

Various technologies and groups of technologies were tested in four segments of the hazardous materials transportation industry and evaluated for benefits to safety, security, and efficiency, as well as benefits to public sector law enforcement and emergency response agencies. Wireless communications systems with GPS positioning provided the primary efficiency gains to motor carriers. Positive benefit-cost ratios were identified in all segments of the industry included in the test. In addition, the wireless communication system provided a baseline vulnerability reduction in the security assessment. Additional technologies used in conjunction with the base system provided incremental reductions in vulnerability levels.

The technologies were also successful in reducing notification times to public sector agencies and providing them with increased accuracy of information. These improvements identified in the notification and emergency response system may also provide safety benefits in the form of accident and incident mitigation and security interdiction scenarios.

Key words: HAZMAT—hazardous materials transportation—transportation safety
PROBLEM STATEMENT

Following the September 11, 2001 terrorist attacks on the United States, the U.S. Department of Transportation was asked to identify areas within the transportation system that were vulnerable to a terrorist attack. Hazardous materials (HAZMAT) transportation was identified as a major area of concern. There are over 800,000 shipments of hazardous materials in the United States each day. These shipments range from high-hazard shipments, such as explosives and toxic-by-inhalation shipments, to small packages of corrosives or flammables. Nearly 300,000 of the daily shipments in the United States are petroleum products by truck, amounting to nearly 3 million tons (U.S. DOT 1998).

When investigating ways to improve the security of hazardous materials transportation, the Federal Motor Carrier Safety Administration (FMCSA) within the U.S Department of Transportation identified the need to have security during all phases of the transportation cycle (pick up, en route transportation, and delivery) and in each element of the shipment (driver, vehicle, and cargo). For each of these elements, different measures may be put in place to reduce vulnerability. These include a regulatory framework, outreach and educational activities, operational and procedural changes, and the increased use of technology, which is the focus of this project.

PROJECT OBJECTIVE

The objective of the Hazardous Materials Safety and Security Technology Operational Test (FOT) was to use existing technological solutions to demonstrate an approach to enhance the safety and security of hazardous materials transportation by highway, with the goal of increasing deployment of effective technologies. The evaluation methodology presented in this paper quantified the benefits and costs of implementing these technologies in the hazardous materials transportation industry.

RESEARCH METHODOLOGY

The research methodology described below was designed for two proposes. The first was to design a system that met the deployment objectives for the project, demonstrating the functionality of the technologies tested. Second, the methodology was designed to facilitate the independent evaluation, which included the benefit-cost analysis for the use of the technologies. This section will provide an overview of the methodology used to meet these objectives.

Risk/Threat Assessment of Hazardous Materials Transportation

Twenty-five functional requirements were identified for the test. These requirements were organized around the pick-up, en route, and delivery phases of a HAZMAT shipment. However, before developing the final approach to test these requirements, an assessment of the risks and threats of various HAZMAT operations and HAZMAT supply chains was conducted. The purpose of this effort was to ensure that the areas of greatest concern (operations with the highest risks and/or vulnerabilities) in HAZMAT transportation were being addressed by the functional requirements and technologies.

The assessment began with a broad look at HAZMAT transportation, including such factors as type of material, quantity of shipment, shipment frequency, type of operation, and routing. These factors were then considered from two different perspectives: intentional (i.e., terrorist) vs. unintentional (i.e., accidental) releases. Then, reference components were established for intentional releases. The primary purpose for defining reference components was to organize, identify, and represent typical vulnerabilities. Each reference component was defined not to represent industry best practices related to security but to reflect the combination of vulnerabilities that can be readily found throughout industry.
Based on this analysis, a number of vulnerabilities were identified for different types and classes of hazardous materials and categorized into four groups: physical, operational, informational, and environmental. Further analysis was conducted to consider HAZMAT groupings from a threat-based perspective as opposed to department of transportation regulatory hazard classes and to consider different types of attack profiles on these hazard groupings. Finally, a consequence analysis was conducted to identify and rank the final set of threat and HAZMAT groupings of highest concern. This ranking was then used as a basis to select the hazardous materials and operational scenarios (based on attack profiles) to be tested.

