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16. ABSTRACT

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Assessment of Graffiti Removal Practices and Initial Development of a Tool for Removing Graffiti from Retroreflective Signs

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AHMCT

Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
Division of Research and Innovation

Abstract

This project is aimed at improving the efficiency of Graffiti Abatement in the State of California. Initial efforts provided an assessment and classification of the graffiti problem and an evaluation of best practices. A comprehensive literature search was performed, along with interviews with several individuals working in the field of graffiti removal. It was determined that, with the exception of signs along the roadway, graffiti removal techniques are largely well developed and well established. However signs, especially retroreflective signs, continue to be a source of difficulty in areas that are hard-hit by graffiti. The goal of the project then focused on the initial development stages of a tool designed to allow a maintenance worker to clean roadway signs from the ground. This report thus presents a conceptual design of such a tool. Due to the sensitivity of the surface of the signs, it was determined that testing solely on the interface between the end effector and the sign needed to be performed. Thus the focus of the report shifted from overall development of the tool to specific design of the end effector in the form of experiments with different characteristics of the tool. The results of the experiments showed that, in order to avoid damaging the sign, the end effector must use a soft scouring pad type of removal medium. They also showed that it was feasible to continue development of the tool.

Executive Summary

The goal of this project is to begin the initial development stages of a tool designed to allow a maintenance worker to clean roadway signs from the ground. Before this idea could be explored, it was first necessary to determine the current best practices for graffiti removal. To this end, a comprehensive literature search was performed, along with interviews with several individuals working in the field of graffiti removal. It was determined that, with the exception of signs along the roadway, graffiti removal techniques are largely well-developed and well-established. However signs, especially retroreflective signs, continue to be a source of difficulty in areas that are hard-hit by graffiti. Further interviews were conducted with sign maintenance personnel in Caltrans, and needs regarding graffiti removal from signs were identified. Development on the tool began, culminating in a final design proposal.

However, due to the sensitivity of the surface of the signs, it was determined that testing solely on the interface between the end effector and the sign needed to be performed. Thus the focus of the report shifted from overall development of the tool to specific design of the end effector in the form of experiments with different characteristics of the tool. The results of the experiments showed that, in order to avoid damaging the sign, the end effector must use a soft scouring pad type of removal medium. They also showed that it was feasible to continue development of the tool.

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Disclaimer

The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, within the Department of Mechanical and Aeronautical Engineering at the University of California, Davis and the Division of Research and Innovation at the California Department of Transportation. It is evolutionary and voluntary. It is a cooperative venture of local, state and federal governments and universities.

The contents of this report reflect the views of the author(s) who is fare and responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the STATE OF CALIFORNIA or the FEDERAL HIGHWAY ADMINISTRATION or the UNIVERSITY OF CALIFORNIA. This report does not constitute a standard, specification, or regulation.

Chapter 1. The Problem of Graffiti

1.1. Introduction

This chapter will examine the current best practices of graffiti removal. These methods were culled not only from an extensive literature search, but also from numerous interviews with individuals working in graffiti removal. First, the methods by which paints adhere to a surface and cure will be examined. Then, a list of the current best practices will be discussed, followed by the results of the interviews. Then the problem of graffiti on signs, especially retroreflective ones, will be closely examined. Finally a summary of the remaining content of the report will be presented.

1.2. Project Preface

For a number of years, graffiti has been a growing problem in most metropolitan areas across the nation. The estimated cost of abatement in 2007 in California alone was upward of $350 million dollars [1], and in 2008, Caltrans spent over $6 million removing graffiti along the roadways, the majority of which was spent in districts 7 (LA/Ventura), 11 (San Diego) and 4 (Bay Area) [2]. For Caltrans, graffiti mostly shows up on soundwalls, overpasses, center dividers, signs and various buildings such as those in rest areas. Dealing with the graffiti can be time consuming and hazardous work, and may also involve lane closures that impede the flow of traffic. However, before the work can begin on developing a solution to this problem, the current practices related to it must be highlighted.

1.3. Formation and Structure of Paint Films

In order to fully understand the mechanisms by which paint removal methods work, it is advantageous to examine how the paint films are formed in the first place. There is a vast array of types and chemistries of paint formulas, the descriptions of which lie outside the scope of this report. Instead it will focus on the formation of a general non-aqueous-based paint film, such as that of spray enamel, since this is the most commonly used type for graffiti.

Paints are comprised of four basic ingredients: pigments, solvents, binders and additives. Of these, the last three play the most important role in film formation, as the pigment only serves to add color. Generally, the liquid paint is comprised of short-chain polymers of various types (for spray enamels, the most common is poly(methyl methacrylate), or PMMA) dissolved in some sort of volatile solvent, with additives used to control either the liquid or solid characteristics of the paint. Ultimately, it is the paint's binder that is responsible for its adhesion to a surface as well as its characteristics when cured [3].

When paint is applied to a surface, it either sticks or runs off. The main factor controlling this behavior is the free energy of the surface; so long as the surface has a higher free energy than the surface tension of the paint, the paint will thermodynamically wet the surface, flowing onto and attaching to it [3]. Generally, non-aqueous solvents have surface tensions around 20-30 mN/m (dyn/cm in non SI units), polymers and resins between 30-50 mN/m, and porous or raw materials such as concrete and metals may have surface energies in the hundreds. However, some coatings, such as fluoropolymers or polysiloxanes, have surface energies below 20 mN/m, and are actively being researched as possible anti-graffiti coatings [4-6].

Once applied, the paint immediately begins curing. First, the solvent in the paint begins evaporating out of the paint (in spray-applied paints, a large percentage of this process takes place while the atomized paint is airborne, between the nozzle and the surface). This allows the polymers in the paint to begin crosslinking to each other through intermolecular forces, most often a combination of covalent bonding combined with van der Waals forces, although in some coatings ionic bonding may also be present. While the paint is curing, the glass transition temperature (T_g, the temperature above which the paint behaves as a liquid, and below which it behaves as a solid) begins to rise. As it rises, the paint changes from a (possibly) loose liquid, to a more viscous liquid, and eventually a tough solid. If T_g rises too high, the paint may become quite brittle and inflexible; additives such as plasticizers are often added to prevent this. Once T_g rises above ambient temperature, the curing process slows down dramatically, as it becomes more difficult for solvent molecules to migrate out of the dense network of crosslinked polymers [3]. Thus, paints may not fully cure for quite a long time, hence the importance of the timeliness of graffiti removal.

