ON TECHNOLOGY READINESS LEVELS AND THEIR APPLICATIONS

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ABSTRACT

In today's competitive environment, companies develop projects involving new technology in order to keep up with rapidly changing environmental conditions and technological developments, to reach their strategic goals, and sometimes to lead these changes. However, the uncertainties and risks involved in the use of immature technology in these projects may cause increases in the project cost or a timeout in the project period. In order to avoid the uncertainties and risks that directly affect the quality of the project, the use of the immature technology that is under consideration should be systematically evaluated. For this purpose, a measurement system has been developed to systematically determine the Technology Readiness Levels (TRLs). In this study, the TRL measurement system is introduced and TRL processes for sample application projects are examined in detail.

Keywords: *Technology management; Technology readiness levels; Project management.*

INTRODUCTION

When rapid change in science and technology is considered together with today's competitive environment, companies use "Technology Management" in order to keep up with the environmental conditions and technological developments or to lead these changes [1]. Technology management is also used not only to establish the connection between management and technical expertise but also to transfer and market technology; in technological planning, designing, and manufacturing; and R&D. In this context, companies need to act effectively depending on the sub-disciplines of technology management in order to develop, manage, control and coordinate their technological capabilities and to achieve their operational and strategic goals. Within this scope, with the use of technology roadmaps, it is possible to plan the technology-product-market relationship by formulating technology strategies within the target time and utilizing them to create products.

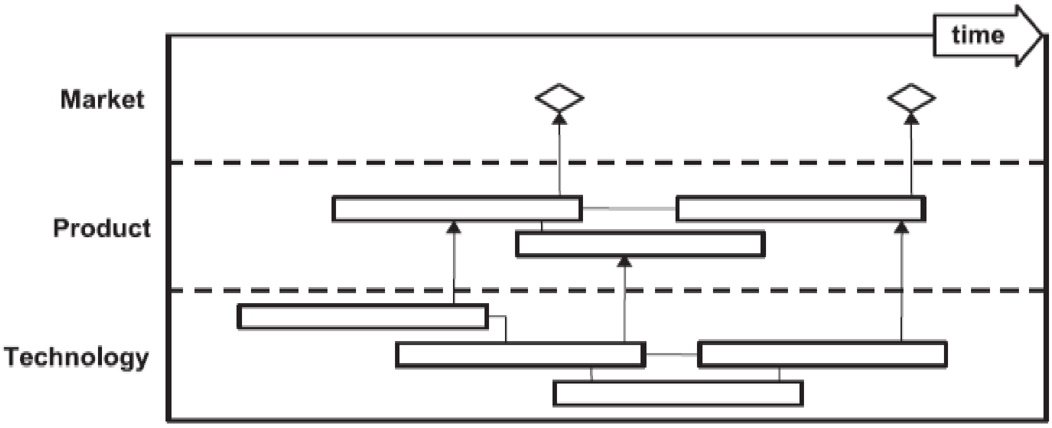

Figure 1. Technology Roadmap [2].

Technology roadmaps show technologies that will be needed for the target market and product. The use of new technologies in creating these products can provide many benefits in areas such as cost advantage, performance increase, customer satisfaction, ease of production, and brand reliability. However, it is often necessary to carry out technology development studies in order to integrate technological developments into products. Because resources are limited, technologies that are proposed for use in the project should be systematically evaluated via technology development studies for the success of the project. Otherwise, the new technology may not comply with the goals of the system into which it will be integrated. Often technology infusion causes delays, cost overruns, and sometimes even cancellations or breakdowns in the project plan. In order to prevent these events, it is necessary to follow the technological developments meticulously and to evaluate the technology.

To evaluate technology, it is necessary to first evalutae the maturity of the technology then its technology development difficulty. Before the project plan is made, the technology development plan, risk assessment, cost plan, and technology assessment should be done. In addition, technology evaluation is a process that must be repeated at different stages of the project as well.

