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National Fuel Cell Bus Program: Advanced Generation Fuel Cell Bus Development

Final Report

PREPARED BY

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New Flyer Industries Canada

SEPTEMBER 2022

U.S. Department of Transportation
Federal Transit Administration

COVER PHOTO

Courtesy of New Flyer Industries

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C

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14. ABSTRACT
This report provides an overview of the development and demonstration of the Advanced Generation Fuel Cell Bus, a 60-ft articulated fuel cell electric bus. The bus, funded by the Federal Transit Administration (FTA) National Fuel Cell Bus Program, was developed by New Flyer and demonstrated at Alameda-Contra Costa (AC) Transit District in California. The objective of this project was to develop and demonstrate an Altoona-tested 60-ft articulated fuel cell bus in real-world service to accelerate the commercialization of this technology

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This report provides an overview of the development and demonstration of the Advanced Generation Fuel Cell Bus, a 60-ft articulated fuel cell electric bus. The bus, funded by the Federal Transit Administration (FTA) National Fuel Cell Bus Program, was developed by New Flyer and demonstrated at Alameda-Contra Costa (AC) Transit District in California. The objective of this project was to develop and demonstrate an Altoona-tested 60-ft articulated fuel cell bus in real-world service to accelerate the commercialization of this technology.

Executive Summary

The National Fuel Cell Bus Program aims to advance the commercialization of fuel cell buses that are used for transit applications. The Advanced Generation Fuel Cell Bus Development Project was funded under the National Fuel Cell Bus Program with the objectives to develop a 60-ft articulated fuel cell bus, submit it for a full FTA Altoona durability bus test, complete the testing, and operate the bus in revenue-service operations at a transit agency. The main goal of the project was to develop and commercialize an Altoona-tested 60-ft articulated bus that is Buy America-compliant.

This project was managed by CALSTART, which served as the prime recipient and overall project administrator. The project team included New Flyer, Ballard Power, Siemens, and AC Transit. The bus was built on a New Flyer chassis, and a battery storage system was installed on the bus. Ballard Power provided the fuel cell stack, and Siemens provided power electronics and controls. The bus arrived at the Altoona Bus Testing Center in July 2016 and completed testing in March 2018. The test demonstrated and documented better gradeability, faster acceleration, and lower noise than a comparable 60-ft CNG-powered vehicle.

After completing Altoona testing, the bus was delivered to Alameda-Contra Costa (AC) Transit District in California, which trained drivers and deployed the bus in revenue-service. During the demonstration, the bus accrued 4,244 miles and generated a cost of $103,263, 89% of which were labor costs. The bus achieved a fuel economy of 4.6 miles per kg of hydrogen. Development of next generation fuel cells and drivetrain components can help to further improve bus performance.

This project marks a major milestone in the development of fuel cell buses. The Advanced Generation Fuel Cell Bus is the first 60-ft articulated fuel cell bus that is Buy American-compliant and has passed Altoona testing. The Advanced Generation Fuel Cell Bus is now a fully commercialized product available for sale. The technology developed during this project accelerated the development and commercialization of New Flyer's 40-ft Xcelsior Charge H2 bus. There is growing demand for these buses; New Flyer has deployed or received orders from AC Transit, Orange County Transit, SunLine Transit, and Champaign Urbana Mass Transit District and is in discussions with other transit agencies to provide fuel cell buses.

Section 1 Introduction

The National Fuel Cell Bus Program is a cooperative initiative between government and industry to advance the commercialization of fuel cell technology in U.S. transit buses. This program focuses primarily on the commercialization of full-size, heavy-duty transit fuel cell electric buses (FCEB) through advancing fuel cell bus technologies. Goals include:

- Facilitating development of commercially viable fuel cell bus technologies
- Improving transit bus efficiency and reducing petroleum consumption
- Reducing transit bus emissions
- Establishing a globally competitive U.S. industry for fuel cell bus technologies
- Increasing public awareness and acceptance of fuel cell vehicles

This project was funded under the National Fuel Cell Bus Program to build on previous efforts to commercialize fuel cell buses. The fuel cell buses in the current demonstration programs have a price premium over other available technologies. The cost of the fuel cell system is a major contributor to that price premium. Synergized efforts are needed to reduce the cost of the fuel cell power system to facilitate the production of a fuel cell bus that can be commercialized.