1.4. Methods of Graffiti Abatement and Removal

This section covers the current best practices for graffiti abatement and removal. There is much literature available on the subject, which covers a wide array of surfaces and techniques. However, only graffiti abatement on concrete masonry and metal surfaces will be covered, since these comprise the majority of the types of surfaces that Caltrans would be cleaning.

There are essentially six graffiti abatement methods: Chemical methods, including sacrificial and non-sacrificial surface treatments; pressure washing, abrasive removal, repainting, laser removal and structural modification. Some of these methods may be combined with each other. However, it should be noted that the most effective methods involve not just cleaning, but also timeliness. Removing graffiti soon after it appears is essential for two reasons: First, the offending materials will not have cured completely, easing their removal [7]. Second, there is a psychological effect on seeing one's work destroyed so soon after its creation, which will lead the graffiti artist to seek out a different location to paint. Additionally, graffiti tends to attract more graffiti, so keeping surfaces clean goes a long way towards abatement [8]. The significance of these effects implies that, whatever removal method is chosen, it is important that it can be applied very quickly and on short notice.

1.4.1. Chemical

Chemical methods use solvents of various natures to soften or dissolve the markings for removal. These solvents are either acidic, alkaline or organic; however, it should be noted that acidic solvents are generally poor at removing paint from surfaces, and in addition tend to aggressively attack calcareous surfaces (such as concrete) [9]. Chemical removal methods are generally coupled with water pressure washing (~2-7 MPa (~300-1000 psi)) as a way to speed up the removal process; sometimes hot water is used.

Chemical methods may be used on three different surface types: untreated, treated with a sacrificial coating, and treated with a non-sacrificial coating.

1.4.1.1. Untreated Surfaces

Generally the best method of removing graffiti from an untreated concrete surface is by making a poultice of absorbent or powder-inert clays or cellulose product mixed with a cleaning solution. This paste is then applied to the stained area and allowed to sit and work; it is sometimes covered with plastic sheeting to slow evaporation. The purpose of this is to allow the cleaners to work for an extended period of time only on the marked surface, and to allow the poultice to pull out the staining material without redepositing it. After a length of time, the poultice is removed and the surface is pressure washed with relatively low pressure [9].

Recognizing that a poultice may take an inordinate amount of time to prepare and use, there are commercial paint removers that come in a thick gel form; however, care must be taken in using these, as their improper use may result in the staining material to be redeposited on a previously clean part of the surface [7, 9]. It is recommended that the manufacturer's instructions always be followed very closely.

Untreated surfaces are cleaned with either alkaline or organic solvents, depending on the type of material being removed and the surface it is on. Each has its pros and cons, summarized in Table 1-1.

Cleaner type	Pros	Cons
Organic	• Good for non-water soluble markings • If used with poultice, draws material from deep in surface • Evaporate completely, leaving no residue	• May be flammable, or pose toxic risk • May cause migration of stain deeper into surface, causing ghosting • Fast evaporation may reduce working time
Alkaline	• Stain will not migrate into pores of surface • Longer working time	• Concentrated chemicals are dangerous • Must be properly neutralized, or staining may occur • May react with iron compounds, creating stains

Table 1-1: Pros and Cons of Organic and Alkaline Cleaners [9]

These chemicals work by way of the cleaner infiltrating into the crosslinked polymer network, swelling and loosening it as it does so. Eventually the paint becomes soft enough that it can be removed with a pressure washer, although it should be noted that the paint (at least the ones which are nuisances) never regains its former liquidity.

1.4.1.2. Sacrificial Coatings

Sacrificial coatings are surface treatments that are removed when any graffiti is removed, which necessitates their reapplication. Most of these are a two-part system: first, a semi-permeable sealer is put on the surface, and then a polyethylene wax emulsion or dispersion coat is put on over that. When the graffiti is removed, so is the top coat, which must be reapplied. Over time, the initial sealer coat may degrade and need reapplication as well.

Generally, the graffiti adheres well to the sacrificial coating, so the mechanism of removal depends not so much on destroying the graffiti itself as it does removing the soft, waxy coating to which it is attached. This is generally quite easily achieved with a pressure washer [10].

1.4.1.3. Non-sacrificial Coatings

Non-sacrificial coatings are not washed away when the graffiti is, thus reducing the need for their reapplication (they still may degrade over time and need freshening up). The most effective of these surfaces are fluoropolymers (like Teflon), which are hydro- and oleophobic and cause paint to ball up and run off. However, these may be expensive, so silicone-based coatings like siloxanes may be a better choice [11]. Essentially these coatings work by having a lower surface energy than the surface tension of the paint being applied to it. Thus the paint is unable to properly wet the surface, instead being more attracted to itself, which causes it to bead and run off [6].

One issue with non-sacrificial coatings is if they degrade in one area, it may be difficult to reapply the coating, because their very nature makes it difficult for subsequent coatings to adhere. It may be necessary instead first to remove the old coating, and then apply a new coating [12]. Of course, this increases the time and cost associated with this method, as well as the risk of damage to the substrate, but should be a quite infrequent course of action, as any non-sacrificial coating should be chosen for its durability.

The aim of each of these coatings is to keep the markings from penetrating into the substrate, keeping them on the surface for easy removal. Generally they also seal the substrate from the environment. This can be a problem with masonry, as it is unable to breathe, and adhesion or staining problems may arise in the interface between the sealing coat and the surface of the substrate [9]. Breathable coatings do exist, but are generally not as effective in preventing the adhesion of graffiti.

