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Evaluation of In-Cab Air Quality for Nonroad Diesel Construction Equipment

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ABSTRACT

Previous research indicates that air quality near the cabs of nonroad diesel equipment may exceed recommended exposure limits for certain pollutants. The objective of this case study was to collect and analyze air pollutant data near the cabs of nonroad diesel equipment while performing real-world activities. Using state-of-the-art instrumentation, the research team conducted 24 tests on nine different items of nonroad equipment. The team collected data related to pollutant concentrations of carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, particulate matter, and black carbon. Average concentrations of carbon monoxide and nitric oxide did not exceed published exposure limits on a consistent basis, but their maximum values occasionally exceeded the limits. Carbon dioxide concentrations frequently exceeded recommended levels for adequate ventilation. The most concerning results belonged to particulate matter and black carbon. Concentrations of respirable particulates often exceeded recommended levels on a sustained basis. Overall, the case study yielded enough information to conclude that studying in-cab air quality in nonroad equipment cabs is necessary to reduce hazards related to human health, safety, and productivity for equipment operators.

Keywords: black carbon, carbon dioxide, carbon monoxide, equipment, particulate matter

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INTRODUCTION

The in-cab environment of nonroad diesel equipment is a result of the interaction between the machine, jobsite, climate, and other sources. The equipment itself emits diesel exhaust with pollutants including oxides of nitrogen (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), and diesel particulate matter (PM). The operator sits in close proximity to the tailpipe that emits these pollutants. Nonroad equipment operates on a wide variety of jobsites under a wide variety of conditions. Other air quality sources include exhaust from other vehicles and equipment, significant point or area source pollution near the jobsite, and operator activity such as smoking or eating in the cab.

Potential health effects of poor air quality may be both short-term and long-term for the equipment operator and other employees working nearby. Symptoms may develop shortly after exposure or, possibly, many years later. Short-term effects may occur after the first exposure or it may take many repeated exposures during a short period. Typical short-term effects include irritation of the eyes, nose, and throat, as well as dizziness, headaches, and fatigue. Although these symptoms are temporary and are easily treatable, they may interfere with the operator's ability to operate the machine in a safe manner or possibly reduce the operator's productivity. Furthermore, these effects often present themselves as symptoms of cold or flu so it may be difficult to determine whether they are the result of poor air quality (USEPA 2020a).

Long-term effects of poor air quality may manifest themselves as respiratory illness, heart disease, or cancer, which may be severely debilitating or fatal. While pollutants found in diesel exhaust are extremely harmful, there is uncertainty regarding the concentrations or periods of exposure necessary to produce specific health problems (USEPA 2020a). In fact, there are no permissible exposure limits or specific guidance for equipment operator's exposure to diesel exhaust or other harmful pollutants. A better understanding of the in-cab environment of nonroad equipment is necessary to provide safer and more productive working conditions for equipment operators.

The main goal of the research was to collect and analyze real-world data from cabs of active nonroad diesel equipment to determine the hazard exposure of the operator. The scope of the study included various items of nonroad equipment operating on various jobsites. The primary output of the study was a database of real-time information related to pollutant concentrations of carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), black carbon (BC), and particulate matter ($PM_{2.5}$). The primary outcome of the study is a better understanding of in-cab environments for nonroad equipment operators, which may ultimately lead to the mitigation of a potential health hazard.

CO is a highly toxic gas that may result in death in cases of acute exposure. Less severe health effects include headache, dizziness, fatigue, nausea, and rapid heartbeat. Nonroad equipment operators must avoid these symptoms in order to ensure a safe work zone. CO is hard to detect by equipment operators because it is colorless, odorless, and tasteless; thus, operators may begin experiencing symptoms of CO exposure without knowing that they were exposed. Although health-related publications report a wide range of exposure limits, a typical short-term exposure limit for CO is 11 ppm for an eight-hour average concentration (Health Canada 1989).

Burning fossil fuels is one of the major sources of CO_2 emissions. Furthermore, CO_2 concentrations in exhaled air from humans is higher than typical ambient conditions (Willem et al 2006); therefore, there may be elevated concentrations of CO_2 in equipment cabs due to diesel exhaust and operator respiratory activity. CO_2 is a simple asphyxiate and potential inhalation toxicant, but it is not harmful for chronic exposures (CCOHS 2020). In case of acute exposure, corresponding symptoms may include shortness of breath, deep breathing, headache, dizziness, restlessness, increased heart rate and blood pressure, visual distortion, impaired hearing, nausea, vomiting, and loss of consciousness.

CO_2 also serves as a general indicator of air quality. When exposed to high levels of CO_2, humans perceive air quality as unpleasant and unacceptable (Martoft et al 2016). Since measuring all potential pollutants in indoor areas is expensive, time consuming, and often impractical, measuring CO_2 helps determine whether ventilation is adequate. The EPA Building Air Quality Guide mentions that CO_2 levels above 1,000 ppm indicate inadequate ventilation (USEPA 1991). For construction equipment operators, personal discomfort due to elevated CO_2 concentrations may serve as a distraction and inhibit the operator's performance, which may lead to safety risks and reduced productivity on the jobsite.

NO is a colorless gas with a distinct smell. It converts readily into NO_2 in air. Inhalation of NO leads to irritation of the nose, throat, and lungs. Constant high-dose exposure leads to medical emergencies including headache, dizziness, unconsciousness, and even death (NJDOH 2009; USEPA 2016). Most regulations related to NO exposure establish permissible long-term exposure limits at 25 ppm averaged over 8-10 hours (OSHA 2018).

NO_2, along with NO, is a gas in the group of oxides of nitrogen. Adverse effects from inhalation of NO_2 are airway irritation, recurrent infection, and exacerbation of existing lung diseases such as asthma. A particular environmental hazard linked to NO_2 is reaction with atmospheric oxygen and vapor to form acid rain, which has subsequent deleterious effects on various ecosystems, such as forests and lakes. It also reacts with volatile compounds in the atmosphere to form ozone. The National Emissions Inventory (USEPA 2018) tracks emissions of NO_2. Long-term and short-term exposure limits to NO_2 range from 1-5 ppm.

Both indoor and outdoor air contain airborne particulate matter (PM), which is mostly comprised of sulfates, nitrates, ammonium, elemental carbon, organic mass, and inorganic material. In terms of size, PM contains coarse and fine particles, where fine refers to particles smaller than 2.5 μm in diameter (USEPA 2015). EPA evaluated a number of studies on short-term and long-term exposure health effects of $PM_{2.5}$ and concluded that there is a relationship between short-term exposure to $PM_{2.5}$ and cardiovascular disorders, such as heart disease and congestive heart failure (USEPA 2009). Furthermore, a relationship between $PM_{2.5}$ and respiratory infections like Chronic Obstructive Pulmonary Disease (COPD) and asthma likely exists. Mortality due to short-term exposure to $PM_{2.5}$ is often the result of the previously mentioned diseases, whereas mortality for long-term exposures is associated with lung cancer. Equipment operators are susceptible to both short- and long-term effects of $PM_{2.5}$.

BC is a major component of PM, both fine and coarse; however, it is more associated with $PM_{2.5}$ due to its smaller molecular size. BC originates from the incomplete combustion of fossil fuels and biomass. Its main characteristic is its ability to absorb light energy with great efficacy. BC absorbs light energy and later emits it as heat and it is a major factor influencing both indoor and outdoor air quality. Approximately 25% of BC emissions derive from diesel sources (Diesel Technology Forum 2020). Health impacts include cardiovascular effects such as blood pressure and heart rate variability, arrhythmias, and ischemia. Other effects are respiratory infection, distress, and difficulties, as well as depression and anxiety (USEPA 2020b).

LITERATURE REVIEW

Diesel equipment operators became at-risk health groups during the 1970s. Decoufle et al (1977) completed a study that identified high frequencies of lung and intestinal cancer in 2,190 deceased construction workers. Likewise, other studies showed a relationship between diesel exhaust exposure and liver and prostate cancer, and heart disease (Wong et al 1985; Seidler et al 1998; Finkelstein et al 2004). Although these studies recognized the negative human health effects of diesel exhaust over time, they did not focus on the in-cab environment of nonroad diesel equipment.

Pronk et al (2009) compiled a comprehensive literature review that revealed that from over 10,000 measurements collected to assess occupational exposure to diesel exhaust, none of them specifically related to equipment operators. In 2013, Hansen measured CO, NO_2, and PM in 13 different equipment cabs and concluded that none of the measured pollutants could be used as an indicator to predict other pollutants. Furthermore, Hansen correlated CO and NO_2 in-cab concentrations with the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values. He found them to be within acceptable limits; however, these limits were not specifically for equipment operators (Hansen 2013).

Organiscak et al (2013) targeted agricultural and mining activities. They measured dust and diesel particulates in four equipment cabs in two different underground silicosis mines to assess cab filtration system performance. They found that three of four cabs were adequately protected and the high level of dust in the fourth was due to a damaged filtration system. In another case study, Moyer et al (2005) tested cab filtration systems for tractors used in orchards to determine if they protected operators from regularly used pesticides; however, no conclusive result was determined. These studies focused on dust and particulates but did not address gaseous pollutants such as NO_x or CO.

Lewis and Karimi (2018) conducted a case study on diesel exhaust concentrations of NO_x, CO, CO_2, and PM for wheel loaders. They concluded that the tailpipe concentrations were many times higher than the exposure limits for these pollutants published by the Occupational Safety and Health Administration (OSHA) (USDOL 2020). Although the operator does not breathe exhaust directly from the tailpipe, the operator sits close to the tailpipe, usually for a long time. Furthermore, they referenced a previous school bus study by the California Environmental Protection Agency that concluded it is possible for vehicles to self-pollute themselves with diesel exhaust (CalEPA 2003). The case study by Lewis and Karimi helped secure another research project on this topic funded by the Center for Advancing Research in Transportation, Energy, and Environmental Health, which is the basis for the research presented here (CARTEEH 2020).

To begin characterizing in-cab air quality, Mosier et al (2017) conducted a case study for six items of nonroad diesel equipment. In this case study, concentration levels of CO, CO_2, NO_2, and total volatile organic compounds (tVOC) were measured as the equipment idled for 20-minute periods. Although no specific exposure limits for these pollutants exist for construction equipment, the measurements were compared to general industrial permissible exposure limits and other screening values. Results revealed that the expected 8-hour time weighted averages for tVOC approached or exceeded some of the published limits. Considering the equipment was idling only, and not fully active, the research team decided to collect additional data while the equipment was performing routine work in order to achieve results that are more representative of real-world activity.

The preliminary work by Mosier *et al*. led to a case study analysis by Lewis et al (2018). The objective of this case study was to collect and analyze air quality data from the cabs of nonroad diesel equipment while they performed real-world activities. Using state-of-the-art instrumentation, the research team collected data for in-cab temperature and humidity and calculated the in-cab heat index. The team measured concentration levels of CO, CO_2, and $PM_{2.5}$. Results indicated that, in some cases, the heat index exceeded cautionary levels, even in winter months. Concentrations of CO did not exceed published exposure limits, but they did approach the limits. Concentrations of CO_2 frequently exceeded recommended levels for adequate ventilation in buildings. Concentrations of $PM_{2.5}$ frequently exceeded recommended levels. In general, the case study yielded enough information to conclude that studying air quality in nonroad equipment cabs is necessary from a worker health perspective, which served as motivation for the new research presented here.

METHODOLOGY

The basic research approach was to gather data related to pollutant concentrations from the in-cab environment of nonroad diesel equipment over the course of a normal workday. This was accomplished through the use of state-of-the-art air quality instrumentation. After the data were collected, descriptive statistics were computed in order to characterize the in-cab air quality environment of the equipment.

The MX6 iBrid by Industrial Scientific was used to collect data for gaseous pollutants including CO, CO_2, NO, and NO_2. The Thermo Scientific Personal DataRAM (pDPR-1000AN) was used for $PM_{2.5}$. For BC, the AethLabs microAeth AE51 was used. All of the instruments were tested, calibrated, installed, and maintained according manufacturer's specifications. Tables 1-3 present the technical specifications for each instrument.

Table 1. Technical Specifications for MX6 iBrid

Gas	Sensor Type	Measurement Range	Temp. Range (C)	Humidity Range (%)
CO	Electrochemical	0-1500 ppm	-20 to 50	15-90
CO_2	Infrared	0-5% volume	-20 to 50	0-95
NO	Electrochemical	0-1000 ppm	-20 to 50	15-90
NO_2	Electrochemical	0-150 ppm	-20 to 50	15-90

Table 2. Technical Specifications for Personal DataRAM pDR-1000AN for $PM_{2.5}$

Specification	Range
Concentration Measurement	0.001 to 400 mg/m^3
Scattered Coefficient	$1.5x10^{-6}$ to 0.6 m^{-1}
Accuracy	-5 to +5% of reading
Particle Size	0.1 to 10 µm

Table 3. Technical Specifications for microAeth AE51 for BC

Specification	Range
Concentration Measurement	0.1 mg/m^3
Precision	± 0.1 $\mu g/m^3$ for 1-min average
Resolution	0.001 $\mu g/m^3$

Although all the equipment cabs were fully enclosed, the in-cab area of the equipment included both indoor and outdoor air. The research team placed the monitors in the cabs as close as possible to the breathing zone of the operator. The team secured the monitors inside the equipment cab in locations near the operator, such as behind the operator's seat, the rear corner of the cab, or an open side storage compartment. The team placed the monitors in the targeted equipment cab before 7:00 am and removed after 5:00 pm in order to collect data over the entire workday. The monitors collected and logged data in one-minute increments.

The case study equipment included two bulldozers, three excavators, one rolling compactor, one rotary mixer, one agricultural-type tractor, and one wheel loader. The equipment performed various construction and maintenance tasks in various locations in College Station, TX. Table 4 presents a summary of the case study equipment. Overall, 24 tests were conducted on these nine items of equipment.

Table 4. Summary of Tested Equipment

Equipment Type	Manufacturer	Model	Engine HP	EPA Tier	Tests
Bulldozer 1 (BD 1))	John Deere	700J XLT	115	3	2
Bulldozer 2 (BD 2)	John Deere	700K XLT	125	4	2
Excavator 1 (EX 1)	John Deere	450D	348	3	5
Excavator 2 (EX 2)	Volvo	EC250E	215	4	1
Excavator 3 (EX 3)	John Deere	200D	159	3	4
Rolling Compactor (RC 1)	Caterpillar	CP-563C	147	3	1
Rotary Mixer (RM 1)	Caterpillar	RM300	260	3	2
Tractor 1 (TR 1)	John Deere	8400	225	4	2
Wheel Loader 1 (WL 1)	John Deere	644K	173	2	5

After collecting the pollutant concentration data, the team computed summary statistics including minimum, maximum, and mean values. The summarized pollutant data included CO, CO_2, NO, NO_2, BC, and $PM_{2.5}$. The minimum values for all pollutants was zero, except CO_2; ambient concentrations of CO_2 are approximately 300-500 ppm. The maximum and minimum values helped interpret the results and provide an overall characterization of the in-cab environment of the tested equipment.

FINDINGS AND DISCUSSION

Table 5 summarizes the maximum and mean concentration values for CO, CO_2, NO, NO_2, BC and $PM_{2.5}$. Many regulations monitor these pollutants for their ambient concentrations; however, it is important to know if they are present in nonroad equipment cabs even if no specific regulations exist for such conditions. Moreover, the presence of these pollutants reduces overall air quality in the cabs and may pose a threat to worker health.

According to the maximum values in Table 5, the monitors detected CO in the equipment cabs in 19 of 24 tests. The maximum concentrations ranged from 4-15 ppm. Even though the mean values (which were approximately eight-hour averages) did not approach the short-term exposure limit of 11 ppm, five tests had maximum concentrations that met or exceeded this level. This implies that it is possible for the CO concentration level to increase to the point that it exceeds the eight-hour average exposure limit.

Ambient concentrations of CO_2 are approximately 300 ppm; elevated levels of CO_2 higher than 1000 ppm indicate poor ventilation and lead to human discomfort. Based on Table 5, three of 24 tests had a sustained average CO_2 concentration over 1000 ppm; however, 11 tests had maximum values that exceeded 1000 ppm. This implies that ventilation in equipment cabs may be generally unacceptable regarding air quality.

Diesel exhaust infiltration is the most likely source of NO in equipment cabs. According to Table 5, 15 of 24 tests recorded the presence of NO. The maximum concentrations ranged from 1-28 ppm. Although none of the mean values approached the long-term exposure limit of 25 ppm, two tests had maximum values of 28 ppm. This implies, however, that it is possible for equipment cabs to achieve sustained levels of NO that could exceed long-term exposure limits.

Like NO, the most probable source of NO_2 concentrations in equipment cabs is diesel exhaust from the tailpipe; however, only five of 24 tests detected any level of NO_2. Maximum values for NO_2 ranged from 0.2-0.4 ppm, which were well below the published long-term and short-term exposure limits of 1-5 ppm. Furthermore, approximately 80% of the tests did not detect any level of NO_2 at all in the equipment cabs.

A typical short-term exposure range for $PM_{2.5}$ is 0.1 mg/m^3 for a one-hour concentration. A typical long-term exposure range is 0.04 mg/m^3 for an eight-hour average (Health Canada 1989). According to Table 5, 13 of 19 tests that successfully acquired data had sustained mean values over the eight-hour period greater than the acceptable long-term exposure range. All but two of the tests had maximum values that were greater than the acceptable short-term exposure range, with values up to 17 mg/m^3. Although it is not possible to distinguish diesel exhaust particulates from dust or other particles, these results indicate that $PM_{2.5}$ has potential to have both short-term and long-term health effects for equipment operators.