This project focused efforts on redesigning the fuel cell and the power plant by using alternate materials, components, and processes that will ease manufacturing, assembly, and service as well as increase durability and overall reliability. Ballard Power Systems designed and developed a low-cost, smaller, lighter fuel cell power plant that retains power and performance. This next generation HD-7 design is based on lessons learned from the fleet of fuel cell buses operating in revenue service as well as advancements made in Ballard and supplier research and development efforts. Under this project, a next gen Ballard fuel cell design was completed and delivered. Desired outcomes of the fuel cell work in the project were to:

- Reduce power plant size
- Improve power plant life/durability
- Reduce power system cost
- Develop, evaluate, and verify performance and projected cost

Section 2

Project Objectives

The objectives of this project were the following:

1. New Flyer Industries, a premier American Bus original equipment manufacturer (OEM), and Siemens will work with Ballard Power Systems to develop a fuel cell variant of an electric drive system for the Advanced Generation Fuel Cell Bus (Adv Gen FCB). The electric drive system will be scaled-up to power a 60-ft articulated bus. The **scaled-up electric drive system, batteries, fuel cell, and H_2 storage will be integrated into a 60-ft bus** glider and tested in preparation for delivery for transit operations.
2. A key step in the commercialization of the Advanced Generation FC Bus is **to complete a full FTA Altoona Durability Bus test**.
3. After delivery and training, a transit property will operate the Advanced Generation FC Bus for 18–22 months in revenue-service operations.
4. On-road fleets continue to be necessary to advance the product development and commercialization process. The project is aimed at **moving this promising technology closer to commercialization**.
5. This work scope for a Fuel Cell Bus Build and Fleet Operations is a priority to enable commercialization and **ensure transit property choices that are "Buy America" compliant**.
6. The Advanced Generation FCB will be "Buy America" compliant and will **create a supply chain template for the bus OEM as well as subsystem suppliers** that will support future production of Advanced Generation Fuel Cell Bus, a clear path to commercialization.
7. This effort for a supply chain template can be used to develop and manufacture fuel cell hybrid buses (scalability) within a U.S. supply base, thus **generating manufacturing and high-technology jobs and enabling U.S. leadership in clean transportation systems**.
8. The project tasks involve specific actions to **improve the commercial readiness and reduce the life-cycle costs** of the technology by increasing its durability and reliability through field monitoring and ongoing development (root cause and corrective action). This project will also include accelerated on-road testing, which is critical for product development and market acceptance. The project is designed to address the key roadblocks to successfully achieving fuel cell bus commercialization, thus moving the U.S. closer to achieving the national goals of reduced traffic congestion, energy conservation, and improved air quality without sacrificing the vehicle performance that bus operators expect.

Section 3 Project Team

This project was executed and delivered by CALSTART, which served as the prime recipient and overall project administrator. New Flyer served as a subrecipient, developing the articulated fuel cell bus. Ballard Power, a world leader in fuel cells, developed its 7th generation FCveloCity fuel cell for this project. Siemens, a world leader in electric drive systems, developed the control system and power electronics for the first two-axle-drive electric bus. New Flyer served as a sub-recipient, developing the articulated fuel cell bus and coordinating the integration and testing of fuel cell, electric drive, and battery storage.

The team completed the first full FTA durability test of a fuel cell bus at the Altoona Test Track prior to delivering the bus to Alameda-Contra Costa (AC) Transit in California for in-service evaluation. AC Transit has been a leader in fuel cell bus evaluations, with a fleet of 13 buses deployed in 2010, which have now reached the end of their useful life.