1.4.2. Pressure Washing

Pressure washing in and of itself is not very useful in graffiti removal. Using pressures high enough to remove the stains by brute force increases the risk that the surface being cleaned will also be damaged, but using pressures low enough not to cause damage to the substrate is ineffective in removing the offending material completely [9]. However, when combined with chemical methods, it is very useful, generally for washing off the chemicals used for removal, whether they are a poultice or a sacrificial coating.

1.4.3. Abrasives

Abrasive cleaning methods use some sort of abrasive media, e.g. sand, baking soda, walnut shells, etc. and spray them at high pressure onto the surface to be cleaned. This method tends to be very effective at removing graffiti, but carries an extremely high risk of damaging the substrate as well. Additionally, a large amount of waste material is created that must be contained and removed from the site. The amount of dust associated with this method as well as the presence of abrasives under high pressure may require the operator to wear more safety gear. Abrasives tend to be useful only on unpainted or untreated surfaces, and some greater measure of success (in terms of lack of substrate damage) has been found with the use of softer blast media such as walnut shells or sodium bicarbonate, or by adding water to and using lower pressures with harder blast media such as sand or pumice.

Abrasive methods work by mechanically breaking up the coating, which being below its glass transition temperature is usually fairly brittle. The shock of the impinging abrasive causes the coating to crack and break off of the surface.

Following are four methods of abrasive blasting, chosen because of their widespread use or possibility for successful graffiti removal. It should be noted that no abrasive methods are suitable for use on signage.

1.4.3.1. Sandblasting

Sandblasting uses dry silica sand as a blast media. This produces a large amount of silica dust, so operators must wear protective clothing and ventilation equipment, and containment and cleanup is necessary. However, wet blasting with sand greatly reduces the airborne environmental toxicity, although containment and cleanup is still required.

1.4.3.2. Sodablasting

Sodablasting uses sodium bicarbonate as a blast media. It is non-toxic and, because it is a softer material, it carries a much lower risk of substrate damage [13]. However, it tends to be slower.

1.4.3.3. Dry Ice Blasting

This method uses pellets of dry ice as a blast media. Because the dry ice sublimates, it leaves behind no waste, other than the removed material. The dry ice is too soft to remove material by abrasion; rather it absorbs heat from the surface, which produces stresses due to thermal shock and causes the material to pop off. Since dry ice is -61°C (-78°F) at standard pressure, gloves must be worn while handling, and if it is used in an enclosed space then ventilation is necessary due to asphyxiation danger [14].

1.4.3.4. Pumice Blasting

In this method, pumice is used as the blasting media, and success has been reported using a medium-pressure pumice wet blast. There is no dust hazard, and the waste requiring cleanup is a paste-like material that is easily retrieved [15].

1.4.4. Repainting

Currently, painting over graffiti is the leading method for graffiti removal, as it is the least expensive and time-consuming method. Although it is best if the paint used is an exact match to the original color of the surface, often colors that are close are used since they can be cheaper or even free (donated). Generally, the best results are achieved if the graffiti is painted over as quickly as possible using large blocks of color, and not merely outlining the markings. Some materials also have the ability to bleed through subsequent layers, so it may be necessary to apply a stain-blocking primer first, or to remove the graffiti before painting over it.

Some programs use roving vehicles with on-board paint matching systems, so colors can be matched on the fly, or they will carry common paint colors used in that district.

1.4.5. Laser Removal

This technique uses laser ablation to remove material from the surface of the substrate. The laser is usually pulsed by Q-switching (in the nano- to microsecond region, about 50-60Hz) and operates in infrared wavelengths (~1-2μm). It heats up the paint, which expands and due to rapid thermal expansion, pops itself off of the surface, vaporizing a little in the process. Because the laser is rapidly pulsed, the substrate does not have time to heat up. This difference in temperature between the cool surface and the rapidly heated material coating it causes mechanical removal of the material. It is a very effective process, often returning the substrate to its original condition, and it is useful for many surfaces, both porous and non-porous (although it is less effective on plastics) [16]. Because both the pulse length and the fluence of the laser can be adjusted, material can be removed to a very specific depth. This makes it an ideal choice where a fine degree of control is necessary (this method is also used in arts conservation) [17].

The lack of waste generated with this method is also one of its major benefits. Compared with chemical or abrasive methods, which result in a large amount of waste material that must be contained and disposed of, the only waste generated from laser ablation is the material that has been removed from the surface. It is easily captured and filtered out of the environment with a vacuum system. If this method for capture is used, then the level of toxicity associated with the operation is greatly reduced as well, eliminating the need for large amounts of protective gear [18].

The main drawback to laser ablation is the speed with which it removes material. Although the area in the fluence is cleaned completely with very few pulses of light, that area itself is quite small. At best, it takes roughly 10 minutes to clean a square meter of surface, which in heavily trafficked areas is not fast enough (though it should be noted that this is a solid square meter of marking; cleaning just the markings and not the surrounding area should be faster) [16].

Another drawback to laser ablation is its poor performance on plastics, which generally constitutes the covering on retroreflective signage. Tests have shown that using lasers on these signs leaves a residue that must then be cleaned off, which reduces the overall effectiveness of this technique. Also, because the graffiti and the sign sheeting are both polymers, there is an increased risk of damage to the sign if it experiences too great of an exposure to the laser [19]. Due to these two drawbacks, and the expense of the equipment, there are currently no ablative products specifically designed for graffiti removal on the market.

1.4.6. Structural Modifications

This method attempts to pre-empt graffiti by preventing taggers from reaching the surface, in this case generally signs. It involves modifying the paths taggers take to get to the surface, and can be either some sort of physical barrier or keeping the surface out of reach.

Physical barriers in the form of fencing, concertina wire, “cheese graters” (Figure 1-1), “cobra shields” (Figure 1-2) and other styles aim to make it impossible to climb to or otherwise reach the surface of a sign or wall. They have varying degrees of success, which really depends on how determined a tagger is. Inventive vandals can still breach them, but with increased risk of personal harm. Generally, though, they are quite effective in deterring graffiti, so long as they are sturdy enough. Cyclone fencing, for example, is easily cut and gives no real protection.