The term technology readiness was first used in NASA (US National Aeronautics and Space Administration) resources in the 1960s [3]. However, in those years, this term was used to express the flight readiness of widely developed systems. In the 1970s, the term Technology Readiness Level(TRL) began to be used to indicate system or technology maturity levels [4-5].

Technology Readiness Levels (TRLs)

The TRL method, which was first prepared by NASA and directly contributed to the success of many projects, has been recommended by the US General Accounting

Office (GAO) for technology procurement and development processes since the 1990s and has been used in many important projects since 1999 [6]. The TRL is a systematic measurement system that offers the opportunity to compare technologies with their maturity levels [3]. The TRL basically creates a common language for R&D studies carried out with technology push and market pull technologies [4-5]. This metric has also been used in many projects involving new technologies in defense industry companies, white goods companies, government agencies and research institutes in recent years [7].

The TRL system, which was first mentioned in the article in 1989, by its pioneer, Stan Sadin [8], contained seven levels [9]. In 1990, the system was revised to include nine levels and in 1995, John Mankins revised the nine-level TRL system to provide a limited definition of each level and success criteria [3]. These levels are shown in Table 1 [3, 10].

Table 1. Technology Readiness Levels [3].

TRL1	Basic principles observed and reported
TRL2	Technology concept and/or application formulated
TRL3	Analytical and experimental critical function and/or characteristic proof of concept
TRL4	Component and/or breadboard validation in a laboratory environment
TRL5	Component and/or breadboard validation in a relevant environment
TRL6	System/subsystem model or prototype demonstration in a relevant environment
TRL7	System prototype demonstration in a space environment
TRL8	Actual system completed and “flight qualified” through test and demonstration
TRL9	Actual system “flight-proven” through successful mission operations

It is not possible to understand the size and scope of a project without clearly revealing the TRL level of all the elements of the system. Determining the TRL of the new technology proposed for use in the project is the first step on the road to project success. Determining TRLs has been wrongly characterized as a difficult and pointless process primarily due to the ambiguity of terminology such as “relevant environment” which is widely misunderstood. For this reason, the TRLs and level definitions shown in Table 1 are simply not sufficient to accurately determine the TRL. The TRL can be determined easily and accurately by following the flow chart

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shown in Figure 2 and considering the correct queries with an expert evaluation team [11].