Section 4

Development of Bus

Bus development centered on New Flyer's Xcelsior articulated bus chassis. As a major goal was to reduce the cost of fuel cell buses, and as the fuel cell was the most expensive component in prior fuel cell buses, it was chosen to base the drive system on a battery-electric-bus concept and use a smaller fuel cell to maintain the battery SOC (state-of-charge). Prior 40-ft fuel cell buses used a 150 kW fuel cell. Testing has shown that in most transit applications with average speeds of 10–15 mph, the average power requirement is only 20–40 kW on a 40-ft bus. Therefore, an 85 kW fuel cell is adequate for a 60-ft bus, and the fuel cell cost is reduced by 50%, provided the batteries are selected with enough power and energy to handle peak loads.

It was also decided to provide two driven axles. This solved winter traction and gear wear issues with 60-ft buses. The center drive axle chosen was the ZF AVE130, as it fits in the same space as a typical non-drive center axle. The rear axle was driven with a Siemens motor, and Siemens developed the controls and inverters to drive both axles as well as accepting the DC output of the fuel cell and boosting the voltage to match a 650-volt battery. The battery was developed by New Flyer, with battery modules and BMS (battery system) provided by A123 Systems. Ballard developed an early version of their HD7 fuel cell, and New Flyer integrated the fuel cell cooling and recovered cabin heating from the wasted heat of the fuel cell. New Flyer also developed the roof-mounted hydrogen storage system with the storage tank weight distributed over both the front and rear cars and fuel transferred across the articulated joint.

Following a period of testing, refinement, and performance evaluation, the bus was delivered to the Altoona Test Track for a full Altoona test. This was the first bus to complete durability and performance testing required for FTA funding, moving the technology forward and advancing the readiness for fleet commercialization.

Section 5

Altoona Testing

New Flyer shipped the XHE60 bus to Altoona in July 2016 for performance and durability testing. Numerous delays were experienced with obtaining on-site hydrogen infrastructure; as a result, no hydrogen fueling capability was under contract until the last quarter of 2016, and the test center experienced a significant delay getting the hydrogen fuel station up and running. The bus completed check-in and jacking and hoisting testing, but durability testing did not start as planned because of the lack of fuel. Fuel arrived early November 2016. With project slips and the fueling delay, the project was behind schedule by 12 months.

Figure 5-1 *XHE60 Bus at Altoona Test Track*

The durability test started in February 2017 and was completed in March 2018. During the 12,500-mile durability track test, which simulates approximately three years of severe service, there were no Class 1 safety-related failures. There were three Class 2 failures, requiring the bus to be towed, and there were 76 other failures requiring unscheduled maintenance. In comparison, a New Flyer CNG bus completed the Altoona test with no Class 1 or Class 2 failures and had 24 unscheduled maintenance failures. The full Altoona report #1615 can be found at https://www.altoonabustest.psu.edu/bus-list.aspx.

The durability test provided extremely valuable feedback and subsequently led to improvements in the fuel cell air compressor, fuel cell control module, fuel cell electrical system, fuel cell compressor motor, radiator, radiator cooling control system, sway bar system, and other product improvements that have now been incorporated into production released models. The Altoona test demonstrated and documented better gradeability, faster acceleration, and lower noise than a comparable 60-ft CNG-powered vehicle. Fuel economy was also recorded as 4.8 miles per kg on a CBD cycle and 7.4 miles per kg on a commuter cycle.

Section 6

Bus Performance in Service at AC Transit

Miles Accrued in Transit Service and Fuel Consumption

After Altoona testing, the bus was refurbished and prepared for in-service operations at a selected transit agency; however, for various reasons, the agency was unable to participate in the program. A significant delay occurred as New Flyer negotiated with AC Transit to assume responsibility for the in-service evaluation and while the bus was modified to meet AC Transit's operational requirements.

The in-service demonstration began in December 2019. AC Transit began using the bus to train drivers in November 2020 and operated the bus through June 2021. Over the course of the demonstration, the bus accrued a total of 4,244.3 miles. Data for daily mileage accumulated and fuel consumed are provided in the appendix.