Success has also been reported by moving surfaces out of reach. For example, signs on surface streets that see high pedestrian traffic are tagged quite often. Moving these signs higher than the currently required seven feet greatly reduces the amount of graffiti present on them, simply because taggers cannot reach them as easily [20].

Figure 1-1: "Cheese Grater" Barrier

Figure 1-2: "Cobra Shield" Barrier

1.5. Interview Results

Fourteen people working in graffiti abatement programs in major metropolitan areas around the country were interviewed and asked questions about the methods that their department uses and how effective they are. Following are the compiled results from those interviews, and **Table 1-2** shows the relative frequency of use of different methods by each department, along with those that are not used. The actual questionnaire and resulting answers from each department can be found in Appendix A: Results of Interviews.

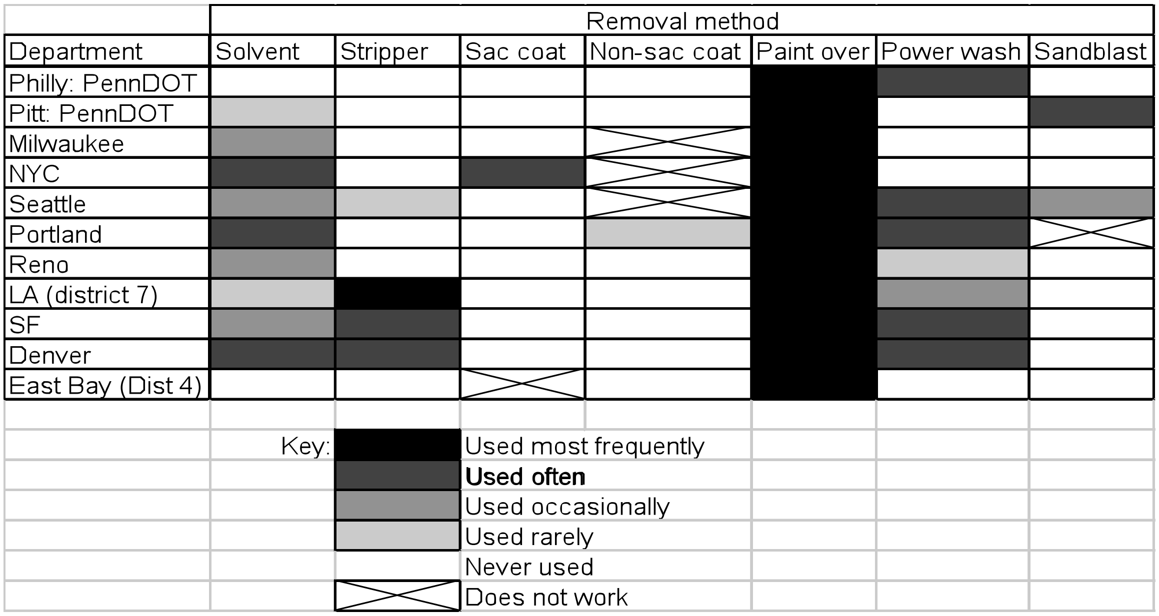

Table 1-2: Frequency of use of various graffiti removal methods

1.5.1. What Works

The methods of abatement used depend largely on the surface from which graffiti is being removed. For example, it is pointless to talk about the effectiveness of using blasting methods for removal from the fronts of signs, as the damage to the sign completely precludes it.

The most common method of abatement on masonry is by far painting over the offending marks. Whether a paint-matching system or typical color scheme is used varies evenly between departments, but overall it is reported that overpainting represents the fastest, safest and most economical solution which requires very little operator training. This method is used for painted concrete, painted metal, the backs of signs, and often unpainted concrete and wood. One of the major drawbacks to this method is the aesthetics of the overpainting which sometimes invites more graffiti, and to a lesser degree the possibility of the new paint being affected by the underlying graffiti (e.g. bleeding through, additives added to graffiti paint, etc.).

The second most common removal method for unpainted concrete is power washing, followed by a combination of chemicals and power washing, then sandblasting. However, most departments report that sandblasting does not work due to surface degradation and, to a lesser extent, etching the paint more firmly into the surface. Only two of the departments surveyed use sandblasting as a primary means of removal.

For signage and some painted metal surfaces, most departments use a solvent-based cleaner (which is the second most common method used, albeit on non-masonry surfaces). A few departments use them on masonry as well, but there is a danger of ghosting unless it is painted over.

1.5.2. What Does Not Work

All interviewees stated that the reason for choosing the methods they use is because they work well. Hence, the methods that they do not use have not worked well for them, whether because of time, expense, or sheer ineffectiveness.

With the exception of one department that is extremely pleased with their effectiveness on newer masonry walls, everyone who has used sacrificial coatings has reported that they are too time consuming or too expensive. One person expressed concern at their use around waterways and storm drains; as they must be power washed off, they are usually carried to a local waterway, which may violate local point-source pollution regulations.

Everyone who has tried non-sacrificial coatings has been displeased with them, because they begin degrading after only a few rounds of power washing and are difficult to reapply because the new coat does not stick to the old one.

Most departments report that there are a wide array of solvent-type cleaners, which tend to be citrus- or soy-based, that are either too slow or do not work at all.

Most departments report that blasting methods have limited effectiveness. Sandblasting either etches the paint into the surface, or completely destroys the surface. Soda blasting reportedly tends to be too slow to use. One system using a mix of pumice, ash and hot water (manufactured by Farrow System USA) worked well but was cost-prohibitive.

None of the departments have tried laser ablation.

1.6. The Problem of Graffiti on Signs

Generally speaking, the methods used for removing graffiti from most surfaces are well developed and effective, and the problem of graffiti tends to be one of sheer volume rather than difficulty in removal. Along the roadways, overpainting accounts for nearly all abatement simply because masonry and other painted surfaces are the most prevalent type of structures. However, one of the most difficult surfaces to clean continues to be that of signs, as they are difficult to reach and in high-traffic areas, they cannot be simply painted over, and their surfaces are reportedly quite susceptible to damage from improper cleaning [21].