Table 5. Summary of Maximum and Mean Values for Pollutant Concentrations

	CO (ppm)		CO_2 (ppm)		NO (ppm)		NO_2 (ppm)		BC (mg/m^3)		$PM_{2.5}$ (mg/m^3)	
Equipment	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
BD1	0	0.0	600	315	0	0	0	0	0.05	0.002	0.95	0.04
BD1	0	0.0	900	390	1	0.0	0.2	0.001	0.24	0.007	1.6	0.06
BD2	13	3.5	1400	557	28	10	0	0	0.00	0.000	0.38	0.04
BD2	15	6.2	600	322	17	6.3	0	0	0.10	0.004	0.19	0.04
EX1	11	0.5	1000	497	4	0.1	0	0	0.02	0.004	NA	NA
EX1	4	0.7	0	0	1	0.0	0	0	0.01	0.002	NA	NA
EX1	8	0.2	3200	1336	0	0	0	0	0.07	0.001	0.91	0.03
EX1	4	0.1	2400	1283	0	0	0	0	0.00	0.001	0.04	0.00
EX1	0	0.0	4600	1656	0	0	0.3	0.001	0.03	0.001	0.09	0.01
EX2	4	1.7	1400	432	1	0.0	0.3	0.001	0.00	0.000	0.42	0.02
EX3	8	2.3	1600	657	11	3.3	0	0	0.31	0.002	1.6	0.14
EX3	6	3.4	900	302	7	3.2	0	0	0.06	0.033	1.4	0.21
EX3	5	2.0	800	304	7	2.8	0	0	0.00	0.000	1.3	0.19
EX3	13	3.5	1400	557	28	10	0	0	0.00	0.001	0.38	0.04
RC1	4	0.5	500	300	0	0	0	0	0.02	0.001	0.30	0.11
RM1	7	3.9	400	300	2	0.3	0	0	1.86	0.016	7.0	2.7
RM1	6	1.8	500	300	3	0.3	0	0	0.07	0.002	18	0.20
TR1	11	2.1	1500	372	13	2.3	0	0	0.00	0.000	NA	NA
TR1	8	2.7	500	407	11	3.4	0	0	0.05	0.003	0.37	0.03
WL1	5	3.6	1500	672	0	0	0.4	0.238	0.01	0.001	0.29	0.03
WL1	0	0.0	0	0	0	0	0	0	NA	NA	NA	NA
WL1	10	0.3	1900	551	0	0	0	0	0.36	0.002	2.7	0.04
WL1	5	2.1	800	527	1	0.0	0	0	0.01	0.001	2.5	0.06
WL1	0	0.0	800	619	0	0	0.2	0.001	0.00	0.001	0.24	0.03

NA = Data not available

As a constituent of $PM_{2.5}$, BC concentrations are lower than those of $PM_{2.5}$. Even though there are no published exposure limits for BC, what was significant here was five tests had maximum values that equaled or exceeded the 0.1 mg/m^3 short-term exposure limit. Likewise, 10 tests had maximum values that equaled or exceeded the 0.04 mg/m^3 long-term exposure limit. Accordingly, BC has high potential to be a health hazard for diesel equipment operators.

CONCLUSIONS AND RECOMMENDATIONS

CO is a toxic gas, and in high concentrations, it may be fatal. In lower concentrations, symptoms of CO exposure include dizziness, fatigue, and decreased manual dexterity – all of which may impair the operator's ability to control the equipment. Because CO is colorless, odorless, and tasteless, operators may not even be aware of their exposure. None of the average values in the tests exceeded CO exposure limits; however, some test results approached these limits. Because CO was present in the cabs for most of the tests, and in some cases had maximum values that exceeded recommended concentrations, CO is a potential health, safety, and productivity hazard for equipment operators.

Although CO_2 is widely known as a greenhouse gas, the scientific community often overlooks it from an air quality and health standpoint. From a human health perspective, CO_2 may be fatal in extremely high concentrations, although it is extremely rare for that to occur. From an air quality perspective, CO_2 is a general indicator of ventilation conditions. The results of this research revealed that CO_2 concentrations frequently exceeded recommended levels for adequate ventilation but not for human health. Although this is primarily a comfort issue for the equipment operator, it still has the potential to serve as a distraction that may reduce productivity and pose a safety threat.

Nitrogen oxides, including NO and NO_2, are major components of diesel exhaust. Many regulations exist to limit tailpipe emissions of these pollutants; however, the nonroad equipment community knows little about their impact on air quality, especially in equipment cabs. Based on this research, results indicated that NO has potential to be a health hazard for equipment operators; however, NO_2 scarcely appeared in the results and likely does not pose as much of a threat as NO.

$PM_{2.5}$ and BC exhibited the greatest potential to be a health threat to equipment operators. Numerous tests yielded results that far exceeded both short-term and long-term exposure limits. Equipment operator exposure to particulate matter largely depends on jobsite conditions; thus, earthmoving activities that stir up large amounts of dust may be especially problematic. This topic requires more research to characterize the problem more accurately and to identify appropriate mitigation strategies.

Results of the research presented here, as well as previous research, prove that in-cab air quality is a topic worth investigating. Work to date has begun to answer questions related to who, what, and where of equipment cab air quality; however, researchers need to learn more about how and why pollutants impact air quality for equipment operators. Future research must address the primary factors that contribute to air quality for nonroad equipment operators. These factors include tailpipe pollutant emissions, in-cab air quality parameters, equipment duty cycles, diesel engine performance, operator behavior, and jobsite and environmental conditions.

Researchers must examine duty cycles of the equipment, such as idling and non-idling, to determine if equipment activity affects pollutant emissions and ultimately in-cab air quality. Likewise, diesel engine performance variables, such as engine load percentage, revolutions per minute and manifold absolute pressure, may affect pollutant emissions. Investigators must evaluate if operator behavior, such as smoking in the equipment cab, opening/closing the door to the cab, and using the air conditioner/heater in the cab contributes to in-cab air quality. Jobsite and environmental conditions, including temperature, humidity, and wind speed may contribute significantly to in-cab air quality. Researchers should synchronize these datasets and identify the relationships among the many variables, as well as identify patterns, trends, and correlations. The main purpose of future research is to identify controllable factors that to reduce the equipment operator's exposure to harmful conditions and improve worker health.

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Prefabrication in Buildings with Focus on Emerging MEP Rack Systems

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ABSTRACT

The growth in technology and automation has influenced the construction industry to explore prefabrication alternatives in building design and construction. In addition, the shortage of skilled labor is accelerating the push for the adoption of prefabrication in building industry. This paper provides an overview of the present construction market and labor trends and summarizes various levels and categories of prefabrication. It then provides detailed information on an emerging MEP prefabricated solution known as the MEP rack systems. The implementation of the MEP rack systems is discussed with the help of a hospital case study project. It concludes with the discussion on the benefits and challenges of implementing prefabrication technologies with focus on the MEP rack systems.

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PREFABRICATION IN BUILDING CONSTRUCTION

Prefabrication is the practice of fabricating building components or assemblies prior to installation and, typically at a location other than the construction site. It is the act of constructing segments of a structure in a processing plant or other assembling sites and then moving these segments to the building site for incorporation in the facility to be constructed (Kim 2009) Prefabrication has been used in construction since ancient times; however, the modern sense of the word prefabrication began in the early 1900's and has evolved greatly in recent years with the advances in technology. The later practice of prefabrication began with the more obvious items, such as interior and exterior walls, doors, and windows. More and more complex building components are now being prefabricated, even including mechanical, electrical, and plumbing (MEP) systems (Bakliwal, et al. 2020; Daniels & Syal, 2020; Electrical Contractor 2021).

The essence of prefabrication is to turn the off-site prefabrication shop as the fabrication or production point, and the construction site as the assembly or installation point. It is truly becoming an acceptable standard for construction, as it allows buildings to be constructed faster, safer, and cheaper. Many believe that use of prefabrication can provide advantage to builders and designers in this competitive and ever-changing landscape of construction (Antillón et al., 2014).

In addition, the shortage of skilled labor is further accelerating the push for the adoption of prefabrication in building construction. In recent years, the need for the labor and related resources has increased, but at the same time, we are confronting an unprecedented skilled worker shortage (Chamberlain 2019). The U.S. Department of Labor states that, as of January 2019, the US economy had 7.6 million unfilled jobs, yet just 6.5 million individuals were searching for jobs (VOX 2019).

As per Dodge Data and Analytics' Smart Market Report on prefabrication and modular construction (2020), off-site construction is attracting increased interest as the construction industry looks to improve cost, schedule, safety, efficiency, quality, and sustainability while confronting cost vulnerabilities, workforce deficiencies, and other challenges. According to a study done by the Associated General Contractors (AGC 2018), 80% of Contractors reported that they were having trouble in finding qualified craft workers. Modular Building Institute's report on the U.S. Construction Industry (2018), states that a national crisis is looming due to the dearth of skilled workers to continue to build the projects in a similar manner as in the past. As per the National Association of Home Builders (2020), more than 300,000 jobs in construction occupations are presently unfilled.

Based on the level of manufacturing and off-site assembly capabilities, there are four traditional categories of prefabrication solutions in building construction. In addition, a fifth category of prefabrication focusing on Mechanical-Electrical-Plumbing (MEP) systems is emerging rapidly (Bakliwal, et al. 2020; Daniels & Syal, 2020; Holt et al., 2021; Electrical Contractor 2021; Limbach 2021).

The first category of prefabrication can be termed as "materials," as it is the lowest form of raw materials that are manufactured in the factory and are used for construction after being transported to the site. It can be further divided into 2 subcategories:

Pre-manufactured "raw" materials – Examples include, 2x4's, floor tiles, brick, CMU, shingles, plywood, etc. While these materials are often referred to as "raw" materials and not thought of as prefabricated construction, the argument can be made that this is the lowest level of prefabrication as these materials are pre-manufactured and pre-sized in a factory and then delivered to the construction site.

Factory-made building materials – These require more processing and have a predetermined purpose. Examples include precast concrete walls, roof trusses, floor joists, structurally insulated panels, etc.

The second category is called "panelization". This refers to pre-manufactured building panels that have built-in structural, MEP, insulation, and enclosure aspects. These include exterior walls, interior walls, and roof or floor panels. These panels are complete and need only to be secured properly once in place.

The third category of prefabrication in construction is "Pre-manufactured building units or modules." This refers to entire rooms or a specialized part of houses that are built in a factory and are delivered to a construction site and placed using a crane. The most common products in this category are bathroom and kitchen modules.

The fourth category of prefabrication in construction is the entire home or unit constructed in a factory in one or multiple modules and then, delivered to the site and set on the foundation. Modular and manufactured homes are examples of this category.

An emerging form of MEP prefabrication is based on a collaborative approach to prefabrication between MEP Contractors, known as the MEP rack systems. These systems are prefabricated racks with mechanical, electrical, and plumbing systems fabricated and assembled within. The MEP components within a rack can vary based on the type of construction, but for the most part, contain ductwork, conduits, cable trays, hot and chilled water lines, and plumbing pipes.

MEP PREFABRICATION

Advances in technology have allowed Mechanical, Electrical, and Plumbing (MEP) Contractors to employ prefabrication for their systems in an integrated fashion. Building Information Modelling (BIM) has been the biggest catalyst to successful MEP prefabrication. With this new technology, MEP contractors have had success designing and prefabricating their intricate components. The modelling system components in 3D help ensure that prefabricated components will get installed without problems on-site.

A great majority of MEP prefabrication has been done at the individual contractor level - the Mechanical Contractor would prefabricate their ductwork, the Electrical Contractor would prefabricate their conduit runs, and the Plumbing Contractor would prefabricate their pipe runs. This approach works well as long as there is a high level of coordination between the separate Contractors. Individual contractor prefabrication has been quite successful up to this point, but with the implementation of collaborative project delivery methods, the overall project performance has begun to take precedence over individual contractor performance. This has led to collaborative MEP prefabrication efforts, such as the MEP rack systems. These are a result of collaborative approach among MEP contractors and has shown many benefits over individual trade contractor-based prefabrication.

Prefabricated MEP Rack Systems

As introduced in the previous section, an emerging trend in MEP prefabrication is the MEP Rack System, which is a prefabricated rack with mechanical, electrical, and plumbing systems fabricated and assembled in it. The MEP components in a rack may vary based on the type and scope of the project, but for the most part, consist of ductwork, conduits, cable trays, hot and chilled water lines, and plumbing pipes. Prefabricated MEP rack systems are usually fabricated off-site and then transported to the project site, where they can be rolled into the building and hoisted into the ceiling space. MEP rack systems are used in corridors of buildings, where MEP utilities are traditionally designed to be installed. Furthermore, the rack systems are typically 5 to 10 feet wide and constructed in 10 to 30-feet long sections, depending on the feasibility of shipping and maneuverability on the jobsite. These sections are designed sequentially, so they can be connected, and the systems can be tied together. Figure 1 shows a typical MEP rack system (Limbach, 2021 and Shaw, 2021).

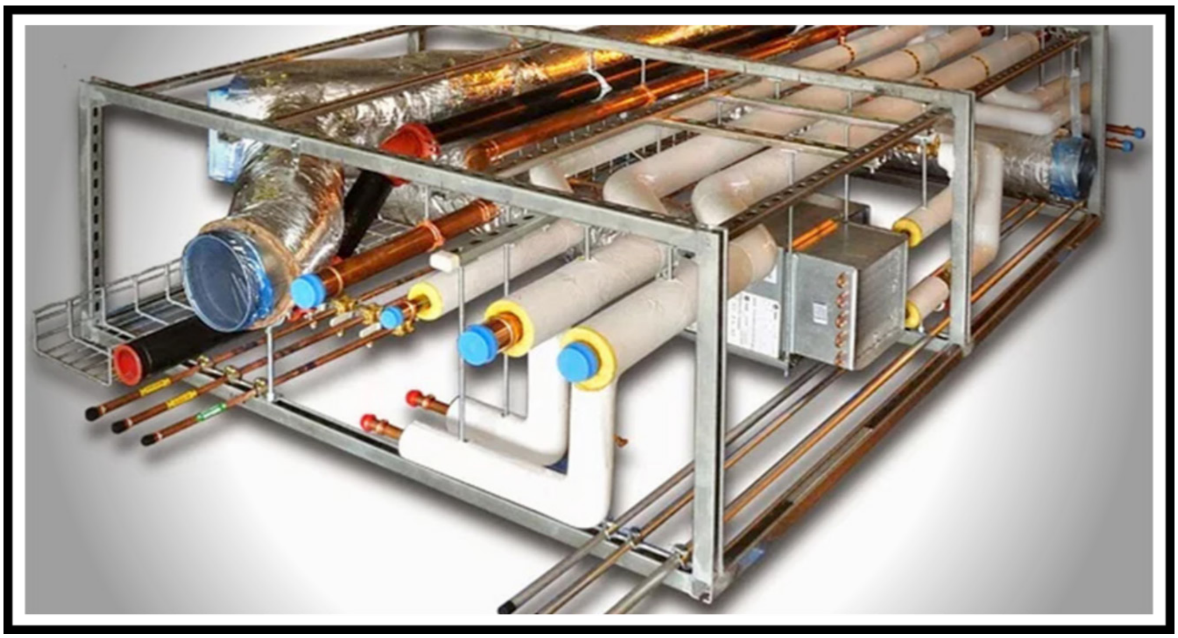

Figure 1: Typical Prefabricated MEP Rack System

MEP rack systems are a result of a collaborative approach among MEP contractors. It has many upsides to it compared to trade-level prefabrication. These upsides include increased coordination, better design, and a higher rate of success. Prior to these joint prefabrication efforts, MEP systems were primarily designed to avoid each other. A fair amount of time and effort are wasted designing and coordinating MEP systems around each other. Collaborative approaches to prefabrication between MEP Contractors have created an environment where coordination is much more meaningful, as systems are designed with each other in mind (Daniels & Syal, 2020).

CASE STUDY HOSPITAL PROJECT IN MICHIGAN

A major hospital project in mid-Michigan, where prefabricated MEP rack systems were implemented, was used as a case study project. This was a ten story, ground-up hospital project that included a medical services building and a cancer center. The newly constructed hospital consists of over 240 beds, 18 operating rooms, and state of the art specialty treatment rooms. Most of the patient rooms are located on floors four through nine, which provide an opportunity for a high degree of standardization. This standardization makes these floors a very attractive target for all forms of prefabrication including the MEP rack systems, hospital headwall assemblies, and bathroom pods (McLaren Hospital 2021; Hospital Headwall, 2021; Daniels & Syal 2021).

MEP Rack System Used in the Case Study Project

MEP rack systems were designed to be used in the corridors of similar layout patient floors, four through nine. The racks were built with a Unistrut frame with welded sections. These framed sections were 8’ 0” wide and 2’ 6” tall so as to fit the width of the corridors and between the building steel above and ceiling grid below. The lengths of the rack sections were designed to match the adjacent patient room widths, typically 20’ 0” long. That way each rack had a standard set of penetrations going out to the patient room.

MEP rack systems were supported by bolting the frames to ½” threaded rod, which were attached to concrete anchors in the slab above. The rack supports were structurally designed as the racks were heavy and the weight of the racks varied greatly throughout the corridors. The racks closest to electrical closets and mechanical shafts were the heaviest, and the racks on the outskirts of the floor were the lightest.

Each MEP rack systems had six casters on the bottom, bolted to the Unistrut frame. There were casters at each corner of the rack and a pair in the middle. These casters were added to the racks immediately after frame construction and their main role was the mobility of the racks in the shop and on the jobsite. The castors allowed for the racks to be easily moved back and forth along the continuous channeled railings that were constructed in the offsite warehouse for rack construction. Even though some racks weighed up to 3,000 lbs., the racks were easily maneuvered by one or two persons. The casters were eventually removed from the racks after the field installation.

The inner space of the MEP rack systems had one cross member, dividing the rack horizontally into two compartments. Within these compartments, there were dedicated spaces for each system and each trade, commonly referred to as fly-zones. Figure 2 shows a typical rack used on this project with various components and their weights. It contained the following provisions for mechanical, electrical, plumbing, and framing trades (McLaren Hospital, 2021; Barton Malow/ Christman, J.V., 2021; Limbach, 2021; Shaw, 2021, Daniel & Syal, 2021):

Mechanical
Ductwork for supply and return air
Ductwork for exhaust air
Piping for various systems, including medical gases
J-Hooks for HVAC controls
Electrical
Conduit for branch power
Cable tray for low voltage cabling
J-Hooks for fire alarm cabling
Plumbing
Piping for domestic water
Framing
Framed stud walls with drywall on each side

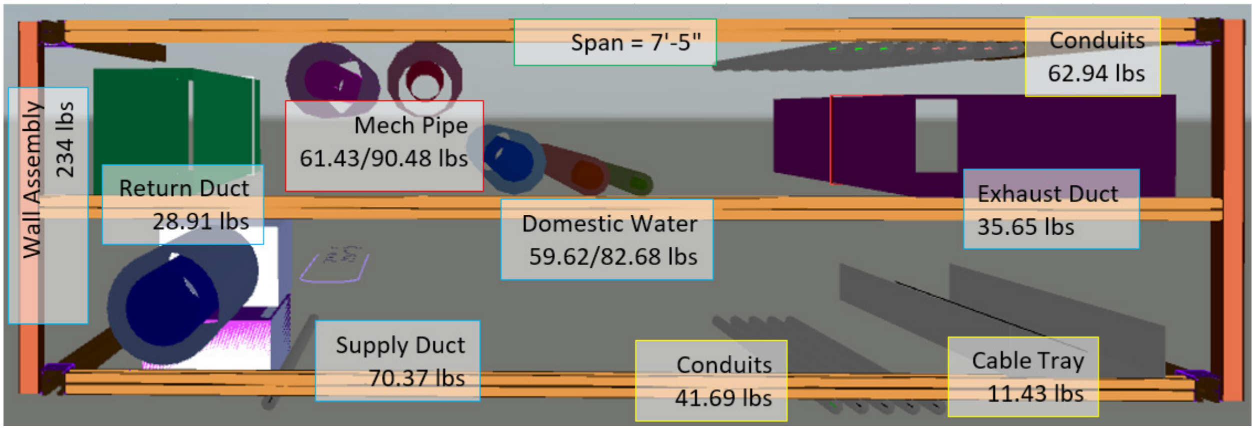

Figure 2: MEP Rack System with Components and Weights

Prefabrication Shop

Three options were considered for prefabrication shop location - to rent a warehouse close to site, to erect a pole barn on site, and to use one of the MEP Contractor's prefabrication shop. It turned out that the pole barn would have been too expensive to set up properly and would not offer enough space for mass production of the racks. The use of the MEP Contractor's prefabrication shops would not have offered enough space either and would detriment that contractor's ability for prefabrication on other projects. The offsite warehouse was selected for its close proximity to the jobsite, rental cost, and the fabrication space.