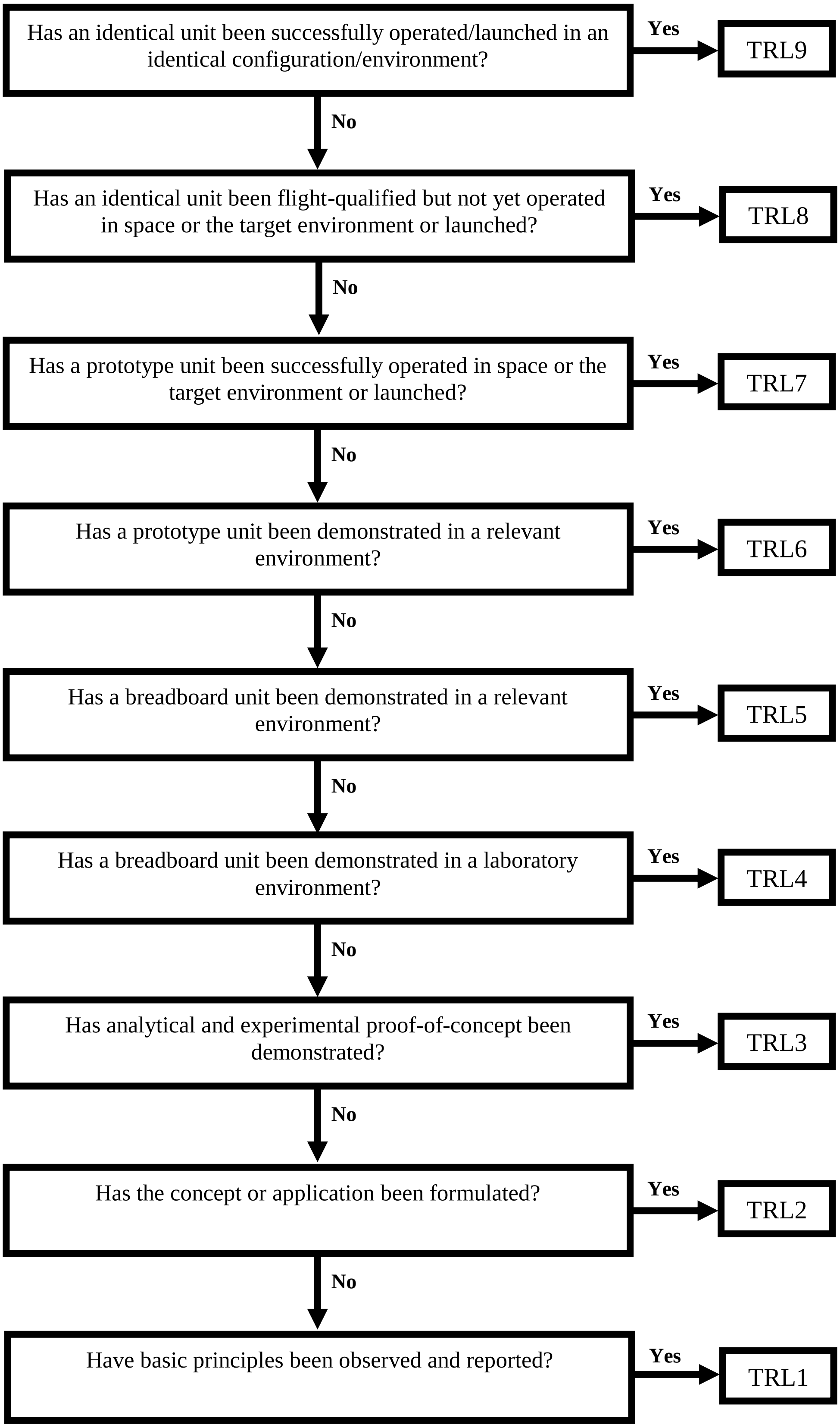

Figure 2. The Technology Maturity Assessment Thought Process [11].

Detailed definitions of the technology readiness levels defined by NASA and application examples for definitions are shown in Table 2 [12].

Table 2. Detailed Descriptions of Technology Readiness Levels [12].

TRL	Explanation	Practice
TRL1	It is the transition process from scientific research to applied research. The basic features and behaviors of systems and architectures have been detected. Descriptive tools are mathematical formulations or algorithms.	Discovery and reporting of a new synthetic rubber compound in the laboratory.
TRL2	It is an applied research process. Theory and scientific principles are focused on a specific application area to define the concept. The features of the application are explained. Analytical tools are developed for simulation or analysis of the application.	Determining the amount of the new synthetic rubber that this discovered rubber can be used for vehicle tires.
TRL3	Concept validation is proven. Research and Development (R&D) is initiated with analytical and laboratory studies. Technical feasibility is prepared by using experimental applications applied with representative data.	Conducting tests for durability and shaping abilities to prove that the rubber is suitable material for a tire.
TRL4	It is the process where independent prototyping is practiced and tested. Integration of technology elements is provided. Experiments are performed with full-scale problems or datasets.	The rubber is tested to see if it has suitable wear properties.
TRL5	Extensive testing of prototypes is carried out in a representative environment. All applications will be tested in a lifelike environment by integrating core technology elements with reasonably realistic support elements. Prototyping applications are suited to target environments and interfaces.	The rubber is used to create a prototype tire and is tested on a wheel.