Graffiti on signs can be hazardous if it obscures enough text that a driver misses important information. Additionally, there are federally mandated minimum maintained retroreflectivity levels below which a sign should be replaced; see Table 1-3. Obscuration or damage to the sign face could cause retroreflectivity to be below these levels, which would require replacement of the sign, and in areas especially hard-hit by graffiti, repeated sign replacement could become quite costly.

Sign Color	Sheeting Type (ASTM D4956-04) ①				Additional Criteria
	Beaded Sheeting			Prismatic Sheeting	
	I	II	III	III, IV, VI, VII, VIII, IX, X	
White on Green	W* G ≥ 7	W* G ≥ 15	W* G ≥ 25	W ≥ 250; G ≥ 25	Overhead
	W* G ≥ 7	W ≥ 120; G ≥ 15			Ground-mounted
Black on Yellow or Black on Orange	Y*; O*	Y ≥ 50; O ≥ 50			②
	Y*; O*	Y ≥ 75; O ≥ 75			③
White on Red	W ≥ 35; R ≥ 7				④
Black on White	W ≥ 50				—

① The minimum maintained retroreflectivity levels shown in this table are in units of $cd/lx/m^2$ measured at an observation angle of 0.2° and an entrance angle of -4.0°.
②For text and fine symbol signs measuring at least 1200 mm (48 in) and for all sizes of bold symbol signs
③For text and fine symbol signs measuring less than 1200 mm (48 in)
④Minimum Sign Contrast Ratio ≥ 3:1 (white retroreflectivity ÷ red retroreflectivity)
* This sheeting type should not be used for this color for this application.

Table 1-3: FHWA mandated minimum retroreflectivity levels [22]

1.6.1. Retroreflectivity

Because many signs incorporate a retroreflective layer, it is important to understand how retroreflection works, what the Coefficient of Retroreflectivity (R_A) is, and how it is measured on signs.

Retroreflection is when light is reflected back towards the source along a vector parallel to the incident rays. This is achieved either by using a spherical refractive medium, such as glass beads, or a corner cube, which is composed of three mutually perpendicular reflective planes [23]. For a retroreflective surface such as that on a sign, the elements used for reflection are small and numerous. Older styles have microscopic glass beads encapsulated in small sections across the surface of the sheet (Figure 1-3), but these films have largely fallen out of use in favor of microprismatic films (Figure 1-4). These films use a microprismatic structure (Figure 1-5) that reflects incident light more efficiently than the glass bead types, however they are more susceptible to damage from excess pressure deforming the structure.