The warehouse selected was located less than 2 miles away from the jobsite, which offered flexible options in terms of scheduling and means for shipping. The selected warehouse had 20,000 sf, just large enough to fabricate an entire floor of MEP rack systems at once. The warehouse was configured with six lanes and each lane had a set of parallel rails that allowed for the racks to be constructed in a continuous row and be moved back and forth with casters during fabrication and while loading on the truck. Figures 3 and 4 show the warehouse layout. Figure 3 shows the assembly area and storage areas for different trades involved (HVAC storage area is shown as pipe & sheet metal storage) as a line drawing and Figure 4 shows the photo of the actual prefabrication shop. (Barton Malow/Christman, J.V., 2021; Limbach, 2021; Shaw, 2021; Daniels & Syal 2021).

Prefabrication Process

MEP rack systems were modelled using BIM and fully coordinated between each trade. From start to signed-off model, the entire process took around a month for each floor and resulting detailed drawings were then passed on to the fabricators. Each lane in the shop was dedicated for one specific corridor of racks. The racks were then constructed continuously along that entire lane to mimic the actual stretch of corridor. The racks were fabricated so they can be divided into 20' sections for transporting them to the jobsite.

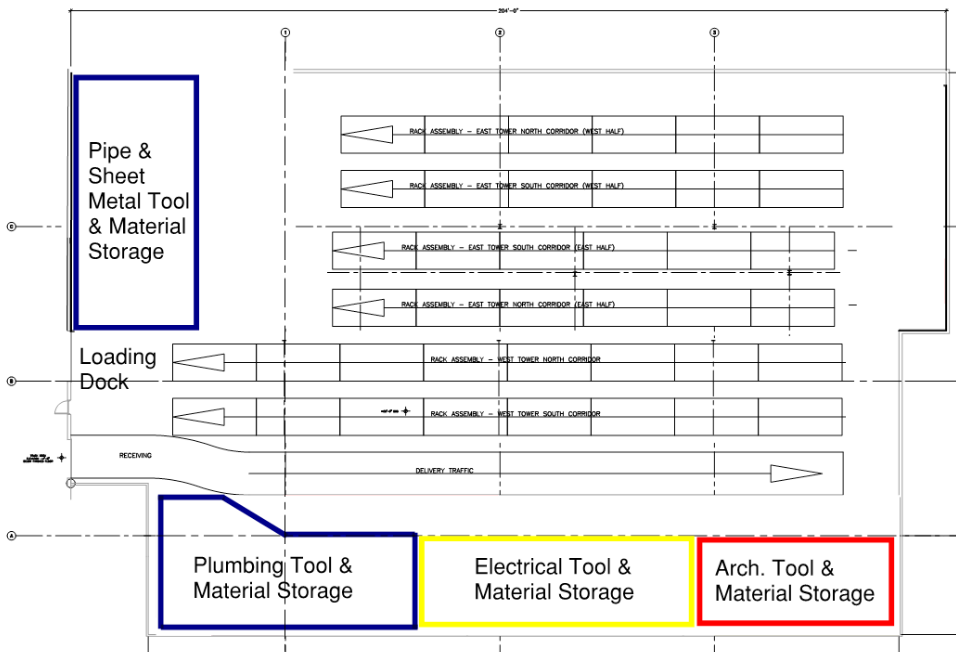

Figure 3: Warehouse Configuration with 6 Lanes of Fabrication Space

Figure 4: Prefabrication Shop

Prefabrication Process

MEP rack systems were modelled using BIM and fully coordinated between each trade. From start to signed-off model, the entire process took around a month for each floor and resulting detailed drawings were then passed on to the fabricators. Each lane in the shop was dedicated for one specific corridor of racks. The racks were then constructed continuously along that entire lane to mimic the actual stretch of corridor. The racks were fabricated so they can be divided into 20’ sections for transporting them to the jobsite.

The first step in the fabrication was to build the structure of the rack. The next step was for each MEP trade to fit out their systems one at a time. Once they were done, the architectural trades would frame out studs on each side of the rack, followed by drywall and fireproof. Overall, the fabrication of the racks was sequenced so that each trade would have around one week to complete a lane of rack.

At the beginning of the project, it was estimated that the first batch of the racks, for the fourth floor, would take around forty-five working days or two calendar months to build. It was also estimated that the subsequent racks will take less time due to the learning curve. As projected, the first batch took around forty-five working days to complete, and the subsequent floors averaged around thirty-five working days per floor.

Transportation

A local trucking and rigging company was used for the loading, transporting, and hoisting the MEP rack systems. Two racks could be loaded onto a forty-foot open-top semi-trailer at once, using a small four-ton carry-deck crane (Figure 5). The jobsite had a ninety-ton capacity crane to unload and hoist the racks with a boom that extended up to 140' that reached up to the ninth floor (Figure 6). The racks were hoisted up and rolled to the floor space underneath their final position in the ceiling space. An average of eight to ten racks were delivered per day, taking around a week to deliver an entire floor of racks (Daniels & Syal 2021, Shaw 2021).

Field Installation

Once the MEP Rack Systems were ready to be installed, a team of six to eight workers would each operate a hand winch lift truck on each rack section to hoist the rack to the deck above. The hanging threaded rods from the deck above would thread through the slotted sections of the racks, and the racks would then be bolted to the rods (Figure 7).

Figure 5: MEP Rack Systems Loaded on the Semi-Truck at the Fabrication Shop

The hanging of the racks for the fourth floor took around 3 weeks, but as the learning curve kicked in, the construction team took around 2 weeks to hang the racks on each of the subsequent floors.

After securing the racks to the corridor deck, the final step to complete the installation was to couple conduits, ductwork, and pipes between the rack sections. This was the most challenging aspect of the rack installation due to limited working space. The installation team took around one month for coupling the racks on each floor (Daniels & Syal 2021, Shaw 2021). Overall, the field installation process went mostly conflict-free.

Figure 6: MEP Rack Systems being lifted at Site

Figure 7: Installed MEP Rack System

BENEFITS AND CHALLENGES OF USING THE MEP RACK SYSTEMS

The authors first conducted literature review and then, were involved in observations and informal interviews on the case study project, to compile a list of benefits and challenges of incorporating prefabricated MEP rack systems on a building project (Antillón et al. 2014; Barton Malow/Christman, J.V., 2021; Daniels & Syal 2021; Electrical Contractor, 2021; Holt et al., 2020; Limbach, 2021; McLaren Hospital, 2021; Shaw, 2021). The authors had access to quantities and estimated labor costs of the electrical contractor on this project, therefore, the benefits and challenges are mainly presented from the electrical contractor's perspective, however, these are generally applicable to other MEP contractors also. The following sections summarizes both categories.

Benefits

Cost Saving: The MEP rack systems provide measurable cost savings when compared to conventional on-site construction methods. The leading contributor to cost savings is the increased labor efficiency which is achieved as a result of the integrated design of the racks, controlled work environment of the prefabrication shop, and the ergonomics of the work space.

The case study hospital project recognized some real labor savings by using MEP rack systems versus what was estimated based on conventional methods. The electrical contractor had over 20,000' of electric metallic tubing (EMT) conduit and 2,500' of cable basket tray to run on floors four through nine. Based on this work scope, labor hours were calculated for the installation using the conventional methods versus the rack systems. Table 1 below summarizes the Electrical Contractor's estimated labor hours versus actual expended hours, and the resulting savings in labor costs. The Electrical Contractor's estimate was developed based on the National Electrical Contractor Association's (NECA) Manual of Labor Units (MLU) difficulty category of normal difficulty (NECA 2020). Using the NECA labor factor score sheet, the hospital project would rank on the upper end of the difficulty spectrum because, in the case of healthcare projects, there is typically a large amount of density of MEP systems above ceiling that usually is not the case on other building projects. As illustrated in Table 1, the electrical contractor used only 2,735 labor hours instead of 4,058 labor hours required or only 67% of the hours required to install an equivalent system using conventional construction methods, resulting in $82,754 of labor cost savings (Daniels & Syal 2021).

Table 1: Estimated Labor Cost vs Actual Labor Cost

Activity Description	Estimated Labor Hours	Added Difficulty %	Adjusted Labor Hours	Expended Labor Hours	Labor Hour Savings	Labor $/Hour $62.55
Tower Fourth Floor Overhead Branch Conduit-Prefab	501.10	24%	621.36	570.00	51.36	$3,212.82
Tower Fifth Floor Overhead Branch Conduit-Prefab	681.60	24%	845.18	354.00	491.18	$30,723.56
Tower Sixth Floor Overhead Branch Conduit-Prefab	447.70	24%	555.15	319.00	236.15	$14,771.06
Tower Seventh Floor Overhead Branch Conduit-Prefab	520.50	24%	645.42	450.00	195.42	$12,223.52
Tower Eighth Floor Overhead Branch Conduit-Prefab	342.40	24%	424.58	328.00	96.58	$6,040.83
Tower Ninth Floor Overhead Branch Conduit-Prefab	342.40	24%	424.58	434.00	-9.42	-$589.47
Tower Fourth Floor Cable Tray-Prefab	87.50	25%	109.38	66.00	43.38	$2,713.11
Tower Fifth Floor Cable Tray-Prefab	87.50	25%	109.38	64.00	45.38	$2,838.21
Tower Sixth Floor Cable Tray-Prefab	74.70	25%	93.38	63.00	30.38	$1,899.96
Tower Seventh Floor Cable Tray-Prefab	87.50	25%	109.38	23.00	86.38	$5,402.76
Tower Eighth Floor Cable Tray-Prefab	48.00	25%	60.00	36.00	24.00	$1,501.20
Tower Ninth Floor Cable Tray-Prefab	48.00	25%	60.00	28.00	32.00	$2,001.60
				Totals	**1,322.77**	**$82,739.14**

Total Savings - Labor Hours and Cost			4,058	2,735	1,323	$82,754

Time Saving: The next most obvious benefit of prefabricated MEP Rack Systems is the time or schedule savings. The fabrication of these racks essentially diverts a substantial amount of labor hours to an off-site facility. The MEP rack systems for the case study project were fabricated just prior to installation on site, but theoretically, these racks can be fabricated much before that. As calculated in the cost saving section above, the electrical contractor used only 2,735 labor hours instead of 4,058 labor hours required or only 67% of the hours required to install an equivalent system using conventional construction methods. This schedule savings is simply due to the efficiency of installation. By comparing the adjusted estimate labor hours versus the actual labor hours spent, as shown in Table 2, the MEP rack systems saved 8.3 weeks or 2 months of total time (Daniels & Syal 2021).

Table 2: Schedule Savings due to Installation of MEP Rack Systems

Total Adjusted Estimate Labor hours	4058
Total Expended Labor Hours	-2735
Labor Hour Savings	1323
Typical Crew (4 workers x 40 hours/week)	160
Schedule Savings (weeks)	**8.3**

Safety: Perhaps one of the more under looked benefits of prefabricated MEP rack systems is the increased safety. A large part of the safety benefits is due to the work environment in the prefabrication shop. In the case study project prefabrication shop, each rack was assembled on railings, essentially placing the rack at bench height versus working on a ladder, scaffold, or on a scissor lift, if assembled conventionally in the field. These field working positions are inherently more dangerous and put workers at a higher likelihood of injury. Another major benefit of working on the railing system at the bench height is that it allowed for much more installer-friendly ergonomics which impacts the long-term occupational health aspects of the installers. Finally, the prefabrication shop provides a controlled environment providing workers a bright, warm, and dry workplace instead of the cold and wet conditions associated with long Michigan winters.

Not all safety benefits were realized in the prefabrication shop. The project site safety also benefited indirectly from the reduced traffic of workers and equipment in the congested spaces in rooms on building floors. On this case study project, the electrical contractor had zero safety incidents over the course of MEP rack systems fabrication, transportation, and installation.

Conflict-Free Installation: The MEP rack systems facilitate a more efficient and coordinated approach to installing above-ceiling MEP systems as the sequencing of above-ceiling systems installation is an area that needs improvement as the current methods can be chaotic and inefficient. Although projects have schedules outlining the major activities of MEP trades, they are usually not detailed enough to capture the intricate and unique installation that these systems require. In general, the trade that is highest in the ceiling space is installed first, then the next highest trade, and so on but this approach does not always work conflict free. The prefabricated rack systems can alleviate potential for such conflicts.

MEP rack systems are mostly designed with the use of BIM. Coordinating building components in 3D has improved field productivity immensely. Most clashes between building system components are mitigated in BIM long before there is an actual clash on the jobsite. The use of BIM has not only increased field productivity, but it has also brought attention to the final design of the above-ceiling systems including the ease of future maintenance, addition of components, and future renovation.

Quality: Each trade has their own “fly-zone” on the MEP rack systems that can standardized for all the racks. As a result, each trade has a long continuous run with their systems. Whereas on conventional installation, each system would have many offsets in their runs, in order to dodge other systems that got into the coordination model before them. This coordination aspect leads to better fabricated systems and also enhanced efficiency during construction. In addition, it will lead to easier maintenance on any of the MEP systems as the maintenance staff will be able to easily identify the systems due to their fly-zones and be able to trace and replace systems with ease due to the long continuous runs and minimal offsets.

The assembled product quality is generally found to be much higher on the MEP rack systems, due to the ergonomics in the prefabrication shop. The workers produce much better-quality systems when installing at bench height and in the controlled conditions of the shop as compared to unfavorable site conditions and working in the air, either on a ladder, scaffold, or on a scissor lift.

Collaborative Project Teams Participation: MEP rack systems allow MEP contractors to participate on collaborative project teams. There is a major shift in construction towards collaborative project approaches with faster schedule timelines. These faster timelines usually mean that actual construction is starting to take place long before designs are finalized. Increasingly, MEP Contractors are brought on as design-assist partners to collaborate with designers to help design and layout their systems. By implementing these rack systems, MEP contractors can better assist with such collaborative design process. This collaborative approach can be beneficially utilized in a variety of delivery systems.

Challenges

Alongside the above-noted benefits, the use of prefabricated MEP rack systems on building projects can provide few challenges. The major challenges are summarized below.

Additional Costs: Before deciding on prefabricated MEP Rack Systems for a project, a thorough cost analysis should be performed. Although the racks are shown to have significant cost and schedule savings, there are a few added direct and indirect costs that should be considered, especially if a separate prefabrication shop needs to be established. The shop related costs include - facility rental, space fit-out to make it a functional and efficient prefabrication shop, and cost of additional supervisory staff. The fit-out may include building the rack lanes, installing power for welders, providing adequate lighting and thermal controls, and organizing the storage space. In addition, costs for added trucking, handling, lifting, and rigging of the racks should also be considered. Another indirect cost factor that should be considered is the added involvement of the contractors' staff, the architects, and the MEP engineers due to additional coordination meetings and design reviews.

Transitioning from Concept to Design to Installation: During the design and the installation process, there can be additional challenges that may be faced by project teams with MEP rack systems.

Sizing the MEP rack systems: In order to achieve most efficiency of prefabrication, standardization of size and layout is the key. On the case study project, the most standardization that the team was able to achieve was by sizing each MEP Rack System according to the size of the adjacent rooms, therefore, making each rack 20' long.

Size limitations of the prefabrication facility and maneuvering of the racks

Size limitations of transporting the racks and whether or not wide load or other special permits are needed.

Size limitations on the project site: On the case study project, one limitation was found related to installation sequencing. It was determined that for easy maneuverability of installation, the racks would have to be delivered prior to any stud walls going up, therefore, this constraint was included in the schedule.

Coordination around various structural components: On the case study project, few oversized columns and beams posed a challenge for fitting the footprint of the racks above ceiling and below the building steel, and that led to some offsets and saddles in the conduits, ductwork, and other piping.

MEP contractors and their components not included in the rack: Sometimes one or more MEP contractors are not involved in the design of the racks and, therefore, their components are not included on the racks. This causes additional work to fit their components in and around the racks. On the case study project, fire suppression was not included in the early rack design decisions. By the time they were able to participate, the rack designs were completed but the designers and MEP contractors were able to adjust the depth of the racks so that fire suppression would have enough space to run their lines below the racks.

Design Changes: As with anything that is prefabricated, late design changes can be a major challenge and this aspect is critical with MEP rack systems. If major design change occurs after the rack is fabricated, e.g., ductwork is upsized, the structural components of the racks may need to be disassembled and other trades would have to remove and rework their components.

Similarly, if a particular component needs to be changed for any reason, it may cause the disassembly and reassembly of a rack, leading to potentially additional costs.

Additional Quality Controls: Additional quality controls need to be in place for each batch of the MEP rack systems. For example, the racks need be checked after loading at the shop and after transportation to the job site to ensure no damage had incurred during the shipment.

Coordination and Roles of MEP Contractors: Perhaps one of the more complex challenges is the coordination and roles of the MEP contractors. On the case study project, the main aspects related to this category were - who is the lead, who is responsible for the structural components, how to share the cost of common components, and the communication between contractors' personnel.

Field Installation and Learning Curve: The last challenge of implementing Prefabricated MEP rack systems is getting used to the new way of doing things for the workers. Initially many workers may feel out of their comfort zone because the racks are a different way of doing things compared to what they have been used to. However, they soon realize that the installation is still done with the same means and methods as traditional install, just done in a different sequence and environment. As a result, the workers may take additional time to learn and get used to the work in initial stages before the learning curve kicks in.

SUMMARY

The paper presents an overview of the prefabrication in building construction. With the advances in automation in construction, BIM technology, and shortage of onsite skilled labor force, prefabrication in building construction is on the path to high growth. This paper focuses on an emerging trend in the MEP prefabrication, known as the prefabricated MEP rack systems. MEP rack is a prefabricated rack with various mechanical, electrical, and plumbing systems fabricated and assembled in it. In this paper, MEP rack systems prefabrication and installation aspects are discussed in detail with the help of a case study hospital project. It further discusses the benefits and challenges of designing, fabricating, and installing MEP rack systems. The benefits include potential for savings in cost and time, and for improved safety, collaboration, and quality. Since this approach allows MEP contractors to participate on collaborative project teams, it provide an interesting area of future research of investigating the ways to effectively utilize this collaboration in different project delivery systems. Overall, MEP rack systems are rapidly emerging an important part of the MEP design and construction on building projects.

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Stick Built vs. Panelize Wall/Truss Framing For New Home Construction: A Time Study Labor Comparison.