TRL6	It is the stage where real problems encountered at full scale are applied to the representative model or prototype in the appropriate environmental environment. It is partially integrated with existing systems. Limited documentation is available. Engineering feasibility in real system application is fully demonstrated.	The tire is mounted and tested on a bumpy road. The vehicle and road used here simulate reality.
TRL7	In the operational environment, the system is prototyped and tested. The system can be used for most function demonstrations and tests. The prototype is well integrated with the supplementary and main systems.	Tire tests are done on the vehicle on a real road.
TRL8	It is the final process of system development. It is fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation have been completed. All functionality tests have been performed in simulated and operational scenarios. Verification is complete.	Certification processes are completed for the use of the tire.
TRL9	It is fully integrated with operational hardware/software systems. The actual system has been extensively demonstrated and tested in its operational environment. All documents have been completed. Success has been achieved in operational experience. Engineering support should be continued at the site of use.	The tire is tested throughout its lifetime to ensure it is safe to use.

Using TRL in Project Management

The TRL indicates the maturity of the technology or the level of readiness for transition to the system. New technologies that are proposed for use in projects should be considered by the project team and the technology readiness levels should be determined. With this method, the difficulties that may arise from new technologies utilized in the project can be predicted and kept under control.

The technology readiness level of a system is determined by the subcomponent with the lowest TRL level. In other words, if the technology readiness level of a subsystem is TRL2, the technology readiness level of the entire system is TRL2. The TRL of the system, subsystem, and components can be prepared using an evaluation matrix as shown in Figure 3. In this matrix, the rows show the system, subsystem, and components, while the columns define the categories to be used to determine the TRL [13].

TRL ASSESSMENT

(Red)	Red = Below TRL 3
(Yellow)	Yellow = TRL 3,4 & 5
(Green)	Green = TRL 6 and above
(White)	White = Unknown
X	Exists

	Demonstration Units						Environment				Unit Description				
	Concept	Breadboard	Brassboard	Developmental Model	Prototype	Flight Qualified	Laboratory Environment	Relevant Environment	Space Environment	Space/Launch Operation	Form	Fit	Function	Appropriate Scale	Overall TRL
1.0 System															
1.1 Subsystem X															(Red)
1.1.1 Mechanical Components															
1.1.2 Mechanical Systems															
1.1.3 Electrical Components					X				X		X	X	X		(Green)
1.1.4 Electrical Systems															
1.1.5 Control Systems															
1.1.6 Thermal Systems							X				X	X			(Yellow)
1.1.7 Fluid Systems		X													(Red)
1.1.8 Optical Systems															
1.1.9 Electro-Optical Systems															
1.1.10 Software Systems															
1.1.11 Mechanisms	X														(Red)
1.1.12 Integration															
1.2 Subsystem Y															(Yellow)
1.2.1 Mechanical Components															

Figure 3. TRL Assessment Matrix [13].

The US Department of Defense (DoD) generally does not use TRL4 and lower-level technologies in systems because technologies with this readiness level involve risk. The gap between technology readiness level and system requirements is defined as technology risk.

The relationship between technology readiness levels and technology risks and uncertainties is shown schematically in Figure 4 [14]. In Figure 4, TRL1, 2, 3 are the levels where technology emerges as a concept and the risk is highest since there is no proof of success.