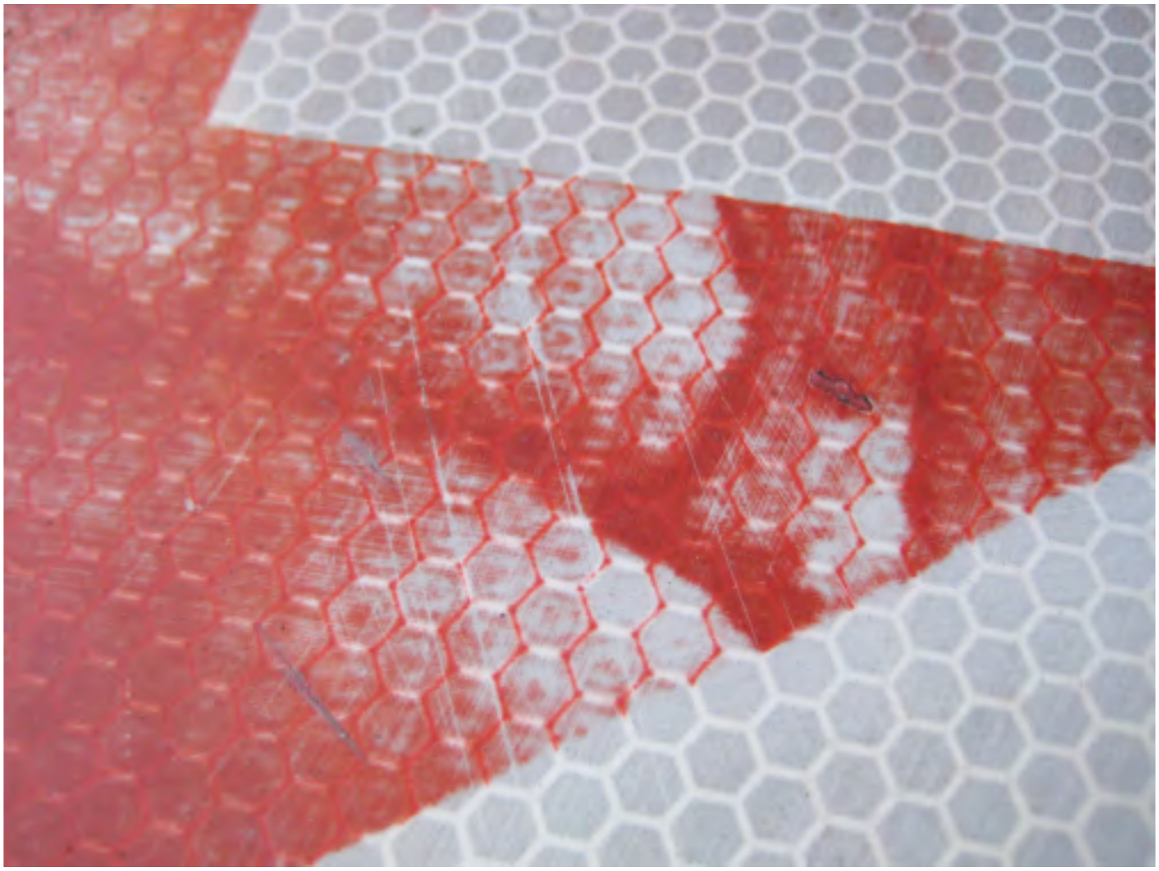

Figure 1-3: Encapsulated glass bead film

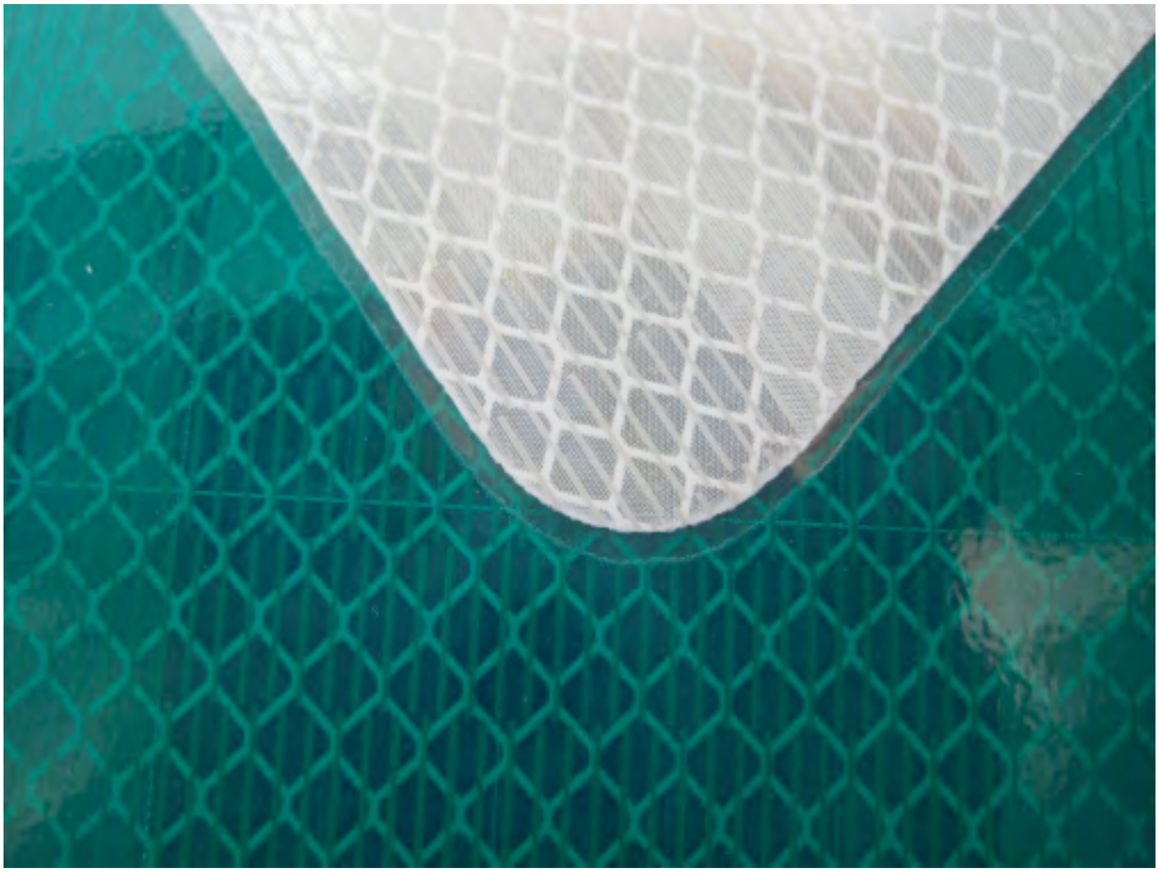

Figure 1-4: Microprismatic film, different layers of lettering and background

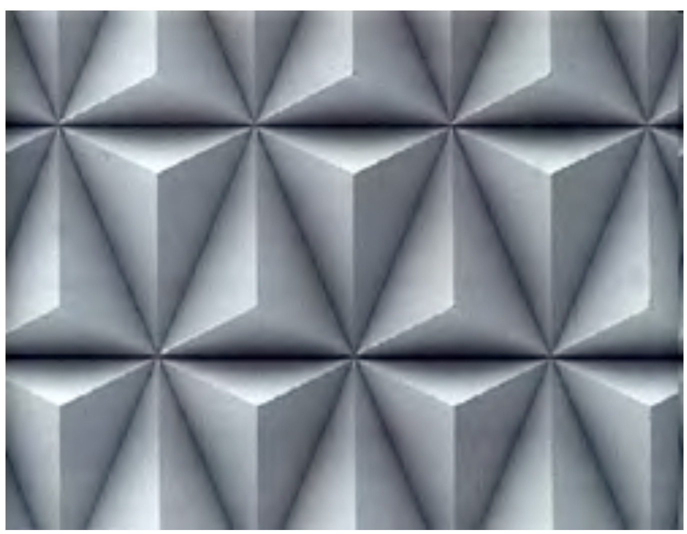

Figure 1-5: Close-up of microprismatic film

The coefficient of retroreflectivity is defined as the ratio of the coefficient of luminous intensity to the area being measured. This can be expressed in SI units as candelas per lux per square meter $\left[\frac{\frac{cd}{lx}}{m^2}\right]$, but this reduces to be dimensionless, so R_A is usually expressed as a pure number. The coefficient of luminous intensity is defined as the ratio of luminous intensity of the retroreflector in the direction of observation to the illuminance at the retroreflector on a plane perpendicular to the direction of incident light [23], and is expressed in candelas per lux. In layman's terms, R_A is basically the amount of light that is reflected back towards the source as compared with the amount of light that falls on the surface. Expressed in another way, it describes the efficiency with which the retroreflector reflects the light that hits it. Microprismatic films are more "efficient," thus their use has increased and the use of encapsulated glass bead films has decreased.

For measuring R_A on signs, geometry plays a significant role because the amount of light reflected changes based on the locations of the source and the observer. The best case for retroreflection is when the source and the observer are in line with each other. However, in a vehicle, the source (headlights) and the observer (driver) are not in line with each other, but are separated by a significant distance. This geometry is taken into account when measuring R_A for signs; for the measurements made for FHWA minimum retroreflectivity standards, the entrance angle of the source must be -4°, and the observation angle of the receiver must be 0.2°, as seen in Table 1-3. Both are coplanar and are measured with respect to the normal to the plane of the retroreflective surface.