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ABSTRACT

Due to many trends in the construction industry (material cost increase, labor shortages, supply chain issues, pandemic, market demand outpacing supply), the homebuilding industry is looking for alternative ways to frame homes. In response to the National Housing Endowment (NHE) Request for Proposal, the researchers reviewed the literature on the housing market's current state regarding the scale and scope of the skilled construction framers shortage and the current market share of single-family framing method; stick-built vs. panelization. Working with industry partners, the team analyzed time studies for multiple new home builds. It was found that panelized wall framing systems save labor hours and reduce cycle times vs. stick-built framing for building homes. But due to the framing labor shortages in many markets and how homebuilders purchase framing labor ($ per sf), homebuilders struggle to see cost savings due to the increased framing efficiencies, so they are hesitant to make the switch. Due to the varying regional cost of materials, labor, and logistics, a home builder needs to fully explore the total cost of ownership for their market to make a switch from stick-built to a panelized construction system.

Keywords: Wood Framing, Stick Built, Panelization, Cycle Times

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INTRODUCTION

Due to many trends in the construction industry (material cost increase, labor shortages, supply chain issues, pandemic, market demand outpacing supply), the homebuilding industry is looking for alternative ways to frame homes (McCoy, Koebel, Sanderford, Franck, & Keefe, 2015; Mosa Alomran, 2019; Nanyam, Sawhney, & Gupta, 2017; Tavares, Soares, Raposo, Marques, & Freire, 2021)but the overall environmental and cost trade-offs between the two construction methods are unclear and influenced by the choice of the structural material. A life cycle assessment was carried out to compare two constructive systems (prefabrication and conventional. These disruptive factors force the housing industry to seek innovative ways to build homes (Usher & Burgett, 2019). The National Housing Endowment (NHE) submitted a Request for Proposal to analyze the alternative home framing methodologies. The goal was to investigate current stick-built framing methodologies compared to panelized and modular construction and their impacts on the homebuilding industry. In response to the NHE RFP, the researchers reviewed the literature on the housing market's current state regarding the scale and scope of the skilled construction framers shortages and the current market share of single-family framing method; stick-built vs. panelization vs. modulization. The scope of this paper is to summarize the findings specific to the labor time comparisons for stick-built vs. panelization construction.

REVIEW OF THE LITERATURE:

Scale and Scope of the Skilled Labor Shortage

A significant component of increased construction costs is a lack of skilled construction labor. The labor shortage is not a new phenomenon. For decades, builders have felt strapped for skilled labor (Allmon, Haas, Borcherding, & Goodrum, 2000; Chini, Brown, & Drummond, 1999). The U.S. Chamber of Commerce Commercial Construction Index 2019 Q1 shows 81% of firms ask skilled workers to work longer hours, 70% struggle to meet deadlines, 63% have to increase costs, and 40% reject new projects(Contractor Mag, 2019). During the Great Recession, home construction decreased significantly, generating a 26.8% overall decrease in employment, and 22 states experiencing a decline of 30% or greater. In addition, in the Great Recession, residential building construction (-262,000 jobs) and specialty trade contractors (-945,000 jobs) lost their jobs. Many of those who left the industry either retired or switched industries completely. This left a large misalignment with the current supply and demand for skilled labor. The next wave of skilled workers to replace those retiring is nowhere to be found (Scopelliti, 2014). With a historically low national unemployment rate, many employment opportunities exist which do not require college degrees or manual labor. Yet younger workers prefer the safety and ease of non-physical labor jobs. Whether in extreme heat or cold, working outside does not appeal to most (Bigelow, Zarate, Soto, Arenas, & Perrenoud, 2019; van Eck & Burger, 2019). In addition, the safety hazards of commercial construction steer people away. The movement towards construction phases being completed in a factory makes the job safer and working conditions more appealing, which is why many builders are wanting to construct as many parts in a factory before heading onsite (Bertram et al., 2019).

A framers' core job duties are to precisely measure, cut, and assemble the framing lumber needed to build residential buildings (Korpella, 2019). In a 2015 Associated General Contractors of America (AGC) survey, 73% of participants stated difficulty finding qualified carpenters for framing. The duties of a framer include constructing major permanent and temporary structural components of buildings. From this, it is reasonable to conclude there will be significant consequences for the construction firms that fail to obtain enough qualified framing carpenters (Nally, 2018)it can be detrimental to the system as a whole. A critical component to residential construction is skilled craftspeople. Without them, there can be no significant physical work completed on any residential project. Currently the component of skilled craftspeople in residential construction is in a state of short supply. Throughout the United States, there is an inadequate amount of craftspeople to fill the demand for their skills. The Central Coast of California is experiencing this issue much like the rest of the nation is, however there are special circumstances to consider. The location and demographics of the Central Coast exaggerate the shortage and the framing trade in this region is taking a particularly hard hit. Framer shortages are crippling residential projects in the area due to the especially critical nature of the work. Solutions to this issue are not easy and they will not happen overnight, but not all hope is lost. With careful thought, short-term and long-term solutions for the skilled framer shortage can be successfully executed in the Central Coast of California (Nally, 2018). In this study, Nally focused on the skilled labor shortage in the Central California coast, specifically a job site in Templeton, CA. The framing construction cost increased from 9% to 42% due to the developer going through three framing subcontractors, affecting the timeline by three months. Although certain market factors of central cost California might make it more prevalent, developers across the country face similar problems. These cost increases and construction delays ultimately drive up consumer prices and squeeze developers' margins (Nally, 2018)it can be detrimental to the system as a whole. A critical component to residential construction is skilled craftspeople. Without them, there can be no significant physical work completed on any residential project. Currently the component of skilled craftspeople in residential construction is in a state of short supply. Throughout the United States, there is an inadequate amount of craftspeople to fill the demand for their skills. The Central Coast of California is experiencing this issue much like the rest of the nation is, however there are special circumstances to consider. The location and demographics of the Central Coast exaggerate the shortage and the framing trade in this region is taking a particularly hard hit. Framer shortages are crippling residential projects in the area due to the especially critical nature of the work. Solutions to this issue are not easy and they will not happen overnight, but not all hope is lost. With careful thought, short-term and long-term solutions for the skilled framer shortage can be successfully executed in the Central Coast of California (Nally, 2018).

Current Market Share of Framing Methods

Panelized construction is a construction technique that builds engineered floor systems, interior & exterior walls, and/or roof trusses in a factory rather than onsite. These rough framed products are delivered to the home construction site to be assembled. Builders fit these pieces together and then add the other essential elements such as plumbing and electricity. The advantages of panelized construction include cost reduction from mass production, lowering construction time through the ease of assembly, requiring a lower worker skillset, quality control, higher workplace safety, and less construction wood waste generated. The disadvantages include high factory capital cost, increased costs for planning and design, engineering requirements, and market perceptions (National Association of Home Builders, 2019).

Data on panelized and modular housing market share is limited due to the lack of consistent definitions of both panelized and modular housing across studies. According to NAHB economist Dr. Robert Diez and the Census Bureau Survey of Construction data, 97% of homes built in North America utilize stick-built framing. Before the Great Recession, modular (4%) and panelized (3%) represented 7% of the market share of homes framed offsite, compared to stick-built. After the recession, the combined market share dropped to 3% (Dietz, 2018).

If panelized construction can be reproduced at a high volume for the same product, then the upfront costs and time can justify panelized construction. A panelized building can be utilized on components of the structure rather than the complete build, leading to greater market adoption. Figure 1 below represents the percentage of residential builders planning on using prefabricated construction for each construction system in the next year or five years, starting in 2019.

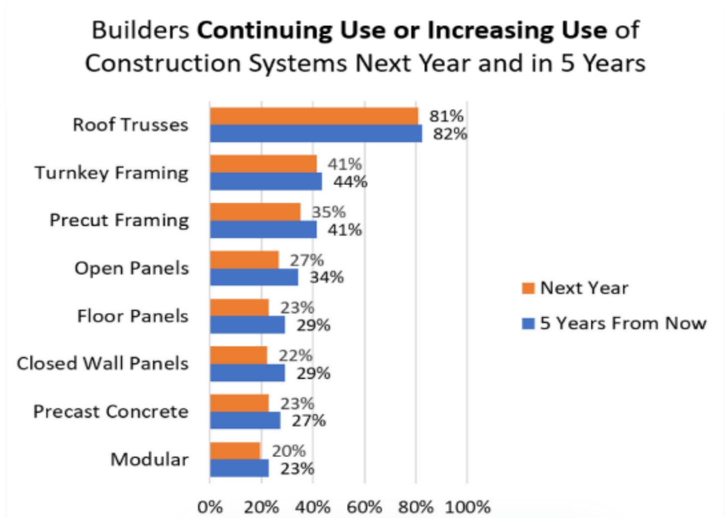


Figure 1: Construction Systems Forecasting (Home Innovation Research Lab, 2019)

The full adoption of total modular or panelized builds may be challenging to achieve, but using the two construction methods for certain components of a build could be widely accepted soon. About 80% of roof trusses are already built in a factory, with turkey framing coming in second. As the quality, technology, and public perception increases, modular and panelized construction is forecasted to increase their market share significantly.

In 2017, Dr. Diez forecasted that the market share of modular and panelization will continue to rise through 2018 and 2019 due to the increased labor shortages and the increased need for affordable housing(Dietz, 2018). This is good news for the modular home building industry, but modular homebuilders who survived the last great recession are cautious. In an interview with a modular home builder, Ken Semler of Express Modular Franchising disclosed one of the frustrating aspects of the offsite homebuilding industry cycle:

> "as the market share increased alongside an increasing homebuilding market volume, modular and alternative framing methods are explored and implemented, but every time a recession happens, and the market cools off, builders seem to forget everything they have learned and revert back to the simplest form of stick-built onsite framing homes."

The benefits significantly must outweigh the costs to cause a large shift in the market share for modular and panelized construction.

DATA COLLECTION AND ANALYSIS

The research team worked with many industry professionals willing to share their studies and data for analysis. A national homebuilder and a regional panel manufacturer/supplier provided stick-built and panel framing study data that the research team used to perform a case study and quantitative analysis.

Internal framing studies completed by an industry partner was shared with the research team to analyze. The first part focused on two prefabrication studies conducted by a singular national homebuilder and aggregated to compare the total labor hours between framing types. The research team acted as an independent 3rd party to analyze the framing task data, producing independent conclusions.

The first part of the study was conducted in the Dallas, TX market, which is a unique location since the predominant framing method is stick-built walls and stick-built roofs. Two single-story homes of the same floor plan were built in a similar neighborhood. The first was framed with stick frame walls and a roof as a baseline, and the second home was framed with wall panels and roof trusses. All the framing tasks were observed and timed, utilizing timesheets and data collection methodology the builder developed and vetted for accuracy. Figure 2 below shows the two different homes overall framing labor comparisons.

1 Story Home – Stick Frame

1 Story Home – Panels & Trusses

- Framed in 150.5 labor hrs.*
- 1,996 Sf
- 6 Framers
- Baseline

*NOTE: Labor Hrs. = Total Hrs. x No. of Framers

- Framed in 79.5 labor hrs.*
- 1,996 Sf
- 4 Framers
- 47% Improvement

Figure 2: Framing Comparisons, Source: National Homebuilder

The stick-built home was completed in 150.5 labor hours, while the panel and truss-built home were completed in 79.5 labor hours, a 47% improvement. Also noted is that the stick frame home required a framing crew of six, while the panel & truss framed home only required a framing crew of four. In analyzing the data, it was found that most of the labor savings were in the wall's panels and miscellaneous framing labor time. Due to the hip roof, the trusses did save time in the roof framing, but the roof framing is still where there is a bulk of the total framing labor. See Figure 3 below.

The second study looks at 23 townhomes in the Maryland market. This study aimed to identify the optimal framing process through the lens of cost-effectiveness, implementation feasibility, and scalability. Stick-built homes were used as a baseline, compared against homes of similar square footage and design utilizing prefabricated components. An onsite representative cataloged framing tasks for each framing crew, including task type, duration, crew members present, and explanation of delay if experienced. Figure 4 below is the floor plan layout.

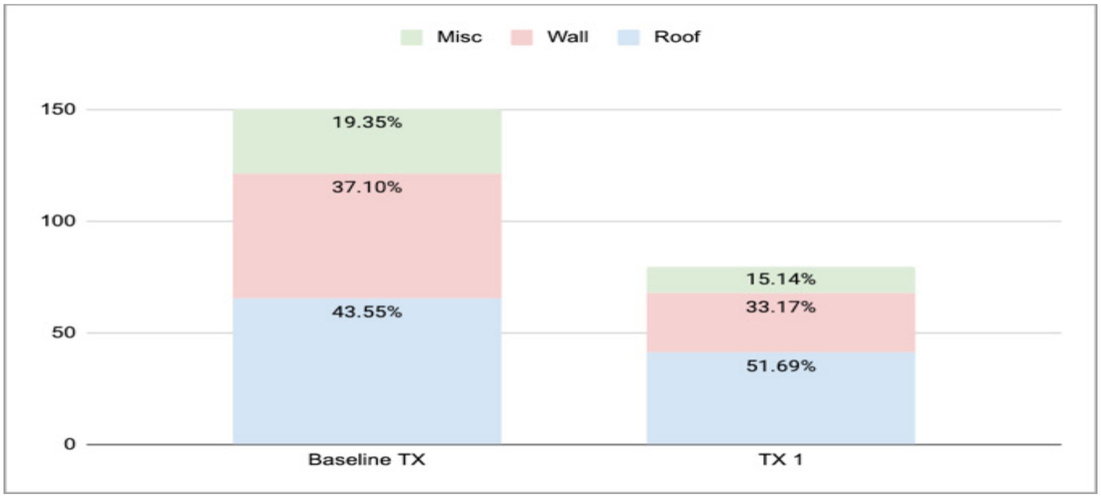
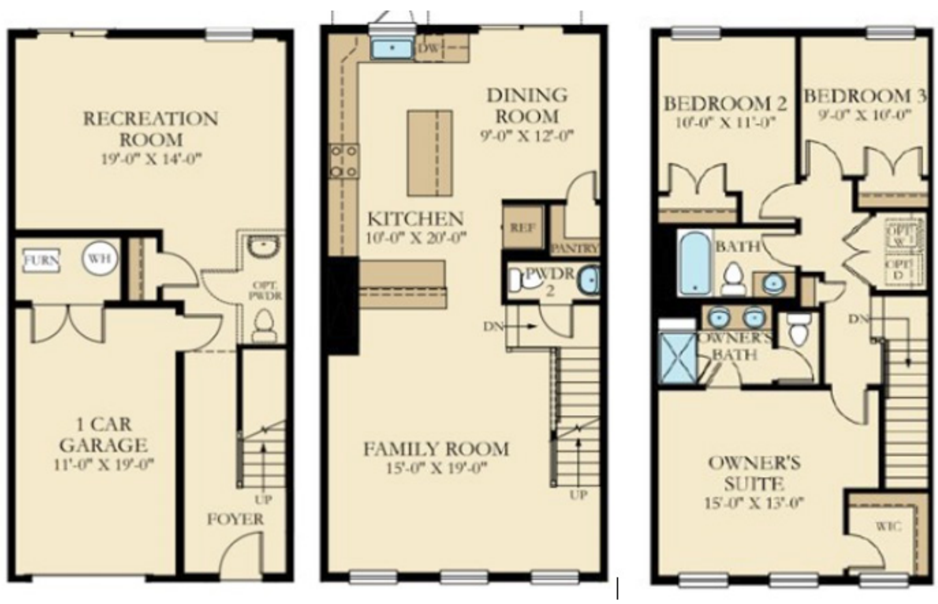


Figure 3: Texas Market Framing Hours Comparison



First Floor Second Floor Third Floor

Figure 4: Maryland Market Framing Study Floor Plan Layout

.Of the original framing data provided to the researchers, individual framing tasks were recategorized into “Misc,” “Wall,” and “Roof” task types to isolate activities directly related to the prefabricated components. Table 1 denotes the Labor Hrs. for each framing task per building. Figure 5 highlights the distributions of each framing activity as it relates to the total labor hours. The activities designated as ‘Wall’ and ‘Roof’ framing tasks were intended to be as close as possible to minimize the skewing of their efficiencies. Please note, if an outlier (framing task) was found on a single building, it was relegated to the ‘Misc.’ category to keep the integrity of the results for ‘Wall’ and ‘Roof’ activities. When compared to the respective baseline, TX 1 utilized both prefabricated panel frame walls and roof trusses; it gained an efficiency of 52.51% (wall) and 36.95% (roof), respectively. While MD 1, MD 2, and MD 3 utilized panel frames for the walls but did not include a stick-built roof system for comparison. Compared to the baseline stick-built home, these floorplans gained wall framing efficiencies of 34.07%, 26.62%, and 54.00%, respectively.

Table 1: Labor Hrs. Allocation per Framing Activity

Floor Plan	Framing Type	Misc Labor Hrs./Home	Wall Labor Hrs./Home	Wall Efficiency	Roof Labor Hrs./Home	Roof Efficiency
TX 1: 1 Story	Panel Frame & Roof Truss	12.1	26.5	52.51%	41.3	36.95%
MD 1: 2 Story	Panel Frame Roof Truss	126.0	51.7	34.07%	36.1	
MD 2: 2 Story	Panel Frame Roof Truss	93.2	57.5	26.62%	30.7	
MD 3: 2 Story	Panel Frame Roof Truss	65.16	36.0	54.00%	25.0	

*Labor Hrs. = Total Hrs. observed x No. of Framers

*Efficiencies = Floorplan Labor Hrs. / Baseline Labor Hrs.

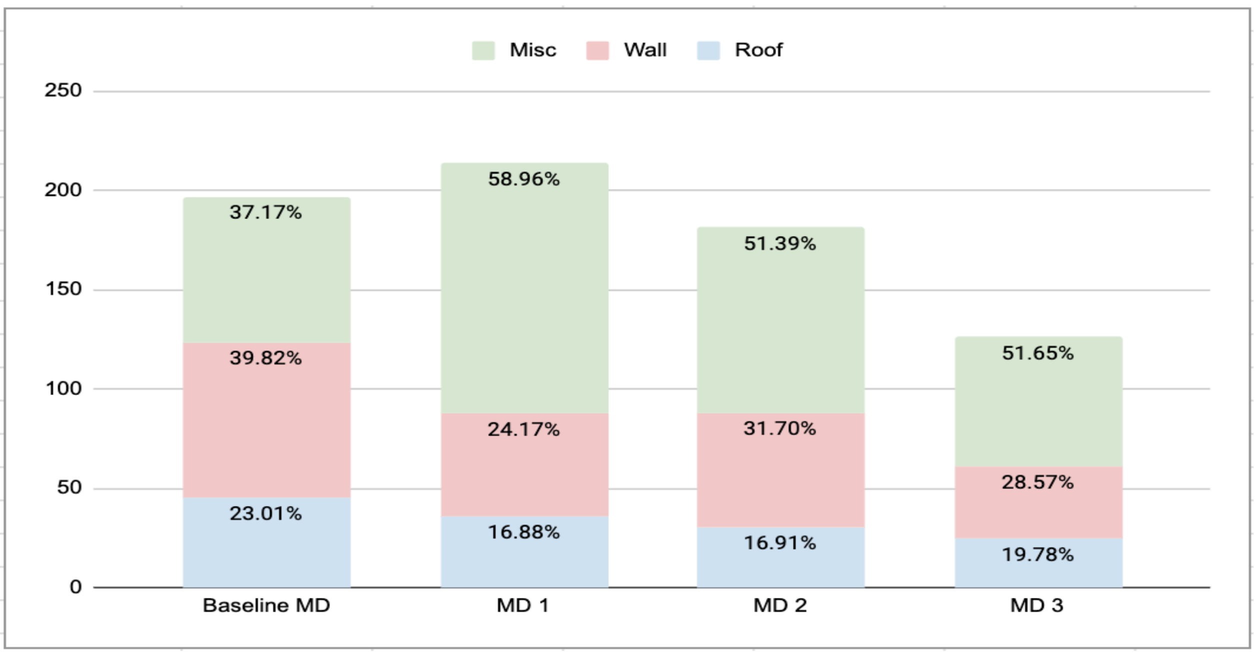


Figure 5: Maryland Framing Activity Distribution

Because the various floorplans between markets had significant differences in design and construction (TX 1 was a ranch plan that utilized panel framing and roof trusses rather than panel framing exclusively. MD was a three-story townhome), total labor hours are not a fair comparison. Instead, the analysis is between the prefabricated floorplans and their baseline. For this analysis, Labor Hrs. are defined as total hours observed times the average number of framers. Efficiency is defined as floorplan labor hours divided by the Baseline labor hours. Table 2 details each floor plan and baseline used in this case study. The data suggests that prefabricated methods showed an average of 20.48% efficiency over the baseline stick-built home.