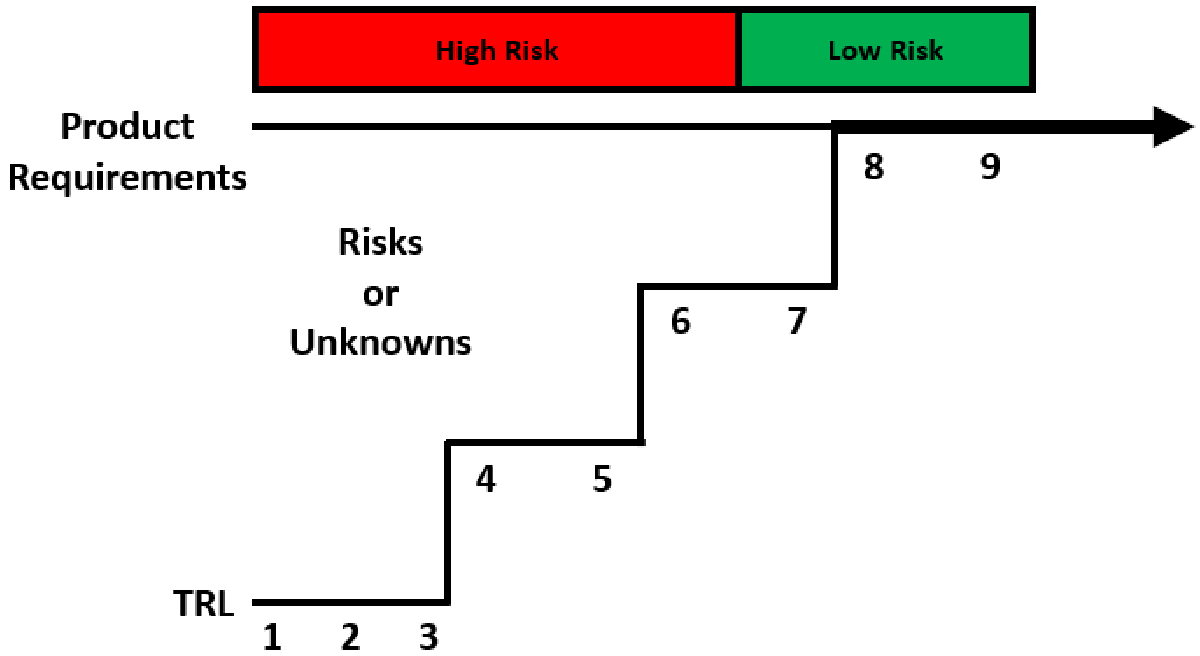

Figure 4. TRL and Technology Risks (Adapted from Ref. [14]).

The risk is lowest at TRL8 and TRL9 since technologies with this maturity have been tested and proven in a real environment. As the uncertainties regarding technology decrease, the risk decreases. In a research report of GAO, 23 technologies with different maturity between TRL2 and TRL9 are included. According to the report, technologies with a low maturity level show that they increase the overall cost of the system, do not comply with the targeted project schedule, and may even cause the performance requirements to be abandoned. In Table 3, the effects of the projects containing technology with different maturity levels in 4 different projects on the product development process are shown as cost and timeout [14].

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Table 3. Cost and Schedule Experiences on Product Developments [14].

Product development and associated technologies	TRL	Product development	
		Cost growth	Schedule slippage
Comanche Helicopter		101%	120%
Engine	5		
Rotor	5		
Forward Looking Infrared	3		
Helmet Mounted Display	3		
Integrated Avionics	3		
BAT		88%	62%
Acoustic Sensor	2		
Infrared Seeker	3		
Warhead	3		
Inertial Measurement Unit	3		
Data Processors	3		
Hughes HS- 702		None	None
Solar Cell Array 6	6		
Ford Jaguar		None	None
Adaptive Cruise Control	8		
Voice Activated Controls	8		

According to this chart, projects using technologies with less maturity than TRL6 may cause a cost overrun of over 100% and a project timeout of 120%. However, there were no cost or time lapses in projects containing TRL6 and higher maturity technology.

The DoD requires that the technology be demonstrated in the relevant environment (TRL6) before milestone B approval, due to project cost and project schedule compliance problems in projects that enter the engineering and manufacturing development phase with immature technologies [15]. Milestone B approval is an important approval point and milestone as the system development phase can begin. The use of the technology readiness metric and technology assessment tools is essential for a successful milestone B assessment. The arrangement of TRLs prepared in this sense is shown in Figure 5.