1.6.2. The Structure of a Sign

In order to understand what makes a sign so delicate, it is advantageous to know how they are constructed. The substrate of the sign is 1.588 mm (1/16 in) 6061-T6 sheet aluminum, and larger signs also may have structural members bolted on to improve stiffness. Next, a retroreflective layer is usually added. Next, color inks are often applied to the sign. These inks are transparent, which allows the sign to remain retroreflective, but are susceptible to damage from harsh chemicals or abrasion (Figure 1-6). Next, lettering of a different color that is made from retroreflective film may be applied (Figure 1-4). Finally, the whole sign may be covered with a protective overlay film which is intended to make graffiti less likely to stick and easier to remove.

Much older reflective signs have the background color painted on and the lettering in non-reflective decals (Figure 1-7), and some have small round prismatic reflectors embedded in raised lettering (Figure 1-8).

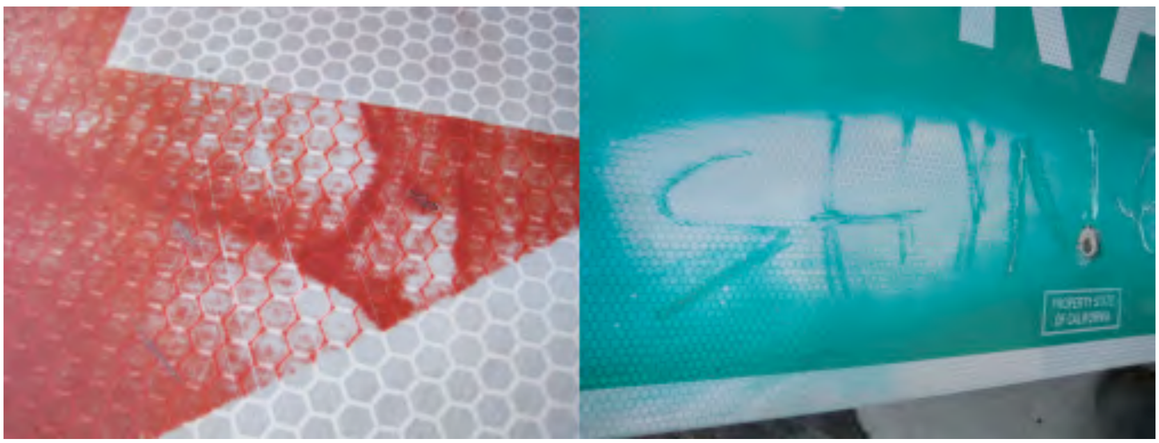

Figure 1-6: Damage to graphics from abrasion and chemicals

Figure 1-7: Older sign with non-reflective decals

Figure 1-8: Older sign with reflectors in raised lettering

1.6.3. Issues with Cleaning Signs

The difficulty in cleaning signs is twofold: the delicate surface of the sign, and the methods required to clean it.

The surface of the sign is susceptible to three different kinds of damage: damage to the retroreflective layer from excess application of pressure, damage to the overlying polymer film from scratching and/or clouding, and damage to any unprotected graphics. Careless cleaning of a sign may subject it to any combination of these types of damage, although usually if the retroreflective layer is damaged, then the overlying layers are too. The surfaces of the non-retroreflective signs described in the previous section are not particularly susceptible to damage since they are not reflective. However, the ones with the raised lettering may present a problem because they have small crevices, which may be difficult to clean.

Signs are often placed at or above head level, requiring maintenance personnel either to clean with their arm stretched over their head, which is uncomfortable; up on a ladder, which can be hazardous, especially on uneven ground; or in a personnel lift, which can impede the flow of traffic if lane closures are required (Figure 1-9). The signs are cleaned using a chemical applied by hand and wiped off with a rag, and any drips must be captured by an absorbent cloth laid out on the ground, in accordance with environmental regulations. The chemical, once applied, must be allowed to sit for a minute or so to take effect and begin softening the paint, then it is scrubbed around and wiped off, hopefully taking the graffiti with it. Sometimes several applications are needed, and a common complaint is that the chemicals work too slowly. Because the process takes a while to perform, and there are sometimes several signs in the area which require cleaning, the aim of cleaning the sign is not necessarily to get it clean, but to get it legible. Often this means that the graffiti on the sign is not completely removed but merely significantly reduced. Finally, because damage to the sign shows up as a reduction in retroreflectivity, and because the signs are cleaned during the day when one cannot tell if the reflectivity to the sign is damaged, it is difficult for a worker to know immediately if damage has occurred.

Figure 1-9: Methods of cleaning signs; far right requires a personnel lift

1.7. Summary of Report Content

The focus of this report will be the initial development stages of a tool aimed at addressing the difficulties associated with cleaning graffiti from the surface of retroreflective signs.

Chapter 2 will chronicle the development of a design concept for the sign cleaning tool, including needs identification, product specifications, candidate designs and a final design proposal.

Chapter 3 will examine some technical issues with component selection for the end effector, and will document the design and execution of an experiment aimed at resolving these issues. Then the results of the experiment will be revealed, along with a description of further tests and their results.

Chapter 4 will review the work done in this report. Some recommendations will be given for some of the critical components of the sign cleaning tool, as well as recommendations for further testing of these components. Finally, all of the work will be concluded.

1.8. Conclusion

This chapter began by demonstrating the problem of graffiti, especially as far as it concerns Caltrans. Then, the formation and structure of paint films was explained, and the current methods for dealing with graffiti on various surfaces were examined. Next, the results from interviews with Maintenance personnel working in the field of graffiti removal were revealed. Then, issues with graffiti on signs were examined. Finally, the remaining content of the report was presented.

Chapter 2. Development of a Design Concept for a Sign Cleaning Tool

2.1. Introduction

This chapter will cover the development of the concept for the sign cleaning tool following the methods outlined by Ulrich and Eppinger [24]. It will begin by taking a set of statements from maintenance workers about the current graffiti removal process and interpret them as a set of needs for the tool. Then, a set of metrics will be developed by which the performance of the tool may be compared to ensure that the needs are met. Finally, different concepts for key characteristics of the tool will be outlined and weighed, and a final design concept will be proposed.