Technology Selection

This FOT was not a technology development activity, but was rather an integration of existing technologies that could address the specific functional requirements. Listed below are the major technological components tested.

- Tracking technologies
  - Wireless satellite or terrestrial communications (with GPS)
  - Geo-fence mapping software
  - Tethered trailer tracking
  - Untethered trailer tracking
- Panic buttons (in-dash and wireless)
- Driver and cargo authentication
  - Global login
  - Biometric identification
  - Electronic supply chain manifest (ESCM)
  - Electronic seals
- Intelligent onboard computers (OBC)
  - Vehicle disabling (remote, local, and loss of signal)
  - Remote locking and unlocking
- Public sector reporting center concept

Technology Tiers

It was recognized early in the FOT that the unique operational characteristics of many of the hazardous materials carriers around the country would not lend themselves to a full-scale deployment of all the technologies described above on every vehicle. To represent these concerns of the market, the FOT team separated the various technology components into six technology tiers, ranging from a low-end cost of approximately $250 per vehicle to a high-end cost of approximately $3,500 per vehicle. See Table 1.
Table 1. Technology tiers

<table>
<thead>
<tr>
<th>Tier (cost)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ($250)</td>
<td>Includes a digital cellular phone with pickup and delivery software with on-phone/on-board directions/mapping; on-site vehicle disabling with the wireless panic remote</td>
</tr>
<tr>
<td>2 ($800)</td>
<td>Includes terrestrial communications with in-dash panic button</td>
</tr>
<tr>
<td>3 ($2,000)</td>
<td>Includes satellite communications with an in-dash panic button and global login</td>
</tr>
<tr>
<td>4 ($2,500)</td>
<td>Includes all of what is in Tier 3 but adds the additional OBC; the other variant includes satellite communications with an in-dash and wireless panic button with biometric authorization, and e-manifest</td>
</tr>
<tr>
<td>5 ($3,000)</td>
<td>Includes satellite communications with an in-dash and wireless panic button with biometric authorization, e-manifest, and an additional OBC; the other variant is swapping the OBC for an untethered trailer-tracking device</td>
</tr>
<tr>
<td>6 ($3,500)</td>
<td>Includes satellite communications with an in-dash and wireless panic button with biometric authorization, e-manifest and e-Seals</td>
</tr>
</tbody>
</table>

The price estimates by tier reflect only the hardware installed on the truck in commercial quantities for the vendors involved in the test. It does not reflect the price of servers and dispatch systems, since this can vary widely depending on customer preferences. In addition, the price estimates reflect the cost of an initial installation (assuming no technology previously installed on the truck). A more comprehensive discussion of the costs is included later in the discussion of the benefit-cost analysis.

Scenario Development

The final step in developing the concept of operations for the FOT was to match up each technology component with a testing scenario. The scenarios were developed to address the functional requirements, threats, and vulnerabilities identified in the threat/risk assessment and the desire of the team to test a wide range of technologies across a range of business types. A summary is shown in Table 2.