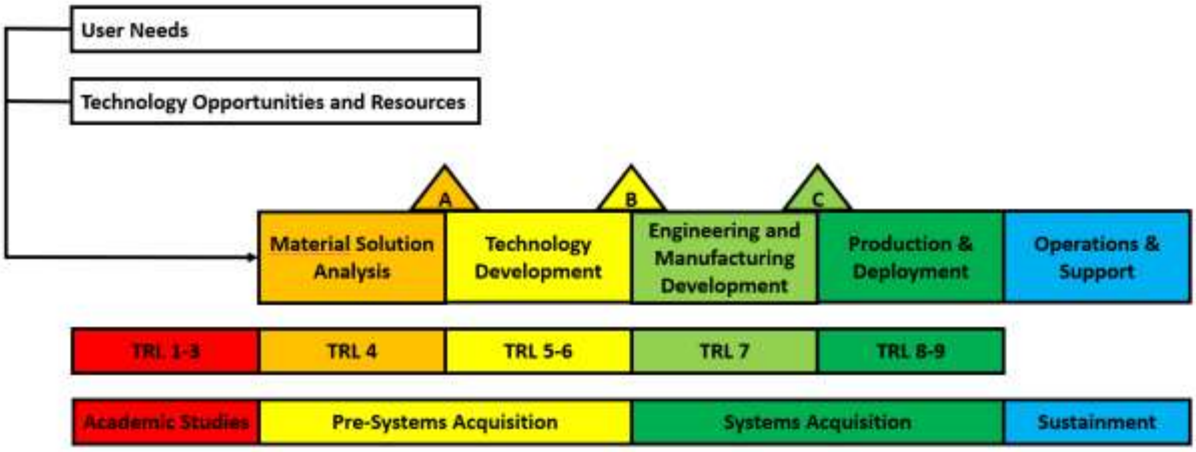

Figure 5. Technology Readiness Levels (Adapted from Ref. [15]).

The impression that milestone B approval completely separates the technology development process from the product development process is incorrect. By associating TRL7 studies with technology maturity and product requirements, product and technology are developed together. Until the milestone C approval, the technology development process and the product development process are intertwined.

Example Projects Using TRL

Since 1999, technology readiness level assessments have been carried out in many important projects and this method has had a direct impact on the success of those projects. In this study, TRL processes applied in projects of Ford and NASA companies are examined in detail.

Jaguar S-Type

In the research of GAO, the timeline of the TRLs of the technology developed by Ford for the Jaguar model is given according to the technology development. According to the report, Ford was working on voice-activated controls technology that would allow the driver to control certain functions, such as windows and the radio, with verbal commands. Market research dated 1993, concluded that with the introduction of other complementary technologies such as processor speeds and low-cost memory, customers ed more features and functions, but fewer distractions while driving. In light of this market information and recognizing the importance of being the first to market this enabling technology, it was decided to pursue voice control technology as a strategic technology for product differentiation. Figure 6 shows the timeline for the development of this technology [14].