Reliability

Reliability issues during Altoona testing included the following:

- Some bolts in the articulation joint failed; failure analysis showed that they were not torqued properly. Additional testing was done to determine if the center drive axle may have been a contributing factor, and it was concluded that load on the joint was not affected by the center drive axle.
- The bus has an optional anti-roll bar. A failure of the bar occurred, and modifications were made to increase durability. A delay occurred while a redesign and new parts were procured.
- Ballard air compressor stall faults occurred. There was a delay in durability testing due to troubleshooting this problem. Eventually, the issue was traced to a bad power supply and was resolved.
- A radiator leak occurred. This was a prototype, and the part had to be replaced.
- The radiator had adequate capacity, but the coolant control system had not been working optimally, and some fuel cell overheats occurred. Changes to the plumbing and thermostatic control valves occurred resolving the overheat problem.

Reliability issues during transit service included the following:

- Q2 2020 – The bus was taken out of service due to an operational issue with the fuel cell, and a field evaluation was conducted to resolve the issue. On July 9, 2020, the necessary parts to conduct the repairs were received, which were completed in July.

- Q3 2020 – The bus had a coolant leak requiring repair. AC Transit received the license plate for the bus, and driver training began in November 2020.
- Q4 2020 – On December 4, 2020, the bus experienced a fuel cell problem. New Flyer worked with Ballard Power to fix the issue.
- Q1 2021 – A hydrogen leak due to a high-pressure hose fitting was identified, and the hose assembly was replaced in March 2021. The fuel cell OEM recommended swapping out the fuel cell power plant to improve performance, and the unit was replaced.
- Q2 2021 – A high voltage issue was found, and battery string 1 and battery pack 1 were replaced. A Siemens recall related to the SIADIS diagnostic software was performed, which updated the operating system parameters.

Cost of Operation

During the period of operation when AC Transit had the pilot bus, the District generated a cost of $103,263 and drove the bus 4,244 miles. Staff labor accounted for about 88% of costs, at $90,715.31. AC Transit staff contributed 1,125 hours of labor towards this project after the bus was delivered and operated and maintained the bus. Staff also received training and helped manage the project. This labor was distributed between different teams at AC Transit. The breakdown of labor between the different teams at AC Transit is shown in Figure 6-1.

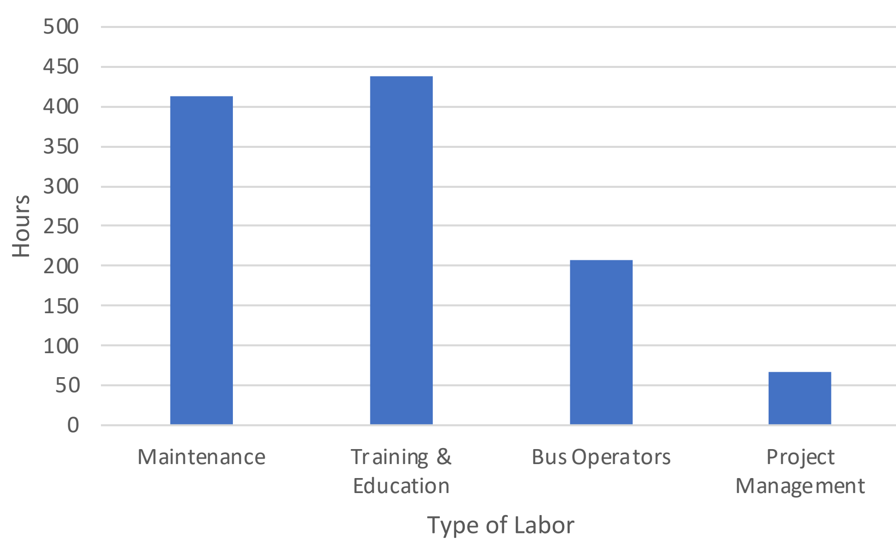

Figure 6-1 *Distribution of labor hours*

Most hours were spent on bus maintenance and repairs and for training and education for maintenance staff and bus operators. Bus operators also contributed hours operating the bus in revenue service, and AC Transit staff contributed by providing labor to successfully manage the project.

Fuel costs were also a component of the project cost. During the demonstration, the bus consumed 923 kg of hydrogen. AC Transit's levelized cost of fuel is $7.79 per kg. Over the course of the demonstration, AC Transit's total fuel costs were $7,190.