Table 2: Floorplan and Baseline Details

Floor Plan	Framing Type	No. of Homes	SF per Home	Avg. Duration (Framing)/Home	Avg. Crew/Day	Avg. Labor Hrs./Home	Total Efficiency Gained
Baseline TX	Stick Walls & Roof	1	1,996 SF	3.1 Days	6	150.5	
TX 1	Panel Frame &Roof Truss	1	1,996 SF	2.4 Days	4	79.5	46.8%
Baseline MD	Stick Walls &Truss Roof	5	2,501 SF	3.4 Days	8.7	196.8	
MD 1	Panel Frame	5	N/A	4.4 Days	5.5	213.8	-8.6%
MD 2	Panel Frame	7	2,519 SF	2.7 Days	7.5	181.4	7.8%
MD 3	Panel Frame	6	2,593 SF	1.8 Days	8.3	126	35.8%
Average:							*20.4%*

*TX 1 is compared against Baseline TX

*MD 1, MD 2, and MD 3 are compared against Baseline MD

*Labor Hrs. = Total Hrs. observed x No. of Framers

*Efficiency Gained = Floorplan Labor Hrs. / Baseline Labor Hrs

All floorplans with prefabricated elements showed a better distribution of workload per framer and required less skilled labor to achieve an upside. This suggests panel frame construction provides a feasible implementation for the average homebuilder if skilled labor is a significant constraint. As shown in Table 2 above, all but one floorplan utilizing prefabrication showed a reduction in total labor hours, while MD 1 showed an increase of (-8.6%). This was due to it being the first home the crew framed and the framing learning curve they had to work through. Upon further inspection, most of the increase can be attributed to the 'Misc' category, which was inflated due to activities such as the layout of materials, trade-ready inspections, and punch out. The data suggests 'Misc.' activities accounted for 58% of MD 1's total labor hours, which should not be considered normal. By looking at labor hours for 'Wall' activities, the efficiency of 52.51% is present, which suggests the prefabricated wall panel still provided a positive advantage regardless of the increase in total hours worked. An adjusted Total Efficiency Gained (excluding MD 1) would be 30.13%. Based on the findings, utilizing prefabricated elements positively impacted total labor hours, and floorplans implementing panel frame or roof trusses reduced the total labor hours for framing by an average of 20.4%.

Panelization Labor Cost Study

A regional wall and truss panel manufacture supplied the research team with wall framing labor and cost data for analysis. They based their study on a 2500 square foot house and Denver labor rates for stick framing and panelization. They found that the framing cycle time was decreased by 46% per house and that by using a panelized wall system, the framing crews could frame four houses per month over 2.4 houses using traditional stick framing, an increase of 54%. The manufacturer could pay their framers $1.50 less per sf (30% decrease in pay per home), but they would make a $7875 increase in monthly revenue (22%) by building almost two more homes each month. See table 3 below.

Table 3: Stick Built vs. Panelization Labor Comparison

	Stick Framing	Panelization	% Change	
Days Worked per month	26	26		
Cycle Time Per House (days)	12	6.5	-46%	Decrease in cycle time
Houses Completed Per month	2.17	4	54%	Increase homes per month
Pay: $ per sf	$5.00	$3.50	-30%	Decrease in $ per sf
Pay per House	$12,500	$8,750	-30%	Decrease in $ per house
Pay Per Month	$27,125	$35,000	22%	Increase in monthly pay
Income Benefit		$7,875		

SUMMARY OF FINDINGS

The studies point to evidence that panel framing packages increase the speed that homes can be framed. By utilizing panelized wall systems, builders would be able to decrease their framing cycle time between two and six days, with an average of four days saved. Framers could reduce their crew sizes by two framers, thus lowering the pressure on the labor market while increasing their crews' efficiency to frame more homes. And builders could pay, on average, $1.00 per sf less on the framing labor per house.

DISCUSSION & CONCLUSION

The research data shows that panelization can be more efficient in labor, materials, and logistics savings. So why are builders not changing framing methodologies? When the research team asked builders if they were changing their framing systems over to the pre-cut and panel systems, they were hesitant. Even though the data shows increased productivity and reduced labor, the framing crews were not giving a lower price to the home builders. Part of the problem is that the way framing packages are priced. It's typical in most markets that framers bid the framing labor as a price per SF. As stated above, labor is one of the most significant issues facing the home building industry. The lack of experienced framing crews has a substantial effect on stick-built, pre-cut, and panel-built homebuilding. In practice, less field experience is needed for each method, with stick-built requiring the most, while setting panels requires the least. Another challenge is that the math in Table 3 above works when builders can guarantee consistent and reliable starts each week. If the weekly starts schedule is disrupted for any reason (weather, logistics, supply chain, etc.), the framers move on to another job because they have to keep their crews working.

The model of paying by the sf makes it hard to negotiate better labor framing rates due to efficiencies. According to the national and regional builders surveyed, framing labor rates vary from $6 to $8 per sf on the west coast and east coast, $4 to $6 per sf in the Midwest, and $2 to $4 per sf in the south/southwest. The builders were paying an upcharge for the alternative framing package and were expecting a reduction in price for the labor from the framers. But due to the labor shortage, the framing crews are holding control of the market pricing, and local divisions were hesitant to rock the boat with their local framing crews. It takes careful negotiations and lots of discussions to convince the framing crews to change how they build and how they get paid.

Another challenge is that moving to panelization means a change in preconstruction practices in the industry. Builders will need to plan ahead, working with the lumber and manufacturer suppliers to resolve their plans structurally and fully code compliance. The common practice of letting lumber yards ship to takeoffs for free, shipping bunks of lumber to the site, and then relying on the framers to manage the materials is a greatly needed culture shift in the homebuilding industry. Many production builders and developers are starting to think about home building in a controlled manufactured mindset to drive this industry change forward.

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Minority and Female Participation in Construction Industry Apprenticeship Programs

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ABSTRACT

According to the U.S. Bureau of Labor Statistic's Current Population Survey, nearly 90 percent of the 10.7 million people employed in the construction industry are white males (2021). This statistic will remain unchanged unless more minorities and females are recruited into the industry. For craft workers, a primary recruitment mechanism is the registered apprenticeship program. This study analyzes the U.S. Department of Labor's Registered Apprenticeship Database (RAPIDs) from 2000 to 2019 to identify trends for new apprentices. The study found that there was no change in the proportion of new female apprentices in the previous 20 years and no change in the proportion of new non-white apprentices in the previous 15 years. The researchers also found that while there appears to be opportunity to grow gender diversity in apprentice programs, the current proportion of new non-white apprentices is consistent with the current available workforce indicating little opportunity for increasing racial diversity. The findings of this study will assist the U.S. Department of Labor, apprenticeship program sponsors, and advocacy groups in understanding the impact of diversity efforts over the past 20 years and in preparing effective strategies to move towards diversity in construction trades consistent with the available workforce.

Key Words: Construction Apprenticeship, Diversity, Inclusion, Underrepresented Populations

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INTRODUCTION

According to the U.S. Bureau of Labor Statistics (2021), of the 10,786,000 people employed by the construction industry, 88.6% are white and 89.1% are male. However, the available workforce looks much different with 78% of workers reported as white and only 53.2% reported as males. Increasing non-white and female participation in the construction industry has been a goal of many organizations, including the U.S. Department of Labor (USDOL), for more than forty years. Title 29 of the Code of Federal Regulations Part 30 Equal Employment Opportunity in Apprenticeship and Training (1978), for instance, prohibited apprenticeship programs and their employers from discriminating based on race, color, religion, national origin, or sex and required them to implement affirmative action practices complete with goals and timetables to achieve those goals.

While 29CFR30 demonstrates an intent to stop discrimination and promote diversity, critics point out that contractors and apprenticeship programs are protected from enforcement penalties for not meeting mandates if "good faith efforts" are documented (Moir, Thomson, & Kelleher 2011, p. 7). So if employers and apprenticeship programs are able to sidestep compliance penalties including deregistration, through good faith efforts, how will apprenticeship programs and the construction industry-at-large ever increase their non-white and female participation? We must first seek to understand ethnicity and gender trends within our apprenticeship programs, then use that data to seek out new initiatives to bolster the USDOL including increased staffing and enforcement.

Without these new initiatives, we are destined to repeat the last twenty years and remain at our current demographic. Therefore, the purpose of this study is to investigate participation in the U.S. registered apprenticeship programs by race and gender over the previous 20 years. The research questions (RQ) that guided this study are:

RQ1: Between the years 2000 and 2019, what is the trend in the number of new registered apprentices and how do new registered apprentices compare to the available workforce in terms of race and gender?

RQ2: Between the years 2000 and 2019, was there a change in the proportion of females that started apprenticeship programs for all trades?

> $H_0 2$: There is no difference in the proportion of females that started apprenticeship programs between 2000 and 2019.
>
> $H_a 2$: There is a significant difference in the proportion of females that started apprenticeship programs between 2000 and 2019.

RQ3: Between the years 2000 and 2019, was there a change in the proportion of racial minorities (non-whites) that started apprenticeship programs for all trades?

> $H_0 3$: There is no difference in the proportion of racial minorities (non-whites) that started apprenticeship programs between 2000 and 2019.
>
> $H_a 3$: There is a significant difference in the proportion of racial minorities (non-whites) that started apprenticeship programs between 2000 and 2019.

The findings of this study will assist the U.S. Department of Labor, employers, apprenticeship program sponsors, and advocacy groups in understanding the participation of non-white and female apprentices over the past 20 years and in preparing effective strategies to move towards diversity in construction trades consistent with the available workforce. It will also assist researchers in developing more effective diversity strategies and may aid lawmakers in facilitating change in diversity policy and funding.

LITERATURE REVIEW

Benefits and Structure of U.S. Registered Apprenticeships

While the system of apprenticeship originated in the Late Middle Ages and helped grow early colonial America (Wallis 2012), programs weren't officially codified into U.S. law until the National Apprenticeship Act of 1937 (USDOL 2021a). Today, according to the U.S. Department of Labor (USDOL), modern apprenticeships are "industry-driven, high-quality career pathways where employers can develop and prepare their future workforce, and individuals can obtain paid work experience, classroom instruction, and a nationally-recognized, portable credential" (September 2020). Because a typical construction apprentice starts at an hourly wage that is fifty percent of a journeyperson's hourly wage scale for that occupation, one of the benefits to the construction employer is that they can pay a registered apprentice at a reduced scale on public works projects as the apprentice becomes more proficient in their skill set. Apprenticeship supporters argue that the lower skill level at the entry level necessitates a lower wage whereas opponents argue that because the employer can use the apprentice for cheap labor, it has an advantage over an employer without a tie to a registered apprenticeship program.

In the multi-employer union construction environment, this tie to the apprenticeship program is made possible through a collective bargaining agreement between an employers' association and the trade union for a craft. Contractor employers typically assign their bargaining rights to the employer association who in turn negotiate on their behalf. The collective bargaining agreement establishes how much the signatory employers will pay into the apprenticeship program. Per the Taft-Hartley Act of 1947, employers were able to pay monies into a trust fund managed by the employers' association and the trade union (Kordus 2012). The amount varies by program and need but is typically based on hours worked by apprentices and journeypersons and is accrued on each workers' pay check. Because several employers are sharing in the cost of the apprenticeship program, this arrangement is commonly referred to as a multi-employer apprenticeship program.

As for structure, jointly managed Taft-Hartley multi-employer construction apprenticeship programs are typically composed of two entities that oversee the activities of the apprenticeship program. First, the sponsor is generally a joint apprenticeship and training committee (JATC) composed of an equal number of management and labor representatives. The management side of the table includes an employers' association representative and one or more contractor representatives. The labor side of the table includes the union business manager and one or more union business agents. The JATC typically meets monthly and is focused on apprentice recruitment, training materials, discipline of apprentices, and appeals. Second, an Apprenticeship and Training (AT) Trust Fund, which is also made up of equal representation from management and labor per Taft-Hartley guidelines, meets quarterly and is focused primarily on the money matters concerning the training. Because assets are involved, both entities (JATC and AT) are required to comply with the Employee Retirement Income Security Act of 1974 and its amendments (Kennedy & Vater 2012). Because of this requirement, all committee members have a fiduciary responsibility to the plan and its assets and therefore are personally responsible to restore any losses to the plan. While the individual trustee may be sued by an individual or entity, the employers' association typically pays the insurance premium to cover the management trustees' risk. Likewise, the union pays for the insurance premium for labor trustees' risk.

The apprenticeship coordinator, who is a member of the respective union, reports to the sponsor and is not a voting member of the JATC or AT Trust. This person is responsible for the day to day operations of the apprenticeship program which includes recruitment, managing curriculum, coordinating courses and related training at the facility, and paying bills associated with the facility and training per limits established by the AT trustees.

Selection of Apprentices

Per 29CFR30, there are four approved methods for selecting apprentices: 1) selection on basis of rank from pool of eligible applicants, 2) random selection from pool of eligible applicants, 3) selection from pool of current employees, and 4) alternative selection methods (1978). Today, the two most used methods in construction apprenticeship programs are the first option, commonly referred to as rate and rank, and the last one, alternative selection methods, which includes the letter of intent. In the rate and rank mechanism, applicants complete an application and submit it to the sponsor. They are then interviewed by the sponsor and often complete a math or skills assessment. Applicants are then ranked based on the interview and assessments. The applicant at the top of the list is the next in line to be employed by the next contractor requesting an apprentice from the sponsor. In the letter of intent mechanism, the applicant is provided with a list of contractors who are signatory to the union craft and must solicit a letter of intent or commitment to hire them as an apprentice. With letter in hand, they often begin safety training at the apprenticeship training center and begin working.

In recent years, as apprenticeship programs update their apprenticeship standards, the Department of Labor has favored the use of the rate and rank method over the letter of intent. Their rationale has been that the rate and rank was more objective. One of the consequences of this change is that it transfers the risk of discrimination, and overall USDOL noncompliance, from the individual employers to the sponsor (JATC).

Previous Construction Worker Diversity

Following a 1976 lawsuit brought by the National Women's Law Center (NWLC) against the USDOL for failing to uphold Executive Order 11246, which prohibited discrimination based on sex among other attributes, the USDOL's Office of Federal Contract Compliance Programs "increased the required participation of women to 6.9% of all work hours on federal construction projects" (2014, p. 1). According to Moir, Thomson, & Kelleher (2011), who analyzed U.S. Bureau of Labor Statistics (BLS) data on women in the labor force from 2008, "thirty-three years after the federal government established the target of 6.9% and mandated an end to hostility to women in the construction work environment, women are less than half that target at 2.7% of the construction trades workforce and harassment, discrimination and intimidation continue to be common experiences among women who are in the trades or are seeking to enter them" (p. 7). Similarly, in a 2014 report, the National Women's Law Center (NWLC) reported that the percent of women in the construction trades remained essentially unchanged (2.6%) for the 30-year period from 1984 to 2014.

Bilginsoy (2003) analyzed apprentice data in the Apprenticeship Information Management System (AIMS) provided by the Bureau of Apprenticeship and Training (BAT) in 1995. The researcher compared the attrition and retention rates of 12,715 construction apprentices in 36 states and found that women and minority completion rates were lower than white men. The researcher also found that apprentices associated with joint union-management programs were more likely to complete their apprenticeship program than non-joint programs (or unilateral programs as he coined). He compared the mean duration (in months) of apprentices with the local unemployment rate and found that as the unemployment rate rose, so too did the mean apprenticeship duration.

A study of Oregon's apprenticeship programs (Berik, Bilginsoy, and Williams 2011) focused on women as well as minority men apprentices. The study, which focused on apprentices that started their programs between 1991 and 2002 and tracked them through 2007, found that white women apprentices graduated at a lower rate than white men but for those white women that did graduate, their training duration was less than their male counterparts. The graduation rates for minority men were not too different than white men. The study also found that apprentices in joint union-management sponsored programs were more likely to succeed than apprentices in non-joint union-management sponsored programs.

Kelly, Wilkinson, Pisciotta, and Williams (2015) interviewed 44 staff and apprentices and surveyed 177 apprentices enrolled in Oregon's highway construction apprenticeship programs over a nine-year period (2001-2010) and found that fewer female and minority apprentices were recruited and retained. They also found that these two groups "disproportionately face challenges with interpersonal interactions, hiring practices, and supervisory practices" (p. 415). The researchers referred to the apprenticeship sponsors, the employer hiring apprentices, as "inequality regimes" – a term popularized by Acker (2006). In her prior research, Joan Acker (1990) challenged the idea of organizational neutrality with respect to gender and asserted that through the division of labor, cultural symbols, workplace interactions, individual identities, and organizational logic, organizations are gendered.

The Diversity Imperative

Previously in this paper the authors presented U.S. Bureau of Labor Statistics data that show the current state of diversity, or lack thereof, in the construction industry. While this is not a new topic, all industry stakeholders including government, employers' associations, trade periodicals, as well as union organizations, are working to diversify the workforce.

In 2016, the U.S. federal government invested over $50 million to establish ApprenticeshipUSA to grow and diversify state apprenticeship programs (The White House 2016). Two years later, the U.S. Department of Labor (USDOL) created the Women in Apprenticeship and Non-traditional Occupations (WANTO) grant initiative. Since 2018, the USDOL has invested over $10 million to recruit females into the industry (USDOL 2021c).