Data Collection

Both quantitative and qualitative data were collected to support the technology-based and system-based evaluations. Qualitative data was derived from on-site observations and personal interviews during the FOT. Information was gathered on such topics as the operational effectiveness of the technology, customer satisfaction, and institutional challenges. For example, drivers were asked about the ease of use of the various technologies and how adding the technology impacted their daily operations. Quantitative data was collected through system-generated archived reports, which provided ongoing data collection of use and performance of technology applications throughout the FOT.
Table 2. Technology components by scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Technology components</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bulk fuel delivery</td>
<td>• Wireless satellite or terrestrial communication</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Global login</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• In-dash and wireless panic button</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• On-board computer</td>
</tr>
<tr>
<td>2</td>
<td>LTL high-hazard</td>
<td>• Wireless satellite or terrestrial communication</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Global login</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• In-dash and wireless panic button</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Wireless panic button</td>
</tr>
<tr>
<td>3</td>
<td>Bulk other</td>
<td>• Wireless satellite communications</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Biometric authentication</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• In-dash and wireless panic button</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Electronic supply chain manifest</td>
</tr>
<tr>
<td>4</td>
<td>Truckload explosives</td>
<td>• Wireless satellite communication</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Biometric authentication</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• In-dash and wireless panic button</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Electronic supply chain manifest</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• On-board computer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Wireless electronic cargo seal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Geo-fencing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Untethered trailer tracking</td>
</tr>
</tbody>
</table>

KEY FINDINGS

The following section describes the three impact areas analyzed: safety, security, and efficiency. The safety impact area was combined with work relating to the public sector, as the goals of both areas are the same: prevention and mitigation of incidents. An overview of the unique methodology for each impact area is also provided.

Security Benefits Assessment

Methodology

The security benefits were measured primarily in terms of the measured reduction of vulnerability, using the following basic vulnerability assessment formula:

\[
\text{Threat} \times \text{Vulnerability} \times \text{Consequence} = \text{Cost}
\]

Threat is primarily a function of terrorist aims and operating procedures. This factor was based on the work completed during the initial threat/vulnerability assessment and held constant in this analysis. Measuring vulnerabilities was accomplished with the assistance of an expert panel that included representatives of industry trade associations, government experts, and security and counterterrorism professionals. The expert panel assisted in recruiting a wider group of experts to serve on a Delphi panel. Two rounds of Delphi questionnaires were undertaken, one to look at the vulnerabilities and threats before the application of the technology solutions, and one to look at the same vulnerabilities and threats after the application of the technologies.
A technique designed to arrive at a consensus regarding an issue under investigation, the Delphi method consists of a series of repeated interrogations, usually by means of questionnaires, of a group of individuals whose opinions or judgments are of interest. After the initial interrogation of each individual, each subsequent interrogation is accompanied by information regarding the preceding round of replies, usually presented anonymously. The participant is encouraged to reconsider, and if appropriate, to change a previous reply in light of the replies of other members of the group. After two or three rounds, the group position is determined by averaging. The Delphi method was originally developed at the RAND Corporation by Olaf Helmer and Norman Dalkey (Linestone and Tuiroff 1975).

Security Assessment Results

The security assessment considered the vulnerability reduction in the three main attack profiles identified in the vulnerability analysis: theft, diversion, and interception by load type. In all cases, the technologies provide some vulnerability reduction, starting with the core element of the wireless communications systems. The additional technologies, such as panic button and vehicle disabling, then provided incremental gains in vulnerability reduction. Table 3 provides a sampling of the vulnerability reduction achieved through the use of selected technologies. Vulnerability reductions from 0% to 10% are considered nil; from 11% to 25% are considered low; from 26% to 50% are considered medium; and greater than 50% are considered high.

Table 3. Select reductions in overall vulnerability

<table>
<thead>
<tr>
<th>Technology scenario</th>
<th>Bulk fuel</th>
<th>LTL-high hazard</th>
<th>Bulk chemicals</th>
<th>Truckload explosives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wireless communications + GPS position (base)</td>
<td>17%</td>
<td>16%</td>
<td>16%</td>
<td>12%</td>
</tr>
<tr>
<td>Driver ID + base</td>
<td>25%</td>
<td>25%</td>
<td>23%</td>
<td>18%</td>
</tr>
<tr>
<td>Panic alert + base</td>
<td>27%</td>
<td>25%</td>
<td>25%</td>
<td>21%</td>
</tr>
<tr>
<td>Panic alert + remote vehicle disabling + base</td>
<td>32%</td>
<td>32%</td>
<td>31%</td>
<td>25%</td>
</tr>
</tbody>
</table>