Parts costs were $5,358 for the pilot period. The majority of the parts costs was due to fuel cell maintenance and repair. The fuel cell was checked at 1,000 hours of service. Later in the demonstration, the fuel cell required some repairs. These instances were responsible for nearly half of the parts costs during the demonstration; the other parts costs were due to repairs on minor bus parts and systems, which included replacing the bus windows, changing the wheels, repairing the overhead monitor, and repairing mirrors.

In the period the pilot bus was placed in service, fuel economy averaged 4.6 miles per kilogram, with a fuel CPM (cost per mile) of $1.69; materials cost achieved a CPM of $1.26, for a combined CPM of $2.95, not accounting for labor. An AC Transit standard 2018 local 40-ft diesel bus achieves a CPM of $1.43 for labor, fuel, and materials combined. Based on the data collected, the pilot bus achieved approximately twice the cost of a 40-ft diesel bus. It is important to note that the pilot bus tested was an older generation than that currently available on the market today.

Section 7 Outreach

In 2018, the AC Transit Creative team began development of a unique livery for the bus to provide the bus with an exclusive look in alignment with the overarching Zero Emission Bus brand. The bus was then wrapped with the custom-created design in January and February 2019; a preliminary photoshoot of the wrapped bus was completed later in 2019. In 2020, a full photoshoot was commissioned to capture multiple views of the bus in a variety of landscapes. These photos were used for promotional communications. AC Transit promoted introduction of the bus into service with curated posts across AC Transit social media channels. Additionally, a fan-favorite promotional item was created—custom paper bus models of this one-of-a-kind coach were fabricated and distributed to stakeholders of the Zero Emission Bus program.

In March 2021, a 40-ft Xcelsior bus, model XHE40, a spin-off of the project, was borrowed from Sunline Transit and toured the Pacific Northwest to raise awareness of hydrogen-powered buses—the “other” electric bus.

Section 8 Steps Toward Commercialization

The Advanced Generation Fuel Cell Bus is the first articulated FCEB to be developed, pass Altoona testing, and qualify for FTA grant funding. Through this project, this bus is now a fully commercialized product available for sale. The technology developed during this project also helped to support the development and commercialization of New Flyer's 40-ft Xcelsior Charge H2 bus.

Other transit agencies are beginning to purchase these bus models. New Flyer has deployed or has on order Xcelsior Charge H2 buses for AC Transit, Orange County Transit, SunLine Transit, and Champaign Urbana Mass Transit District and has had ongoing discussions with other transit agencies to supply FCEBs.

The success of this project, the lessons learned, and the commercial orders received and anticipated are incentives to continue developments and improvements in FCEB. It is expected that Ballard's Eighth Generation FCmove fuel cell as well as improvements in electric drive systems, batteries, and hydrogen storage will further improve FCEB technology.

Section 9

Buy America

All key major components—fuel cell, electric drive system, batteries, hydrogen storage, and balance of the bus body—are now manufactured in America, creating a path to Buy America compliance for FCEBs.

Section 10

Lessons Learned

This project provided several lessons for developing FCEB technology. The project involved the coordination of multiple entities and vendors to develop and deploy this technology. Through this process, it became apparent that establishing efficient communication channels with all entities and vendors is important to resolve problems quickly.

The deployment of the bus also provided lessons for future demonstrations. Before deploying a vehicle, it is vital to understand its capabilities because deploying a vehicle on a route with an appropriate duty cycle is important to ensure that the bus demonstration is successful. It is also important to deploy the vehicle on multiple routes to gain performance data under a range of operational conditions. Also, training operators for bus deployment can be a lengthy process. For future projects, it is advisable to include additional time into the project timeline to accommodate this.

Section 11 Project Outcomes

The project demonstrated that a smaller fuel cell with an appropriate battery pack can successfully operate in many transit applications. Compared to previous deployments with 150 kW fuel cells in 40-ft transit buses, it was demonstrated that even a 60-ft bus could operate with an 85 kW fuel cell, providing a path the reduced cost of fuel cell buses. Of note is that the smaller fuel cell can maintain highway speed of only 65 mph for a limited time based on the battery pack size; therefore, specific operational requirements need to be considered.