Over the last several years, industry employers' associations have created focus groups, summits, grants, publications, and other initiatives to improve diversity and inclusion. The Associated General Contractors' includes diversity and inclusion as an industry priority under workforce development. In addition to creating a special council, the organization offers a resource titled Culture of Care where organizations assess their diversity and inclusivity culture and take a pledge to improve their efforts. AGC also offers diversity and inclusion awards and a white paper titled The Business Case for Diversity and Inclusion in the Construction Industry detailing returns on diversity and inclusion investments such as driving a positive safety culture, increasing market share, improving productivity, mitigating employee turnover, and driving innovation (AGC 2021). The Associated Builders and Contractors' Inclusion, Diversity, and Equity Program includes resource groups, an annual summit, grants, and awards (ABC 2021). The Mechanical Contractors of America Association created the Women in the Mechanical Industry Initiative to recruit and mentor women in the mechanical trades (MCAA 2021). Similarly, the Engineering News-Record (ENR) has created a new business section alongside safety and health, workforce, and finance titled diversity and inclusion (ENR 2021).

Union organizations have also been involved. In partnership with the US Department of Labor and the American Federation of Labor & Congress of Industrial Organizations (AFL-CIO), the

St. Louis Building and Construction Trades Council created Building Union Diversity (BUD), a five-week pre-apprenticeship program, "to recruit, train and equip people of color and women for successful high demand union careers in the construction trades" (Missouri Works Initiative 2021). Similar three to five-week pre-apprenticeship programs sponsored by both union and nonunion organizations have popped up around the country.

Summary

The previous review of literature provides a foundation for the current study. The authors began by providing background information on the structure of sponsored apprenticeship programs and the selection process for new apprentices. The selection process is of critical importance as it ultimately impacts the participation rates of women and minority groups. Next the authors discussed the diversity in apprentice programs and the diversity imperative, which is central to the current study. For many years, promoting diversity has been a prevalent theme in the construction industry. With this study, the authors sought to investigate if the substantial efforts being made to grow a diverse workforce have made an impact on registered apprentice programs.

METHODOLOGY

To investigate the research questions this study employed a quantitative, descriptive survey design (Leedy & Ormrod, 2005). The Registered Apprenticeship Sponsor Information Database (RAPIDS) was the primary source for the data used for this study. The RAPIDS database is publicly available through the U.S. Department of Labor website (USDOL 2021b). While the RAPIDS database is extensive, it does not include the full population of registered construction apprentices. According to the USDOL website (2021b), "RAPIDS captures individual record data for the 25 states administered by the Office of Apprenticeship and 18 of the 28 states/territories administered by State Apprenticeship Agencies (SAA), so it does not represent a complete national dataset."

The data file was limited to construction trades, identified using the standard occupational classification taxonomy. According to O*NET, Construction and Extraction occupations use an O*NET-SOC code of 47 (O*NET 2021). New construction apprentices between January 1, 2000 and December 31, 2019 were included in the final dataset. While data was available for 2020, the researchers chose to exclude it from their analysis due to potential influences of the COVID 19 pandemic.

A combination of descriptive and inferential statistics was applied in the data analysis. The Pearson's chi-square test was used to test for differences in proportions of the independent variables. Following a significant results with the chi-square test, the Marascuilo procedure was used to perform post-hoc, pairwise tests between sample groups (Anderson et.al, Chapter 12, 2019). Twenty years of new apprentice data were used for this study. While the descriptive demographic statistics are presented by year, the chi-square data analysis was performed in five-year groupings, 2000-2004 (Period 1), 2005-2009 (Period 2), 2010-2014 (Period 3), and 2015-2019 (Period 4). The researchers employed the four, 5-year periods to limit the influence of anomalous one-year demographic changes and to reduce the impact of increased familywise error rates from multiple post-hoc comparisons.

Each five-year period was limited to a random sample of cases when applying the chi-square test. Calculations for estimating the sample size at a 95% level of confidence are provided with each test. The researchers chose to use the random sample in lieu of the entire dataset because "as the sample size becomes extremely large, the margin of error becomes extremely small and the resulting confidence intervals become extremely narrow" (Anderson et.al 2019, p.399).

The researchers identified the following limitations to this study. While the RAPIDS database is extensive, it does not include all apprenticeship programs, limiting the inferential power of the study. In addition, while all cases in the database included gender (male or female only), some cases did not report the race of the apprentice. Therefore, the overall demographic characteristics of the dataset and hypothesis tests including race were potentially influenced by the missing data. The RAPIDS data file does not include any personally identifiable information. Therefore, it is possible that some individuals may have been included more than once if they chose to change their occupation. Finally, no consideration was given to whether the apprentice actually completed the program or remained in the construction industry, limiting inferences on the impact of the overall construction workforce.

FINDINGS

Descriptive Statistics and Summary Data

The RAPIDS data file was limited to construction trades for apprentices who started their program between January 1, 2000 and December 31, 2019. The full dataset for construction trades included 1,230,838 cases representing all 50 United States, the District of Columbia and Guam. It included 41 distinct construction occupations (O*NET codes). 3.2% of the final dataset were female, 96.8% were male. While gender was reported for all cases, some apprentices chose not to report their race. When performing analysis involving race, the dataset was reduced to 1,069,957 cases. Of the reduced dataset, the racial composition was 4.4% American Indian or Alaska Native, 1.5% Asian, 11.6% Black or African American, 2.0% Native Hawaiian or other Pacific Islander, .02% multiple race reported, and 80.3% white.

The following summary descriptive statistics address the first research question: Between the years 2000 and 2019, what is the trend in the number of new registered apprentices and how do new registered apprentices compare to the available workforce in terms of race and gender? Trends in the number of new registered apprentices are presented along with a comparison between new registered apprentices and the available workforce in terms of race and gender.

Figure 1 presents the frequencies for all new apprenticeships between 2000 and 2019. From this table we see periods of growth and decline. The sharp decline following 2008 coincides with the US Great recession. Between 2010 and 2019 the chart shows steady growth in the number of new apprentices.

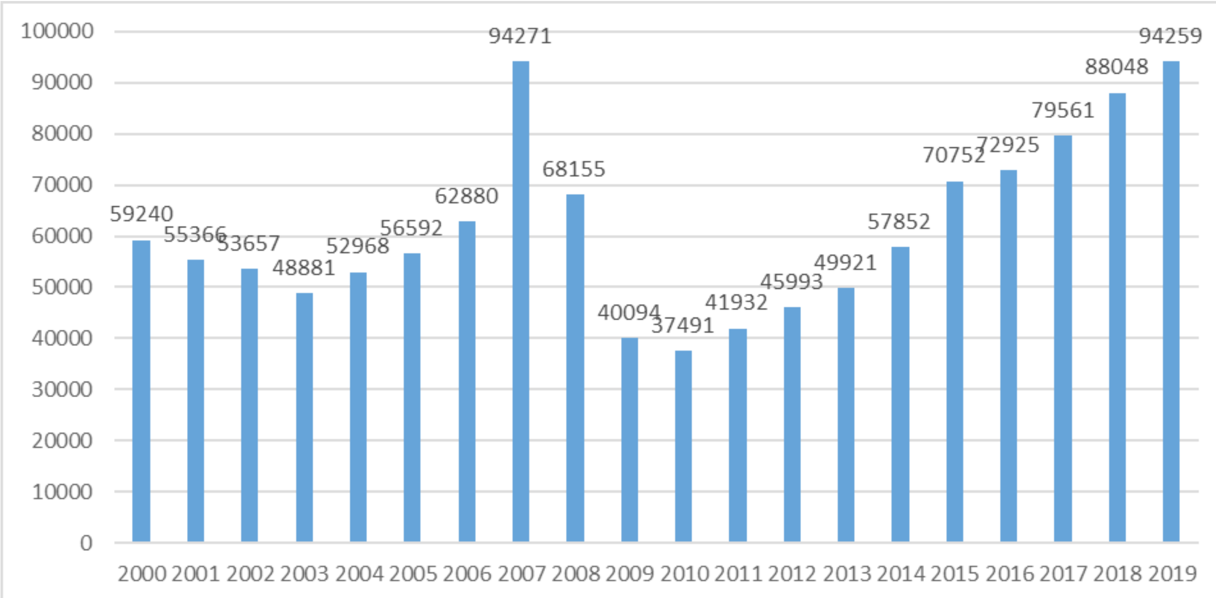

Figure 1. All New Apprentices, 2000-2019

Figure 2 presents all new female apprentices between 2000 and 2019. The trend of new female apprentices appears to follow the trend for all new apprentices shown in Figure 1, with a drop following the recession of 2008 and steady growth following 2010.

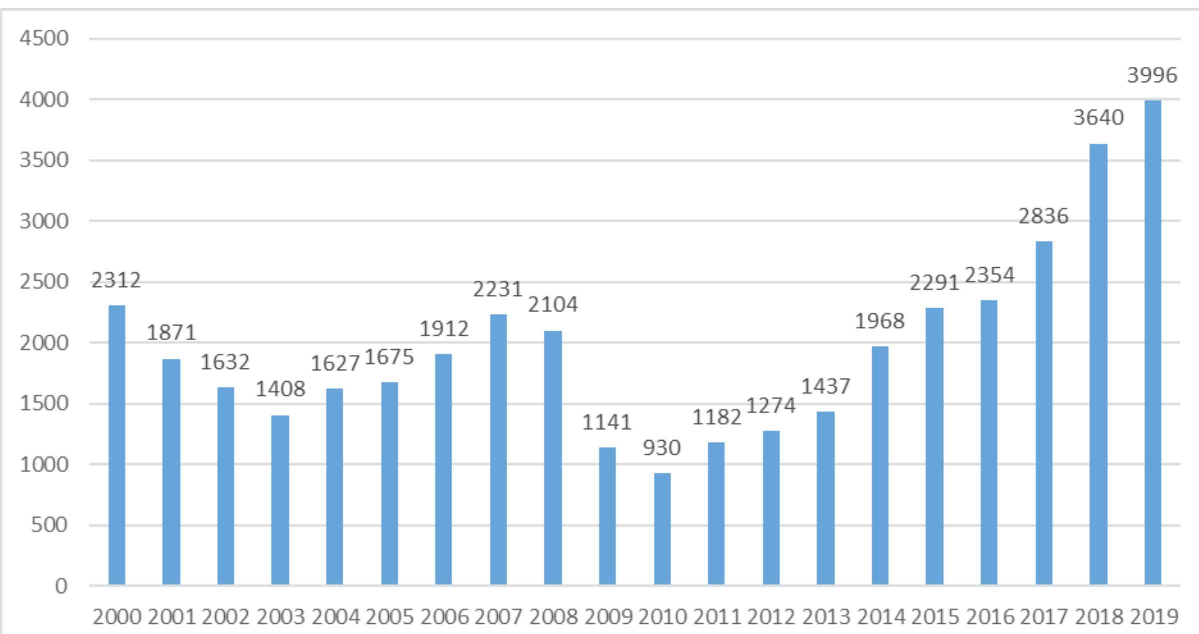

Figure 2. All New Female Apprentices, 2000-2019

Figure 3 shows the proportion of new female apprentices per year between 2000 and 2019. New female apprentices make up 2.4% - 4.2% of all new apprentices for the 20-year period. From the chart the overall trend appears to be flat.

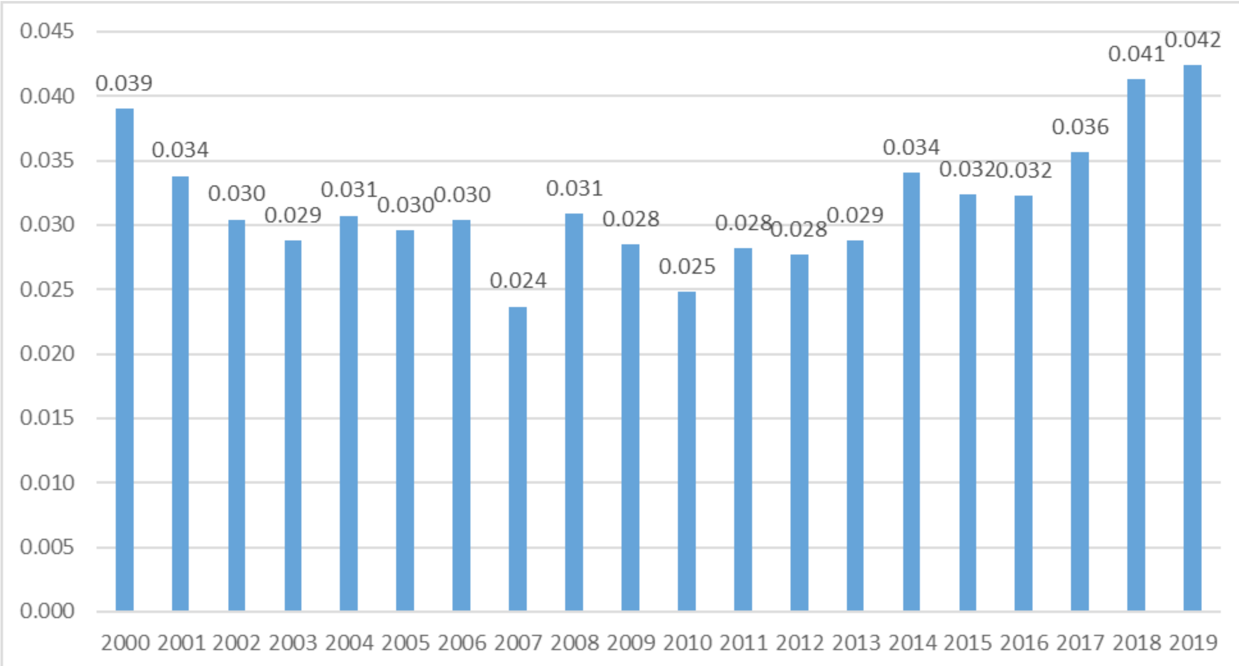

Figure 3. Proportion of New Female Apprentices, 2000-2019

Figure 4 presents all new non-white apprentices between 2000 and 2019. The trend generally appears to follow the trend for all new apprentices shown in Figure 1 with a drop following the recession of 2008 and steady growth following 2010.

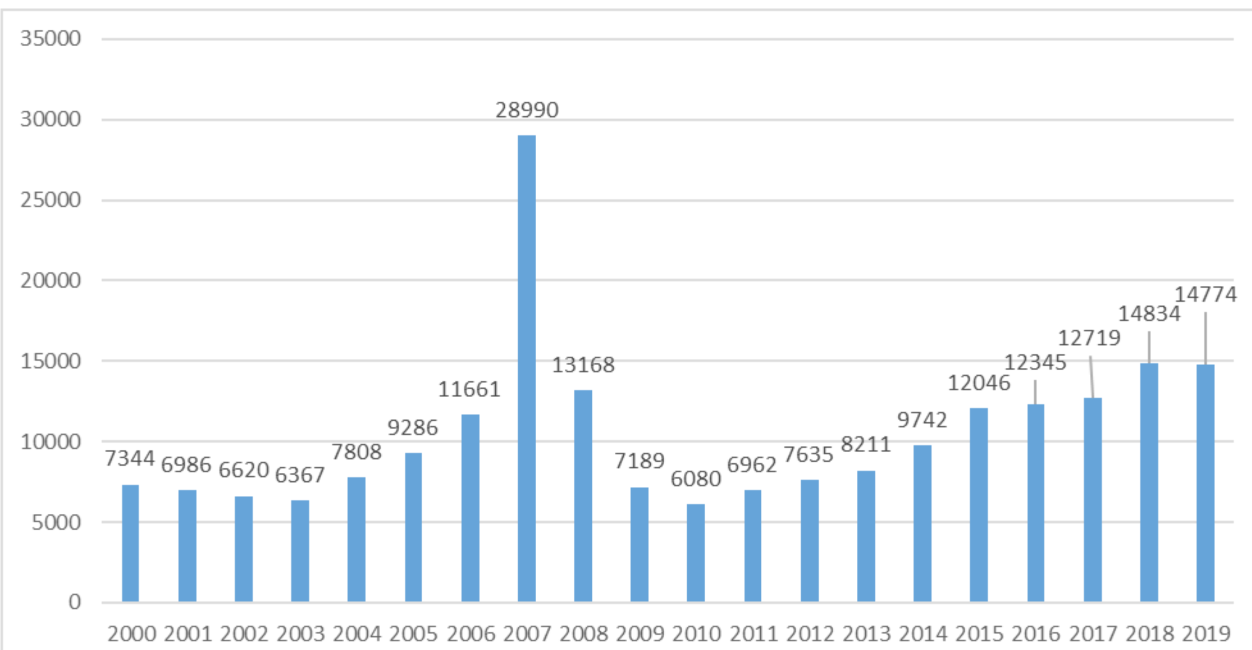

Figure 4 All New Non-White Apprentices, 2000-2019

Figure 5 shows the proportion of non-white new apprentices per year between 2000 and 2019. New non-white apprentices make up between 12.3% and 31.8% of all new apprentices for the 20-year period. The proportion of new non-white apprentices appears to increase following 2004, then remains generally flat through 2019. An anomalous increase in the proportion of new non-white apprentices is shown in 2007.

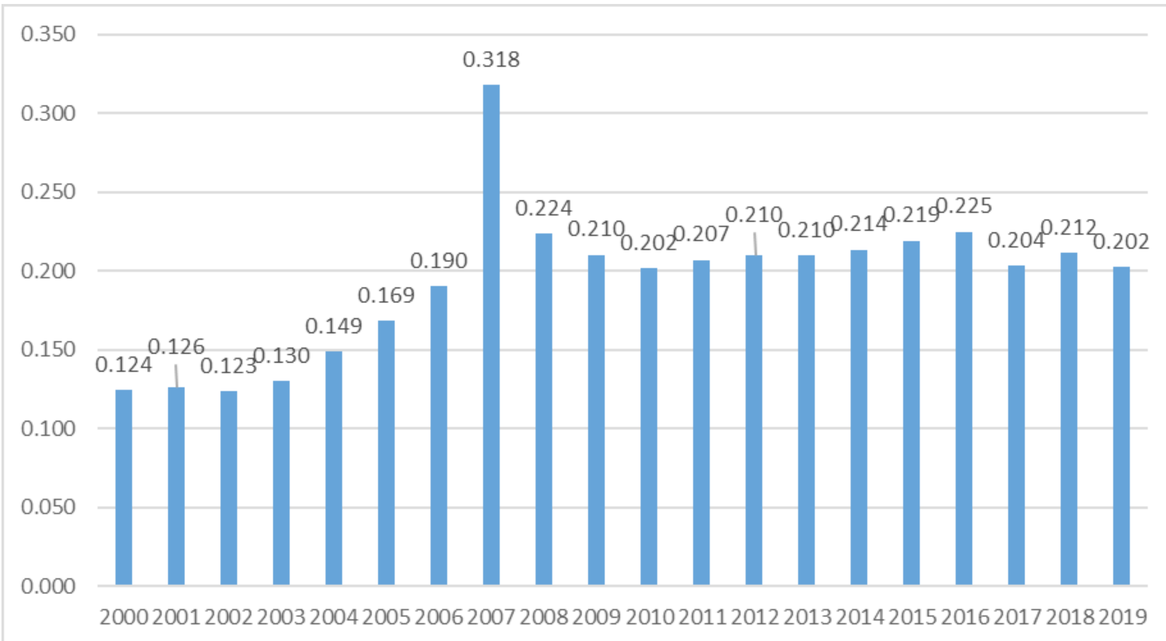

Figure 5. Proportion of New Non-White Apprentices, 2000 – 2019

In addition to reporting new registered apprentice trends over time, the authors investigated how new apprentices compared to the available workforce. Table 1 shows summary demographic statistics from 2000-2019 for new registered apprentices along with current U.S. Bureau of Labor Statistics data on the available workforce (BLS 2021).