Table 4 provides information regarding the vulnerability numbers focusing on theft. The vulnerability reductions in Tables 3 and 4 make it apparent that the technologies are more useful for reducing the vulnerabilities relating to theft, which included hijacking, than for other potential scenarios. Table 4 provides a view of the different methodologies employed while studying the effects of the technologies on vulnerability reduction. First, the vulnerability reduction was calculated, and then multiplied by potential consequences to develop the overall benefits. Then, benefit-cost ratios were calculated on an annual basis. Finally, realizing that threat can be unpredictable and vary over time, breakeven numbers of successful attacks that needed to be prevented via the technologies to equal the costs of deploying the technologies was calculated.

The breakeven number of attacks is presented as a decision tool: if one believes that the probability of an attack (threat) is greater than the breakeven for a technology combination for a load type, and then for society, the investment in the technology combination can be considered sound. For example, preventing one attack over the three-year period would easily surpass the breakeven point in the bulk fuel scenario shown below.
Table 4. Select benefits for theft of bulk fuel scenario

<table>
<thead>
<tr>
<th>Technology</th>
<th>Vulnerability reduction</th>
<th>Benefits (000,000)</th>
<th>Benefit-cost ratio</th>
<th>Breakeven point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wireless communication with GPS (base)</td>
<td>23%</td>
<td>$622</td>
<td>1.5</td>
<td>.108</td>
</tr>
<tr>
<td>Base + driver ID</td>
<td>40%</td>
<td>$933</td>
<td>2.1</td>
<td>.117</td>
</tr>
<tr>
<td>Base + panic button</td>
<td>42%</td>
<td>$955</td>
<td>2.3</td>
<td>.114</td>
</tr>
<tr>
<td>Base + panic button + vehicle disable</td>
<td>52%</td>
<td>$1,207</td>
<td>2.6</td>
<td>.123</td>
</tr>
</tbody>
</table>

While the technology combinations tested show promise for reducing the vulnerabilities of truck-based hazardous materials shipments, the Delphi panelists and the test participants provided a clear message that not all solutions are foolproof. Their responses also indicated that not all solutions perform the same in a dynamic real world environment in which human and technology failures can occur and where the adversary is looking for new ways to subvert security efforts. The implementation of technology is only one part of a thorough security strategy, and the results show that technologies can have an impact on vulnerability reduction and therefore improve security.

Efficiency Benefits Assessment

Efficiency Benefits Assessment Methodology

The operational efficiency assessment examined return on investment (ROI) by using the formula

\[ \text{ROI} = \frac{\text{Total Benefits Achieved}}{\text{Total Investment Costs}} \]

The motor carriers’ primary viewpoint for operational efficiency is focused mainly on the ability to communicate efficiently with drivers, know where vehicles are located and to be able to manage these assets, track driver and vehicle operating performance, and plan loads more efficiently. Two different methodologies were employed. For the bulk fuel and LTL pick-up and deliver scenario, a driver productivity model was found to be most appropriate. Analysis of the other scenarios focused on an ROI model measuring the following direct benefits to motor carriers:

- Reduced telecommunications costs
- Increased driver-dispatcher ratios
- Reduced on-the-road downtime, which translates into potential load increases or trips
- Reduced fuel consumption and engine wear
- Reduced maintenance costs and increased revenue through decreased repair downtime
- Reduced miles

Efficiency Assessment Results

The operational efficiency assessment shows a positive benefit-cost ratio in all fleet segments that were part of the FOT, with a high-end ratio of 7.2:1 for a truckload explosives carrier, with payback in only three months. Past surveys have indicated that the market penetration rate reaches nearly 60% if the payback period is between one and two years (ATRI 2002). The best case scenario payback in all four segments of the industry was in less than six months. The costs shown below included purchase and installation costs amortized over three years, plus ongoing messaging with hourly positioning and maintenance costs. Table 5 is a summary of the efficiency assessment.
Table 5. Efficiency assessment summary