Although not all major components at the time of manufacture of this bus were manufactured in America, the project served to develop relationships with suppliers and to incent investment, such that at the end of the program, the fuel cell, hydrogen storage tanks, batteries, electric drive system, and the balance of the bus chassis are made in America, and Buy America-compliant XE40 and XHE60 buses are currently available. It is anticipated this will lead to green-energy American jobs, as both major components and complete vehicles are now made in America.

Technical deficiencies were identified in the fuel cell compressor, electrical control, and wiring, which led to design improvements to increase reliability in current HD7 and HD8 fuel cell engines. The fuel cell stack worked flawlessly, as has been demonstrated in previous projects.

Technical and quality deficiencies in radiators, sway bars, and articulation joints led to design improvements to increase reliability if production build of current fuel cell buses.

The project resulted in the development and validation of an articulated bus with both a rear and center drive axle, improved acceleration and gradeability, axle gearing reliability, and excellent traction in winter conditions. This product is now available in both fuel cell and battery electric buses.

The project resulted in the first fuel cell bus to meet the requirements of Altoona Bus testing, qualifying the XHE60 FCEB for FTA grant funding. The project also facilitated Altoona testing of the XHE40 FCEB by reducing the amount of testing required at Altoona.

Appendix

Daily Mileage and Fuel Consumption

The daily mileage and the amount of hydrogen fuel consumed is detailed below:

Date	Miles	Hydrogen Consumption (kg)
12/20/2019	48.0	10.4
12/20/2019	2.9	0.6
1/15/2020	106.7	23.2
4/30/2020	153.9	33.5
6/24/2020	165.6	36.0
7/28/2020	38.5	8.4
8/31/2020	143.6	31.2
11/9/2020	96.5	21.0
11/9/2020	15.0	3.3
11/10/2020	279.2	60.7
11/22/2020	76.6	16.7
11/25/2020	2.2	0.5
11/25/2020	120.8	26.3
11/28/2020	89.7	19.5
12/3/2020	143.8	31.3
12/7/2020	6.3	1.4
2/10/2021	112.7	24.5
2/25/2021	15.5	3.4
2/26/2021	111.9	24.3
3/2/2021	86.7	18.8
3/4/2021	92.6	20.1
3/18/2021	79.5	17.3
3/19/2021	67.9	14.8
3/23/2021	34.5	7.5
3/24/2021	13.7	3.0
3/24/2021	62.5	13.6
3/26/2021	52.1	11.3
3/29/2021	74.8	16.3
3/31/2021	78.9	17.2
4/1/2021	39.6	8.6
4/2/2021	38.5	8.4
4/5/2021	40.8	8.9
4/7/2021	114.0	24.8
4/8/2021	37.3	8.1
4/12/2021	50.4	11.0

Date	Miles	Hydrogen Consumption (kg)
4/13/2021	40.6	8.8
4/14/2021	46.8	10.2
4/15/2021	37.7	8.2
4/16/2021	54.4	11.8
4/27/2021	31.0	6.7
4/28/2021	23.0	5.0
4/29/2021	37.6	8.2
4/30/2021	46.8	10.2
5/3/2021	38.7	8.4
5/4/2021	35.6	7.7
5/10/2021	72.3	15.7
5/11/2021	44.1	9.6
5/12/2021	36.2	7.9
5/13/2021	30.4	6.6
5/14/2021	28.6	6.2
5/17/2021	35.3	7.7
5/18/2021	27.7	6.0
5/19/2021	36.1	7.8
5/20/2021	31.8	6.9
5/21/2021	34.4	7.5
5/25/2021	48.2	10.5
5/26/2021	179.0	38.9
5/29/2021	158.8	34.5
6/1/2021	132.2	28.7
6/1/2021	12.4	2.7
6/4/2021	147.8	32.1
6/28/2021	67.4	14.7
6/29/2021	36.2	7.9

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