Table 1. Demographic Comparison, New Registered Apprentices (RA) & Current Available Workforce

	% Women	% Men	% Non-White	% White	% Asian	% African American	%
New RA 20 Years	3.20%	96.80%	19.70%	80.30%	1.50%	11.60%	21.5%
Current Workforce	46.80%	53.20%	22%	78%	6.40%	12.10%	17.60%

From Table 1 we see that in regard to gender, the percentage of new female registered apprentices (3.2%) is much less than the available workforce (46.8%). However, in regard to race, the percentage of new non-white registered apprentices (19.7%) is approximately the same as the available workforce (22%). Values for Asian, African American, and Hispanic (ethnicity) are also published by the BLS and are provided here for additional perspective. It appears that the percentage of new African American apprentices is consistent with the available population and new Hispanic apprentices represent a higher percentage than the available workforce.

Hypothesis Testing

The second research question (RQ2) asked: Between the years 2000 and 2019, was there a change in the proportion of females that started apprenticeship programs for all trades? The researchers performed the Pearson chi-square test to investigate changes in the proportion of new female apprentices over time. The twenty-year period between 2000 and 2019 was divided into four populations, 2000-2004 (Period 1), 2005-2009 (Period 2), 2010-2014 (Period 3), and 2015-2019 (Period 4). The proportion of new female apprentices for each 5-year period is presented in Figure 6. The following formula (Anderson et.al, 2019, p.395) was used to estimate the required sample with a margin of error (E) of .025 (+-2.5%) at 95% confidence ($Z_{\alpha/2}$) based on the largest observed female population proportion (p) of .038.

$$n = \frac{(Z_{\alpha/2})^2 (p)(1 - p)}{E^2}$$

A random sample of 235 apprentices was selected from each five-year period. The results of the Pearson chi-square test indicate no difference in the proportion of new female apprentices within the four distinct time periods between 2000 and 2019 $X^2(3) = .21$, $p > .05$. Therefore, the null hypothesis is supported. Although Figure 7 does appear to show an increase in Period 3 and Period 4, the increase is not statistically significant.

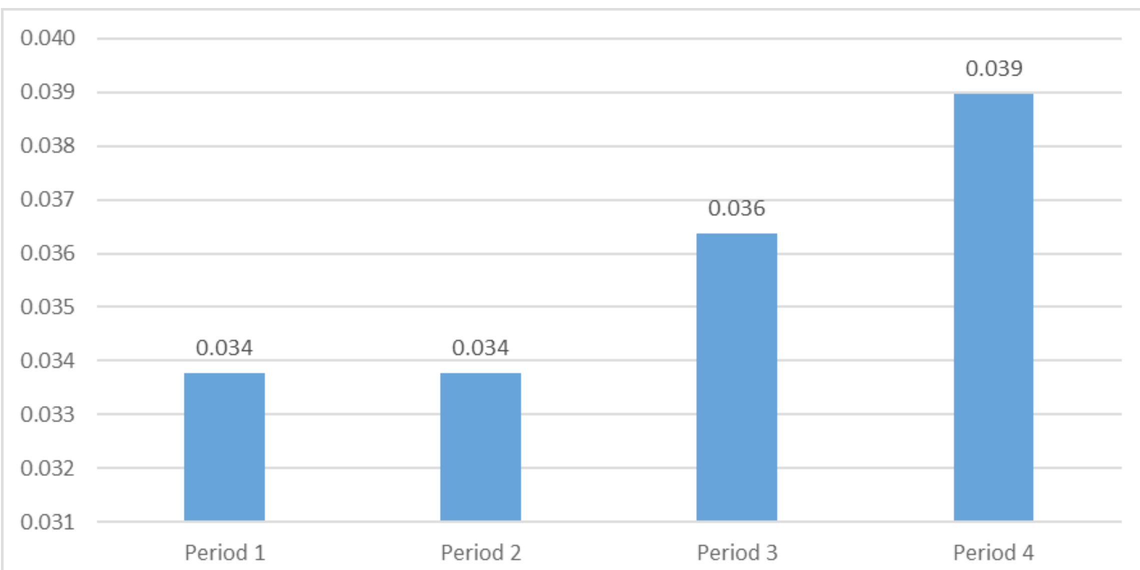

Figure 6. Proportion of New Female Apprentices, 5 Year Periods, 2000-2019

Research question three (RQ3) asked: Between the years 2000 and 2019, was there was a change in the proportion of racial minorities (non-whites) that started apprenticeship programs for all trades? The researchers performed the Pearson chi-square test to investigate changes in the proportion of new non-white apprentices over time. As with the previous question the twenty-year period between 2000 and 2019 was divided into four periods. The proportion of new non-white apprentices for each 5-year period is presented in Figure 7. The same formula was used to estimate the required sample size for non-white apprentices with a margin of error (E) of .025 (+-2.5%) at 95% confidence ($Z_{\alpha/2}$) based on the largest observed female population proportion (p) of .21.

A random sample of 985 apprentices was selected from each five-year period. The results of the Pearson chi-square test indicate a significant difference in the proportion of new non-white apprentices within the four distinct time periods between 2000 and 2019 $X^2(3) = 20.72$, $p < .05$. Therefore, the null hypothesis is rejected.

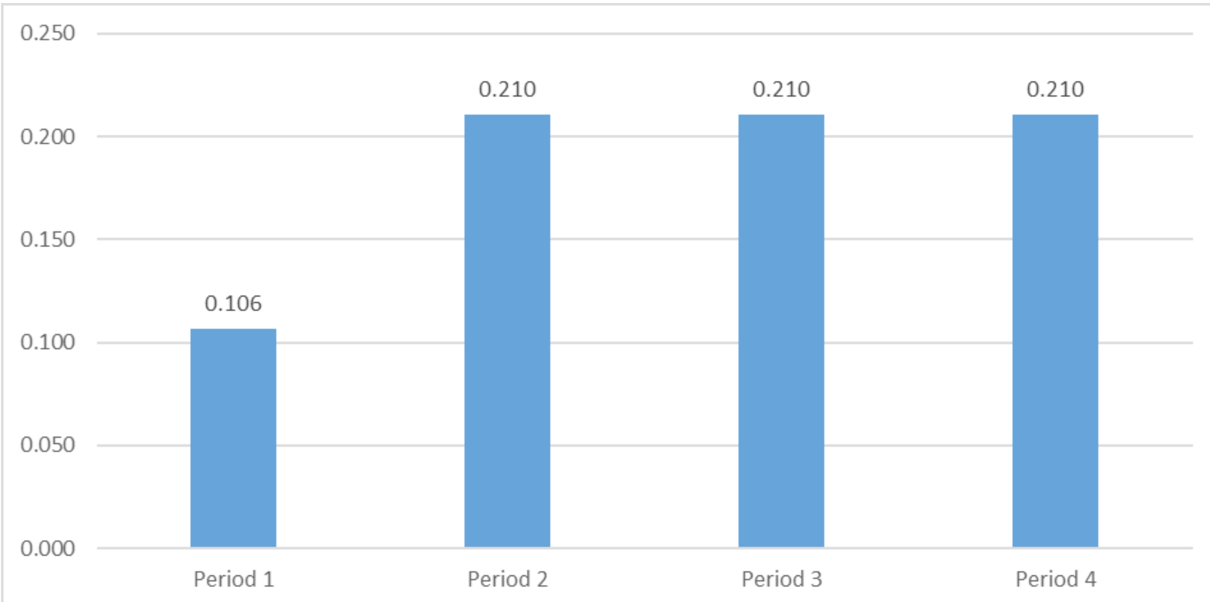

Figure 7. Proportion of New Non-White Apprentices, 5 Year Periods, 2000-2019

Based on the significant findings, the Marascuilo procedure (Anderson et.al, Chapter 12, 2019) was performed to further investigate pairwise differences in the proportion of new non-white apprentices between 2000 and 2019. From Figure 7 we see what appears to be an increase between Period 1 and Period 2. For the time period between Period 2 and Period 4 there was no difference in the proportion of new non-white apprentices. Table 2 presents the results of the Marascuilo procedure showing the absolute value of each pairwise sample difference (pi-pj) and the critical value calculated at the overall significance level of .05.

Table 2. New Non-White Apprentices, Pairwise Comparison, Marascuilo Procedure

Difference	Value	Critical Value	Significant
Period 1 & Period 2	0.1039	0.0728	Significant (.05)
Period 1 & Period 3	0.1039	0.0728	Significant (.05)
Period 1 & Period 4	0.1039	0.0728	Significant (.05)
Period 2 & Period 3	0.0	0.0821	Not Significant
Period 2 & Period 4	0.0	0.0821	Not Significant
Period 3 & Period 4	0.0	0.0821	Not Significant

The results of the Marascuilo procedure displayed in Table 2 show a significant increase between Period 1 and Period 2. However, following Period 2 there is no significant change in the proportion of new non-white apprentices.

CONCLUSIONS AND RECOMMENDATIONS

The findings presented in the previous section provide valuable insight into workforce trends and opportunities for registered apprentice programs. While the number of new registered apprentices has fluctuated in the 20 years between 2000 and 2019, the past 10 years have shown strong annual growth. In regard to race, the percentage of new non-white apprentices appears to be consistent with the current available workforce. Therefore, while increasing racial diversity is a prevalent contemporary issue, there appears to be little opportunity for apprentice programs. In contrast, the percentage of new female apprentices is much less than the available workforce. Increasing gender diversity appears to be a growth opportunity for apprenticeship programs.

In regard to RQ2, the authors found that there has been no increase in the proportion of new female apprentices in registered apprentice programs between 2000 and 2019. This is consistent with previous reports (Moir, Thomson, Kelleher, 2011; NWLC, 2014) on the participation rate of women in the overall construction workforce. This finding indicates that efforts to increase gender diversity have to date not been successful. As identified in the previous section, increasing gender diversity appears to be a real growth opportunity for apprenticeship programs.

In regard to RQ3, the authors found a significant change in the proportion of new non-white apprentices between 2000 and 2019. However, the increase happened in the first five years and the proportion has remained unchanged for the past 15 years. While these results may appear discouraging, it is important to remember that the overall percentage of new non-white apprentices is consistent with the available workforce. Therefore, there appears to be little opportunity for growth for new registered apprentices in regard to race.

To continue to increase our understanding of apprentice programs and the construction workforce, the authors propose the following recommendations for future study. Future studies should investigate the length of the apprenticeship terms and completion rates based on gender and race. Understanding completion rates is of particular importance as the goal is not only recruiting, but also to transition women and racial minorities into the workforce. While the current study looked at changes in diversity for all trades, future work should also consider trends within occupational classifications and geographic settings.

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Case Study of Using Unmanned Aircraft Systems to Support Bridge Inspections

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ABSTRACT

This paper presents the results of a case study conducted to evaluate the potential benefit of unmanned aircraft systems (UAS), commonly referred to as drones, as a tool to improve the bridge inspection workflow. The study conducted two experiments to determine how well deficiencies could be detected using a UAS. Both experiments were conducted using the same test bridge. The first experiment was carried out by the bridge inspection engineers (BIEs), who had previously inspected the bridge using traditional methods. They used the drone to search for inspection points identified in the inspection report. The second experiment was conducted by BIEs, who were unfamiliar with the bridge and had not read the inspection report. They inspected the bridge and identified deficiencies that they could detect using only the drone. In both experiments, over 90% of the inspection points could be sufficiently observed to evaluate their condition. It was estimated that this technology would save approximately 27% ($1,440) on a routine inspection of the test bridge.

Keywords: Drone, UAS, Bridge Inspection, Remote Inspection

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INTRODUCTION

Over the last several years, the use of unmanned aircraft systems (UAS), commonly referred to as drones, has increased dramatically. In late 2020, the FAA reported that nearly 500,000 commercial drones had been registered, and over 200,000 people have earned their remote pilot certificate (FAA 2020a). To put that into context, the FAA also reports that there are 220,000 manned civil aircraft registered and 665,000 manned aircraft pilots (AOPA 2019; FAA 2020b). The growth of the UAS market and advancements in technology have significantly driven down the cost of many high-functioning aerial platforms. The reduced cost, coupled with the relaxation of FAA regulations, has opened many opportunities for state departments of transportation (DOTs) to incorporate this technology into their operations. A survey conducted by the American Association of State Highway and Transportation Officials (AASHTO) found that 35 of the 44 state DOTs that responded had deployed drones to support their operations (AASHTO 2018). A Tech Brief provided by the Federal Highway Administration (FHWA) indicated that "inspections of in-service bridges are one of the more promising potential uses of UAS" (FHWAa 2019 p. 1). Some of the advantages of using UAS to support bridge inspection engineers (BIEs) include increased safety, improved productivity of inspection, reduced impact to the public, cost savings, reduced environmental impact, and higher quality inspection documentation (Banks et al. 2018). Jeong, Seo, and Wacker (2020) stated it succinctly when they said that "Quantifying damage [with UAS] plays an essential role in better bridge inspection and maintenance (p. 5)."

To evaluate the potential benefits of this technology in their bridge inspection workflow, a pilot study was conducted with the South Carolina Department of Transportation (SCDOT) using a DJI M210 UAS, 30x optical zoom sensor, and a real-time kinematic ground control station to inspect an in-service test bridge. The test bridge was selected in coordination with the DOT to ensure that it was a good representative of the state's bridge inventory in terms of structure, condition, and access. The researchers conducted several mock inspections to ensure the fidelity of the experiment design prior to involving the BIEs.

Two experiments were conducted using the same test bridge. The first experiment's purpose was to evaluate how many of the defects the drone could identify given optimal conditions. For this experiment, the BIEs that recently inspected the test bridge using an under-bridge inspection truck (UBIT) were tasked to re-inspect the bridge using only the drone. The second experiment was designed to evaluate the number of deficiencies that could be identified given real-world conditions when the deficiencies were not known. For this experiment, a second BIE crew unfamiliar with the test bridge was given the same drone inspection task.

LITERATURE REVIEW

The use of UAS has significantly increased over the past four years in the United States. In August of 2016, the FAA released Title 14 Part 107 of the Code of Federal Regulations, which removed much of the regulatory limitations on the use of UAS for commercial applications (FAA 2019). There are many applications for drones that are currently being explored. Some of the applications that have shown promise in the literature are bridge inspections (Gillins et al. 2018; Otero et al. 2015), construction safety monitoring (Gheisari et al. 2014), disaster management (Adams et al. 2014), and construction progress monitoring (Lin et al. 2015) just to name a few. The World Road Association (WRA) conducted a comprehensive international study of how UAS can be leveraged to improve roadway design, construction, and maintenance (WRA 2017). In their report, they recommended four primary areas that could benefit from UAS technology. The four areas include bridge inspection, automated asphalt pavement inspection, asset inventory, maintenance, and pre-construction surveys. As-built conditions of future roadway projects are commonly obtained by aerial imagery captured by crewed aircraft. The WRA report (2017) indicates that "Using a survey-grade UAS with RTK GPS and Red Green Blue (RGB) imaging capabilities can be a very good alternative to traditional methods" (p. 1). The report defines "survey-grade UAS" as one with geo-referenced, high-resolution imagery that can create a point cloud within 3 centimeters (cm) accuracy. The objective of this study is to see if commercially available, off-the-shelf UAS (i.e., which are not necessarily "survey-grade") and software can be used to create surveys that are within these tolerances and be a benefit to the state DOT.

Opportnity for UAS to Support Bridge Inspection

Another civilian use case for UAS is bridge inspections. The FHWA authors the Bridge

Inspector's Reference Manual (BIRM), which provides the standard for bridge inspections (Ryan et al., 2012). Bridges are most commonly inspected visually, involving walking on decks, using binoculars to observe points of interest, or using an under-bridge inspection truck (UBIT) for difficult-to-reach places (Dorafshan and Maguire 2018). UBITs require skilled and qualified operators (Zink and Lovelace 2015). They can be challenging to schedule as there are generally only a limited number of them in any given district (Dorafshan and Maguire 2018). Other issues with UBIT include congesting traffic, added weight to bridges, and endangering inspectors and the traveling public. The indirect cost of using UBIT can exceed the direct cost of the inspection making alternative methods very desirable (Dorafshan and Maguire 2018). One such alternative is UAS, and several state DOTs have started researching their use to support bridge inspections (Brooks et al. 2015; Gillins et al. 2018; Stacom 2016).

Past Evaluations of UAS Supporting Bridge Inspections

Gillins et al. conducted a comprehensive review of formal UAS DOT research projects as part of their research with the Oregon DOT (ODOT) and the FHWA (2018) (Gillins et al. 2018). They found that multiple states have made significant strides in testing UAS to support their agency's mission. For example, Arkansas DOT was one of the first DOTs to study drones for collecting traffic data, but the time regulations were too burdensome for practical application (Frierson 2013). The study was conducted three years before Title 14 Part 107's adoptions removed many of those restrictions. The Connecticut DOT (CDOT) experimented with a small multi-rotor UAS to photo-document the Gold Star Bridge over the Thames River in 2016 (Stacom 2016). CDOT found that they were able to document the bridge with aerial photographs in 30 minutes which would have usually taken several hours using a UBIT and climbing equipment.

The FDOT collaborated with the Florida Institute of Technology to evaluate if drone-captured images compared with images collected during conventional inspections (Otero et al. 2015). They used several bridges and high mast luminaires to conduct their testing. They found that the two photo groups were mostly comparable. However, there were still gaps in the drone data that should be explored further in the future. Similarly, the Florida DOT (FDOT) and the Michigan DOT (MDOT) also evaluated drones for bridge inspections but expanded their study to traffic monitoring as well (Brooks et al. 2015). In Brooks et al., authors evaluated a five-drone platform system with various sensors, including optical, LIDAR, and thermal. The findings were very supportive of the technology. Minnesota DOT (MnDOT) supported a study to conduct a multi-phase evaluation of drone supplemented bridge inspections (Lovelace and Zink 2015). Their initial results were very favorable, so the study was expanded to include bridges with various structures, including steel arch, high steel truss, corrugated steel culvert, and movable steel truss (Wells and Lovelace 2017). The expanded study was also very positive, noting that augmenting an inspection with a UAS could provide a cost savings of as much as 66%.

Oregon DOT (ODOT) also evaluated the potential of using drones as a cost-saving tool with their inspections. They used a UAS to conduct a structural inspection of six bridges and three communication towers and found a benefit-cost ratio of 9 and an estimated average cost savings of $10,000 per bridge (Gillins et al. 2018).