<table>
<thead>
<tr>
<th>Operation type</th>
<th>Factors</th>
<th>Annual cost/truck</th>
<th>Annual benefit/truck</th>
<th>Benefit-cost ratio</th>
<th>Payback (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTL (pick-up and delivery)</td>
<td>Driver productivity</td>
<td>$1,188 (terrestrial GPS)</td>
<td>$1,920</td>
<td>1.6:1</td>
<td>13</td>
</tr>
<tr>
<td>Bulk fuel</td>
<td></td>
<td></td>
<td>$5,832</td>
<td>4.9:1</td>
<td>3</td>
</tr>
<tr>
<td>Bulk chemical</td>
<td>• Reduced call stops</td>
<td>$1,524 (satellite GPS)</td>
<td>$1,560–$7,116</td>
<td>1.0:1–4.7:1</td>
<td>5–34</td>
</tr>
<tr>
<td>LTL-high hazard</td>
<td>• Improved maintenance scheduling</td>
<td></td>
<td>$2,352–$9,840</td>
<td>1.5:1–6.5:1</td>
<td>3–17</td>
</tr>
<tr>
<td>Truckload explosives</td>
<td>• Reduced out-of-route miles</td>
<td></td>
<td>$1,824–$11,004</td>
<td>1.2:1–7.2:1</td>
<td>3–25</td>
</tr>
<tr>
<td></td>
<td>• Improved utilization</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

An example of the typical operational efficiency gains measured and assessed by the evaluation team under this effort is a bulk fuel motor carrier. Based on data from 19 drivers over an 11-week period, the weekly driver productivity reports demonstrated an overall increase in driver productivity of 11%, bringing the aggregate level to approximately 90% of the target the carrier had set. Based on this data, the evaluation team calculated an average savings of $5,800 per year per truck for bulk fuel carriers (versus a case of no technology).

The ROI model developed was based on actual operational efficiency data provided by three of the carrier participants. In addition to the overall efficiency assessment, to explore the low-end efficiency benefits the project drew on previous work that indicated that not all carriers were able to gain benefits in all areas. For those areas where this situation pertained, a minimum benefit was calculated, with benefits shown as a range. For example, all carriers may not be able to generate additional revenue by hauling an additional load or by adding another truck to their fleet. The annual costs defined in Table 5 include the costs of hardware and installation, amortized over three years (1/3 hardware costs) plus service fees for a year.

Safety and Public Sector Benefits

Overview

Although the primary focus of this project was to look at the technology from the perspective of the private sector user of the technology, some effort was also spent conducting testing with public sector agencies. Three functional requirements involved public sector agencies:

1. Hazardous materials driver identification and verification by roadside safety enforcement officers
2. Hazardous materials cargo route adherence by the dispatcher and roadside safety enforcement officers
3. Real time emergency alert message notification by the dispatcher

In addition to using the technologies that were already part of the test to study the interaction between the public sector and the on-board technologies (specifically, satellite communications, global login, biometric login, electronic supply chain manifests, geo-fencing and panic buttons), a new technology concept, the “public sector reporting center,” was developed by integrating the data into a single database. This allowed users of the data to specify when they would like alert messages and how they would like them.
receive them. For example, an agency could specify that it would like alerts when an unauthorized driver alert is generated for a vehicle carrying hazardous materials. This message was then delivered via phone, e-mail, fax, or to a wireless handheld device as specified by the user. In addition to the public sector users, it was also shown that the individual trucking companies had a need and desire for this capability.

**Evaluation Methodology**

The public sector evaluation effort focused on two hypotheses:

1. The response times for emergency and enforcement personnel to respond to a hazardous materials safety or security incident can be improved through the implementation of the technologies and the public sector reporting center operational concept.
2. The quality of information provided to first responders will improve through the implementation of these technologies and the reporting center operational concept.