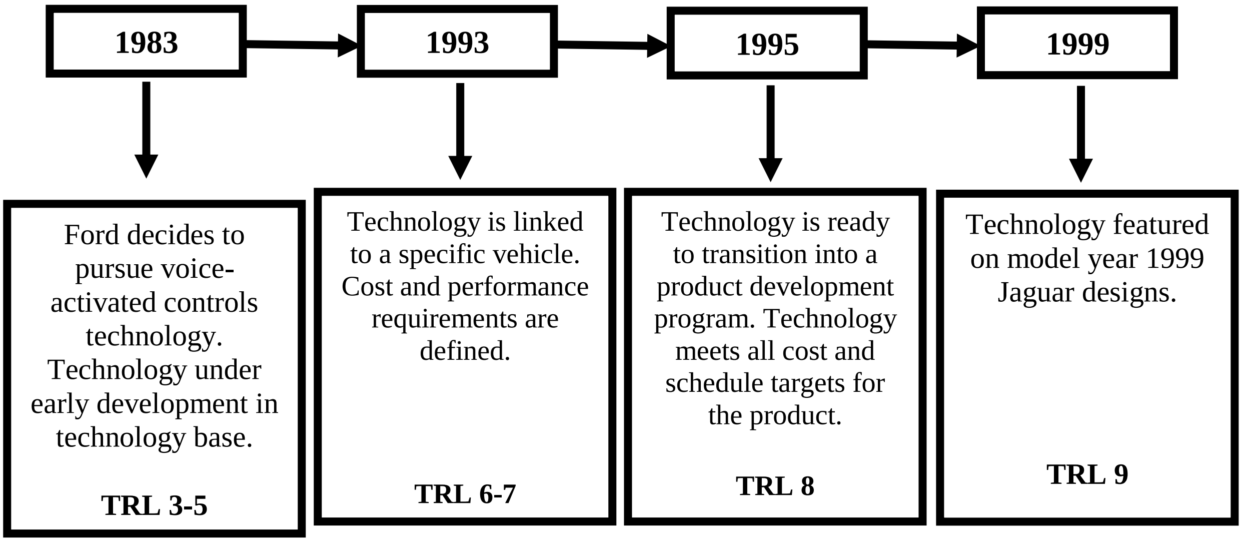

Figure 6. Timeline for Ford's Development of Voice Activated Controls Technology [14].

Between 1993 and 1994, based on conversations with customers, Ford developed cost and performance requirements for the technology. In September 1995, when Ford allowed the technology to enter the development program for a new Jaguar design, voice-activated controls were cited as an integrated system suitable for Jaguar. Ford officials stated that the product met all cost and project duration targets set at the beginning of its development [14].

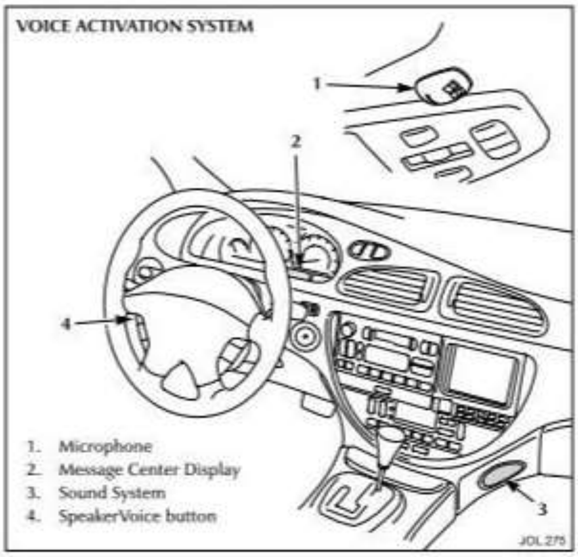

Figure 7. Jaguar S-Type Voice Activation System [16].

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Chevron Nozzle

NASA initiated the Chevron Nozzle project in the early 1980s as part of its program to improve the sound performance of jet motors. Within the scope of this project, it aimed to reduce the sound pressure by dividing the turbulence, which are formed by the mixture of the hot air coming out of the motor and the cold air passing by, with a nozzle.

In the first phase of the project, basic and academic research for nozzle design were carried out and the technology was brought to TRL2 maturity. In the early 1990s, laboratory tests were completed for small-scale nozzles. TRL5 maturity was reached by completing model tests for acoustics and aerodynamics between 1995 and 1997. Between 1998 and 2000, tests were carried out with the system prototype, the technology development phase was completed, and the technology matured to the TRL6 level.

The final design was obtained by completing the tests of the system prototype in the real working environment between 2001 and 2005. Certification processes were initiated in 2005, and lasted for 10 years, after which the Federal Aviation Agency issued the certification in 2015 and Chevron Nozzles were put on the market.

Figure 8. Chevron Nozzle Project TRL Process [17].

RESULTS AND DISCUSSION

To make the technology management of companies more sustainable, it is recommended that a technology roadmap in parallel with the product roadmap is prepared, to determine the immature technologies in the subsystems and components of the desired product, and to determine the technology maturity levels with an expert team. By doing this before the system development work of the desired product in the product roadmap is begun, the technology development studies for that product can be completed and engineering and manufacturing development studies can be initiated with mature technologies.

Today, many companies use the TRL methodology, which is a systematic measurement method, for technology maturity assessment in projects involving new technology. It is recommended that the technology maturity evaluation of the new technology that is proposed for use should be made with an expert team before the project plan in order to ensure the compliance of the projects with the targeted quality, cost and project duration.

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