The FHWA has taken notice of the benefits of UAS technology. In a publication by FHWA's Center for Accelerating Innovation (2019b), they note that "construction inspectors that use UAS are reducing inspection time, improving effectiveness, increasing safety, and lowering costs" (para 2). The center has also financially supported states wishing to deploy the technology through several research initiatives, including the State Transportation Innovation Council (STIC) incentive program, Accelerated Innovation Deployment program, and the Accelerating Market Readiness program (CAI 2019).

Remote Bridge Inspection

The use of sensors to evaluate bridge conditions is not a new concept. Vaghefi et al. identified 12 categories of remote sensing: photogrammetry, optical interferometry, spectral reflectance/absorption, and digital image correlation (Vaghefi et al. 2012). Each sensor type has a different application and effectiveness. Some of these sensors, especially RGB (red, green, blue) imagery needed for photogrammetric models, are well served with UAS technology. As Yang et al. identified, four main limitations are keeping commercial drones from significant expansion into a wider use case field (Yang et al. 2018). The limitations include regulatory specific to flight within line-of-sight, poor connectivity for video transmission, inaccurate tracking based on global navigation satellite system (GNSS), and hardware specific to battery life. The current literature is largely silent on case studies where UAS video is live-streamed to a remote inspector. Much of the literature focuses on innovative ways of improving connectivity between the pilot and drone (Censi et al. 2013; Kagawa et al. 2017; Ono et al. 2013). However, other fields such as sports broadcasting (Wang et al. 2017), journalism (Gynnild 2014), and tourism (Wu et al. 2016) have had success with remote broadcasts, although noting that video latency can be a significant issue.

METHODOLOGY

The goal of the study was to evaluate the effectiveness of using a UAS to support bridge inspections at a state DOT in the Southeast. Two experiments were conducted using the same test bridge to assess this. The purpose was to evaluate how many of the defects could be identified with a drone given optimal conditions. Hence, the inspection team that recently inspected the test bridge using a UBIT was tasked to re-inspect the bridge but this time using only the drone. The inspection team had access to the previous inspection report, so the deficiencies were known. The results gave the researchers an understanding of the maximum number of deficiencies that could be identified given optimal conditions. Essentially, could the bridge inspection engineers find the deficiency if they knew it was there? The second experiment was designed to evaluate the number of deficiencies that could be identified using a drone when the BIE did not know what deficiencies were present. For this experiment, a second BIE team unfamiliar with the test bridge was given the same task of inspecting the bridge with only the UAS.

Selection of Test Bridge

Desirable characteristics of a test bridge were identified as having scale-to-benefit significance from a drone inspection and not having major obstructions that would make drone flight dangerous. A total of 12 bridges were identified by the BIEs as potential candidates and observed by the researchers as they were inspected using traditional methods. The structure varied from concrete, steel, and timber pile caps. Their length and number of lanes of traffic also varied. Some of the bridges were over rivers, while others had streets, rail, or a dry stream bed under them. Ultimately, the Bates Bridge was selected (see Figure 1). The Bates Bridge is a two-lane bridge over a large river. It is approximately 0.3 miles long and has a concrete structure.

(a) (b)

Figure 1: (a) Test bridge and (b) DJI M10 RTK UAS used in the inspection

Equipment Used

The aircraft selected for the experiments was DJI's M210 RTK (Figure 1). The M210 RTK is a general-purpose quadcopter in DJI's enterprise line. It can support several different sensors, including the Zenmuse Z30 camera (Z30). The Z30 sensor was used for this experiment because it has a 30 times optical zoom. This allowed for detailed observations without having to fly the drone in close proximity to the bridge structure. This model also features a real-time kinematic (RTK) positioning ground control station. The RTK unit was located on a tripod away from the bridge. The RTK unit located itself via satellite and then helped position the M210 RTK drone. TB50 and TB55 are two different battery types supported by the M210. (TB55 batteries only support the second generation of the M210.) TB50 is the smaller of the two and will sustain flight times of approximately 17 minutes when the Z30 is mounted. The research team found that a supply of 16 TB50 batteries was sufficient to charge batteries at the same rate they were depleted continually. Like most bridge sites, power was not available, so a generator was procured. The charging station at full capacity drew 1,000 Watt (W), so a 2,000W generator was also used to support various other electronics like laptops, controller battery chargers, tablets, and cell phones. This aircraft allows for the camera to be controlled by a second person with another controller. For this experiment, two Cendence controllers with 19.94cm CrystalSky monitors were used. The pilot controlled the aircraft while the BIE controlled the camera. The controller and monitor are both powered with a WB37 battery. The researchers found that four batteries in use while another four were charging (8 total) was sufficient to keep the two controllers continually operational.

SET UP OF THE EXPERIMENTS

As stated earlier, the first experiment's purpose was to understand how much of a traditional bridge inspection could be performed with a UAS given optimal conditions. The second experiment's primary goal was to verify how much could be inspected given real-world conditions the deficiencies were unknown ahead of time. The team for both experiments also consisted of several state DOT employees, two of which are in the Department of Engineering Technology & Research, and the others were BIEs. For the first experiment, the BIEs had been the lead inspectors who assessed the test bridge approximately one year prior. In the second experiment, the BIEs were from a different district and were unfamiliar with the bridge. Several graduate and undergraduate students also assisted with the investigation. Prior to experiments, the bridge's air space was determined to be class G and that no authorizations were needed. It was rechecked the day of and if the FAA published any temporary flight restrictions (TFR) or noticed to airmen (NOAM). The "base camp" consisted of a 6ft table under a tent with sidewalls. The sidewalls proved very helpful when reducing glare on laptop screens and keeping the equipment out of direct sunlight. The generator was located approximately 50ft away so that the noise and exhaust were not an issue. The heat was a safety concern, so a truck was located and left running with the air conditioning on. This truck was designated as a cool-down space and used exclusively for this purpose. The team began the experiment with a safety talk where major hazards were identified, such as crewed aircraft, traffic, boats, and contact with the UAS's propellers. The team intentionally stayed out of the traffic line as they did not want to be a distraction. The drone was either flown under the bridge or a minimum of 150ft above the bridge deck. Two participants were charged with watching for cars around the base camp as well as for looking for crewed aircraft. They were issued walkie-talkies and also air horns for emergency notification if operations needed to stop immediately. Before the experiment, the aircraft was inspected using a pre-printed inspection checklist. The aircraft performed a series of test maneuvers to verify it was responsive to the controls. For both experiments, one of the BIEs was designated as the lead and was given control of the camera. The control of the aircraft remained with the pilot at all times.

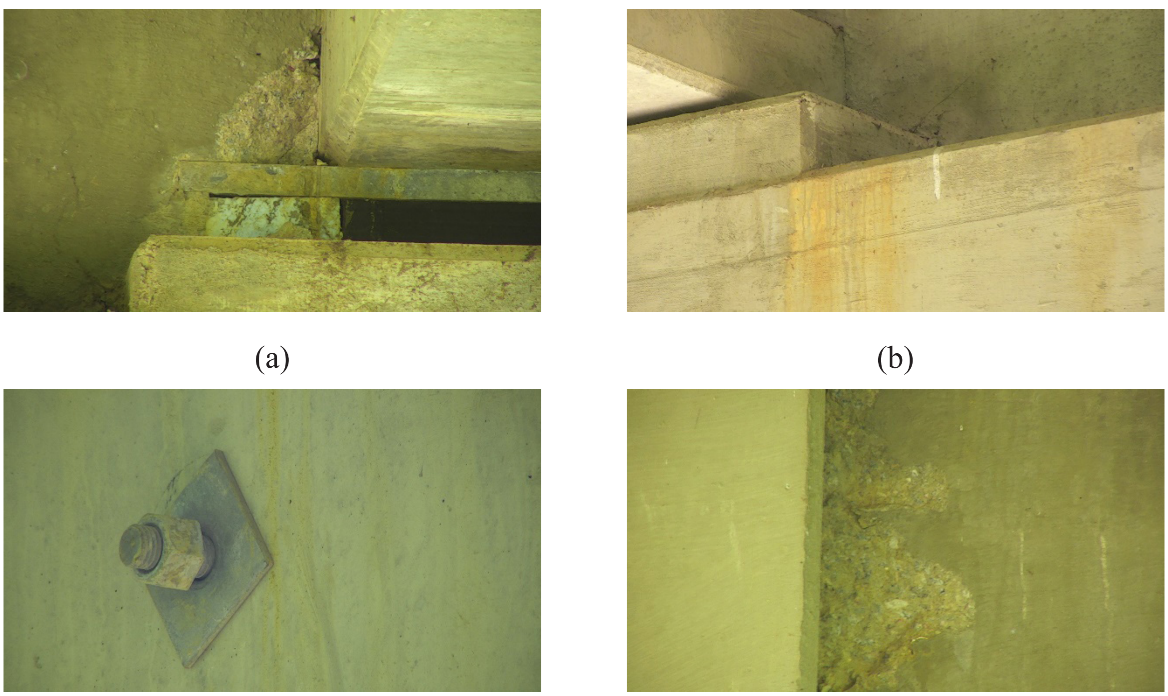
EVALUATION OF DRONE PERFORMANCE

The inspection report, which was created approximately one year prior to the experiment, contained 120 inspection comments. Some of the inspection comments were very specific such as "Span 11 - had typical diagonal cracking in the web of beam 5." Other comments were more general, such as "hairline longitudinal cracking throughout the deck." During the first inspection, a three-person crew inspected the bridge. The pilot for the aircraft, the BIE controlled the camera, and a third "note-taker" called out the deficiencies from the inspection report. The pilot and the BIE positioned the aircraft and camera to see if they were able to observe the deficiency. The note taker would then record either "yes" or "no" as to if the deficiency could be observed sufficiently for the BIE to determine its condition.

The second experiment was similar; however, a different BIE controlled the camera. The inspection report was also not provided to the BIE. The BIE was tasked with inspecting the bridge using only the drone. As with the first experiment, the inspection team also consisted of the same individuals for piloting and note-taking.

Experiment 1: Bridge Inspection Observations

The first experiment was completed between 8:00 am and 3:00 pm. As the BIE had never used this technology before, the initial flights were slow and the communication cumbersome. However, as the experiment continued, the speed of communication and the logistical operation continued to improve. The BIE was able to see hairline cracks, spalling, bolts, and decking effectively. See Figure 2 for examples. The concrete and pads located in dark crevasses were challenging to observe. At the end of the mission, an After Action Review (AAR) was conducted. The BIE had a positive response to the technology and felt that it was a useful tool that they could take advantage of. They noted that not every condition could be observed, so the tool could not replace traditional practices entirely. They also stated that the tool would primarily be used during routine inspection during off years.



(a) (b) (c) (d)

Figure 2: (a) Bearing unable to see sufficiently. (b) Hairline cracking observed with the drone. (c) Anchor bolt not tightened down. (d) Minor spalling observed with drone

Experiment 2: Bridge Inspection Observations

The experience from the BIE from the first experiment was remarkably similar to the second. The learning curve with the technology was overcome very quickly. As before, the pilot began to anticipate the BIE's needs, which increased the speed of the process. It took approximately the same amount of time for both BIEs to observe the inspection points. The first BIE conducted his inspection by observing points in the order that they were presented on the checklist. The order of inspection points was the same logical sequence that the second BIE crew inspected the bridge. There was no significant difference in the amount of time it took to observe and evaluate an inspection point from either BIEs. Essentially, both BIEs inspected the same points, in the same order and for the same duration, but were recording their observations either with or without the benefit of the traditional inspection. The second BIE was able to see the same deficiencies and had the same limitation observing components that were not well illuminated. Specifically, airline cracks, spalling, bolts, and decking were easily observed. The concrete and pads located in dark crevasses were again difficult to see and could not be evaluated. There were no deficiencies observed by the first BIE crew that were not observed by the second. From this experiment, it did not appear that having the previous inspection report increased the time or quality of the inspection. This team also has a very favorable opinion of the technology. They acknowledged that not all components could be observed but that many could be safer and more efficient. They note in particular that this tool would significantly reduce the need and duration of a UBIT when supporting traditional inspection methods.

DISCUSSION

The BIE's overarching opinion was that drone technology is a valuable tool to support the process but was not a complete replacement for in-person inspections. UAS could be used to reduce the length of use of UBITs, make documentation more convenient, and reduce the safety hazard to the inspectors.

Benefits of Drone Technology with Bridge Inspections

The majority of the inspection points (91%) out of checklists could be observed with a drone in both of the experiments. The UAS in the experiment provided a much more convenient way of capturing images and documenting the condition of the bridge than with traditional methods. A key advantage of drone deployment is the reduced need for a UBIT. UBIT often requires closing a lane of traffic and placing BIEs in harm's way. This was the case with the Bates Bridge test site. Operating a UAS can be done away from traffic and be nearly invisible to the traveling public. With the experiments conducted, the time needed to inspect with the drone was equivalent to traditional methods. However, it is important to note that this was the first time the BIEs had used UAS technology to assist with their inspections. As the inspection progressed, the time it took to observe an inspection point decreased. As the technology becomes more commonplace, UAS inspections will likely be more time-efficient. The researchers found that using a UAS to augment in-person inspections will reduce the time needed for the UBIT, be safer, and improve documentation than traditional methods.

Cost Comparison

To further evaluate the use of this technology, a cost-saving analysis was conducted. The Bates Bridge has two lanes (one in each direction). One of the lanes was required to be shut down in order to stage the UBIT. This necessitated six traffic control workers to coordinate alternating flows of traffic on a single lane safely. Traffic control also required two illuminated signs, six stationary signs, and approximately 75 cones. A crash attenuator trailer was staged behind the UBIT. Additionally, because the bridge was located over a waterway, a boat and an operator were deployed for emergency water evaluations. The inspection started at approximately 8:00 am and finished at 5:00 pm for an 8-hour workday. A summary of the approximate costs is provided in Table 1. The unit costs used were from published state DOT average costs databases, and when not, available RS Means by Gordian (Data 2017). The estimated cost to conduct this inspection using traditional methods was $5,242.

Table 1: Comparative Estimate of Traditional vs. UAS Augmented Bridge Inspection

	Traditional Inspection				UAS Augmented Inspection			
Cost Item	Qty.	hrs.	Unit Cost	Cost	Qty.	hrs.	Unit Cost	Cost
Bridge Inspection Engineer	3	8	$53.40	$1,281.60	3	8	$53.40	$1,281.60
Traffic Control Worker	6	8	$20.55	$986.38	6	4	$20.55	$493.19
Safety Spotter / Boat Operator	1	8	$22.55	$180.40	1	4	$22.55	$90.20
Under Bridge Inspection Truck	1	8	$298.60	$2,388.82	1	4	$298.60	$1,194.41
Illuminate Signs	2	8	$3.77	$60.28	2	4	$3.77	$30.14
Traffic Control Signs	6	8	$0.05	$2.28	6	4	$0.05	$1.14
Boat	1	8	$6.22	$49.78	1	4	$6.22	$24.89
Crash Attenuator Trailer	1	8	$33.19	$265.50	1	4	$33.19	$132.75
Cones	75	8	$0.05	$27.00	75	4	$0.05	$13.50
Drone Rental (lump sum)	0	0	$450.00	$0.00	1	n/a	$450.00	$450.00
Safety Spotter / Visual Observer	0	0	$22.55	$0.00	1	4	$22.55	$90.20
Total Costs				$5,242.03				$3,802.01
Difference								$1,440.02

To assess the savings a UAS could provide, several assumptions need to be made. As determined in experiments #1 and #2, not all inspection points could be seen with the UAS, so even if a drone was deployed, a UBIT would still be needed, albeit for a shortened time. It was not practical to time how long it would take to inspect only the inspection points that could not be seen (approximately 9% of the inspection points), so a professional judgment was made. It took approximately 8hrs to inspect the bridge using traditional methods, so the researchers are assuming that if one removes 91% of the inspection points, the remaining 9% could be inspected with the UBIT in 4hrs. This includes time to mobilize, demobilize, and inspect under each bent. It is also assumed that once the unfamiliarity of the UAS and initial instruction time is removed, inspection of 91% of the inspection points could be observed with the drone in 4hrs. Essentially, the overall inspection time would remain the same, but the equipment and traffic management resources would be reduced by half. Hence, the estimated cost to inspect the Bates Bridge with the UAS was found $3,802, as itemized in Table 1. This is a savings of approximately $1,440 for a single bridge.

Challenges of Drone Technology with Bridge Inspections

Despite the advantages, there are still several significant limitations of the technology that at present can only be met by in-person inspections. One example is that with traditional inspections, tactile contact with the structure is required. This includes chipping away loose concrete or rust and also sounding out material such as woodpiles. Another limitation is the difficulty in flying under bridges where GPS signals are blocked. When GPS is available, especially when an RTK ground station is used, commercially available UAS can hold a static position with very little drift even in the presence of wind. However, under a bridge, the GPS signal is lost, and the aircraft is susceptible to drift. On-board accelerometers and proximity sensors help stabilize the system, but flight controls are challenging for even seasoned pilots. The researchers found that much of the inspection can be performed under and to the side of the bridge where a GPS signal can be established and can zoom and angle up to the underside of the bridge of interest. Taller bridges allow for a more aggressive angle improving the field of view. Using lower-cost drones may be more advantageous than higher performance rigs with zoom cameras for under-bridge inspections. Lower cost drones would be utilized to fly closer to observe the bridge when an increased risk of collision exists when such risk would be offset by the lower cost to replace the unit. Bridges with vegetation around them also limit the value of drone use. Even with a GPS lock established, a small branch, which may not be detected by on-board sensors or visible in the pilot's first-person view screen, could cause a crash if it collides with the propellers.

CONCLUSIONS

After the two experiments, the overall opinion of both BIE crews of the technology was positive. Over 90% of the inspection points could be sufficiently observed using the drone. The 30x optical zoom sensor significantly reduces the need to fly close to obstructions. The researchers found flying in a GPS denied environment difficult and that the RTK provided little value. However, much of the inspection could be performed to the side of the bridge, where the GPS signal was maintained. An alternative approach discussed is to use a smaller, less costly airframe in GPS denied areas. A significant advantage of drone deployment noted was the reduced need for a UBIT. A UBIT often requires closing a lane of traffic and placing BIEs in harm's way. Operating a UAS can be done away from traffic and be invisible to the traveling public. With the experiments conducted, the time needed to conduct the inspection with the drone was equivalent to that of traditional methods. However, as familiarity with the drone increased, so also did the inspection speed. BIEs gave significant feedback on several key points that can and cannot be observed by the drone.

The researchers found that drones can be an invaluable tool for bridge inspections. The drone has the benefit of observing some inspection points significantly faster and from a location that does not put the BIE in harm's way. Additionally, using a drone allows the operator to document the asset's condition conveniently and more thoroughly when not using a UBIT. A cost estimate was created for inspecting the bridge using traditional methods and when using a UAS. It was found that deploying the UAS would have an estimated cost savings of approximately $1,500 for this test bridge.

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