The qualitative interviews with the public sector participants were used to collect information concerning the quality and timeliness of information provided by the technologies tested. Additional information was gathered to determine user perceptions of effectiveness and appropriateness to the enforcement operational environment. Tailored testing and staged events were used to assess whether the systems met the functional requirements and quantify and qualify the improvements in alert notification timeliness.

**Results: Response Time Improvements**

The first hypothesis is accepted based on the data generated from field testing at the four on-site locations and comments from law enforcement and emergency response personnel. The following is a summary of the results, organized according to the functional requirements tested with the public sector.

**Driver identification**

Typically, without the use of technology, driver identification takes from 30 minutes to 2 hours and may require a trip to the local police station. Biometrics and global login allow on-site verification in minutes.

**Route adherence**

Motor carrier estimates for locating an off-route vehicle range between four and eight hours, while electronic geofencing identified the situation in approximately one hour based on standard positioning rates, which could be increased if necessary based on carrier needs and the sensitivity of the load.

**Panic alerts**

According to the Center for Technology Commercialization (CTC), the best estimate for notification time (including exact location information) to state police agencies in the event of an incident is 27 minutes. The CTC serves as NASA's Northeast Regional Technology Transfer Center, covering the six New England states plus New York and New Jersey. The CTC acts as a gateway for the transfer of NASA and other federal technology to private industry. The CTC's Public Safety Technology Center is an informational clearinghouse focused on the development and uses of advanced technologies that can help reduce violent crime, promote officer safety, and impact public safety's ability to effectively combat crime and respond to terrorist threats. Other sources, including the COMCARE alliance and Operation Respond, indicate an elapsed time of 20 minutes. The FOT technologies performed this task at a maximum time of two minutes, showing a potential savings of 18 minutes for alert notification and
location information. In some cases, material type was included with the alert as well, further enhancing response capabilities.

Results: Hazardous Materials Information Improvements

The second hypothesis was also accepted based on the data discussed above. The following is a summary of the results organized according to the functional requirements tested with the public sector.

Driver identification

The biometric and global login provides accurate, truthful information about a driver during roadside inspection activities. With laptop access in remote locations, law enforcement can verify driver identity and, with ESCM capabilities, ensure that the correct driver is associated with the correct vehicle/cargo.

Route adherence

Wireless communications and geofencing provide direct, timely, and accurate data on the location of a vehicle. The PSRC approach gave exception-based alerts to law enforcement by whatever means they chose, and it functioned quickly and reliably. The alerts included all available data, including GPS position and manifest information.

Panic alerts

Panic buttons provide an effective way to transmit emergency event information directly to law enforcement through the PSRC and provide the exact location of the subject vehicle utilizing the GPS position.

CONCLUSIONS

The core enabling technology, wireless communication systems with GPS positioning, is the technology that showed the primary operational efficiency gains. Productivity gains in terms of increased personnel and asset utilization are found to outweigh the costs of deploying the technology with a payback on investment in less than one year in many cases. With the proven reliability of the technology in the market place and the appropriateness of application to a wide range of fleets, significant industry net benefits could be realized through full deployment. Even with attractive ROI and low payback periods, however, full deployment is likely to be a long-term scenario.

Moreover, this core enabling technology also provides significant security benefits, through the reduction of identified vulnerabilities. The implication is that the wireless communication system with GPS has the capability of more than covering its costs to motor carriers while providing a significant security benefit to society. The remaining technologies, while providing considerable potential security benefits (societal benefits), do not provide direct operational efficiency benefits to the motor carriers.
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The views expressed herein are those of the authors and do not reflect the opinions of the U.S. Department of Transportation, the FMCSA, or the other organizations involved. Status updates and reports can be found at the FMCSA (website www.fmcsa.dot.gov) and at the project team website (www.safehazmat.com).

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