2.2. Customer Statements, Interpreted Needs and Metrics

In the course of doing research on graffiti abatement methods, Caltrans maintenance personnel were interviewed about their experience with the subject, especially cleaning signs. Table 2-1 shows a distillation of those interviews into a set of statements regarding the current sign cleaning process in the first column, which is then interpreted as a set of customer needs for a sign cleaning tool in the second column.

Customer Statements	Interpreted Needs
Typical Method	
I need to clean graffiti from signs.	Sign Cleaner (SC) removes graffiti from sign
I need to clean signs quickly.	SC removes graffiti quickly SC can be set up quickly
Some signs are on pavement, some on uneven ground or hills.	SC can be used on rough or uneven terrain SC can be easily maneuvered around obstacles
I have a favorite cleaner I like to use.	SC can be used with different types of cleaners SC is made from inert materials
I use an absorbent rag to scrub the graffiti off.	SC removes excess cleaner along with graffiti SC applies scrubbing motion
The graffiti I clean is often higher than I am tall, but not always.	SC can reach both high and low marks SC is extendible
I often need to clean the same signs over and over again.	SC cleans sign while leaving it serviceable
Likes—Current Method	
It does not take up much room.	SC is compact
It is easy to use.	SC controls are easy to understand SC is light SC does not require much physical exertion SC is maneuverable SC is easily disassembled for cleaning Parts of SC are easy to replace
It is cheap.	SC uses off-the-shelf components SC is rugged and long-lasting
I can spot clean, and focus my efforts on the thickest paint.	SC can clean specific areas
I can throw it in my truck and forget about it until I need it.	SC is portable SC does not require much maintenance
I can use whatever chemical is best for that type of sign.	Cleaner type can be switched
Dislikes—Current Method	
I often have to get on a ladder or lift.	Worker can clean signs from the ground
I have to be careful not to damage the sign when I clean it.	SC does not damage sign
I cannot let any fluid drip on the ground; I need to catch it all.	SC recovers used cleaning fluid for disposal
It takes a long time to work sometimes.	SC cleans more quickly than current method
I have to put on gloves to use the cleaner.	Worker does not come into contact with chemicals SC does not expose worker to harm
Cleaning overhead signs requires a lane closure.	Overhead signs can be reached from the roadside
Suggestions for Improvement	
Something to scrub the paint off faster; we are told not to use anything because it scratches the sign.	SC abrades paint but does not mar sign
A way to know if the sign is not reflective enough.	SC checks retroreflectivity after cleaning

Table 2-1: Customer statements and interpreted needs

Table 2-2 shows these interpreted needs brought together into a hierarchical list, with importance ratings shown by the asterisks (3 = critical importance), with exclamation points indicating latent needs, or characteristics of the tool that are not expected but are very useful.

	The SC cleans graffiti faster than current method
***	SC removes graffiti from sign
**	SC removes graffiti quickly
*	SC cleans more quickly than current method
!	SC applies scrubbing motion
	The SC can be used anywhere
***	SC can be used on rough or uneven terrain
***	SC can be easily maneuvered around obstacles
!	Overhead signs can be reached from the roadside
**	SC is maneuverable
**	SC is portable
	The SC can accommodate any cleaner
***	SC can be used with different types of cleaners
**	SC is made from inert materials
**	Cleaner type can be switched
	The SC can reach all graffiti
***	SC can reach both high and low marks
*	SC is extendible
***	SC can clean specific areas
	The SC is easy to set up and use
**	SC can be set up quickly
***	SC controls are easy to understand
*	SC is light
	The SC does not damage the sign
***	SC cleans sign while leaving it serviceable
!	SC abrades paint but does not mar sign
***	SC removes excess cleaner along with graffiti
!	SC checks retroreflectivity after cleaning
	The SC is easy to store and maintain
**	SC is compact
***	SC is easily disassembled for cleaning
**	SC doesn't require much maintenance
	The SC is inexpensive to use
**	SC uses off-the-shelf components
***	Parts of SC are easy to replace
***	SC is rugged and long-lasting
	The SC is safe to use
***	Worker can clean signs from the ground
**	SC does not require much physical exertion
***	SC does not expose worker to harm
*	Worker does not come into contact with chemicals
**	SC recovers used cleaning fluid for disposal

Table 2-2: Hierarchical list of interpreted needs

Table 2-3 is the needs-metrics table for the sign cleaning tool, which shows a set of metrics that will be used to determine how well the needs are met by the tool.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	unit	ratio	s	s	m	kg	dBA	s	m	m/s	s	m^2	Subj.	m	s	s	US$	N	%	Subj.	Binary
	Metric	Coefficient of Retroreflectivity	Time to remove graffiti	Time to set up and break down	Height range of tool	Mass of tool	Noise produced by tool	Time of direct contact with chems	Radius of turn	Rate over rough terrain	Time to learn how to use tool	Area of end effector	Compatibility of cleaner and materials	Dimensions of tool	Time to disassemble	Operating time between maintenance cycles	Cost of tool	Force applied to end effector	Volume chem applied/Volume chem recovered	Tool applies scrubbing motion	SC checks retroreflectivity after cleaning
	Need																				
1	SC removes graffiti from sign	•																			
2	SC cleans sign while leaving it serviceable	•																			
3	SC abrades paint but does not mar sign	•																			
4	SC removes excess cleaner along with graffiti	•																			
5	SC removes graffiti quickly		•																		
6	SC cleans more quickly than current method		•																		
7	Cleaner type can be switched			•																	
8	SC can be set up quickly			•																	
9	Overhead signs can be reached from roadside				•																
10	SC can reach both high and low marks				•																
11	SC is extendible				•																
12	Worker can clean signs from the ground				•																
13	SC is light					•															
14	SC is portable					•															
15	SC does not expose worker to harm					•	•	•													
16	SC is easily maneuvered around obstacles					•			•												
17	SC is maneuverable					•			•												
18	Worker does not contact chemicals							•													
19	SC can be used on rough or uneven terrain									•											
20	SC controls are easy to understand										•										
21	SC can clean specific areas											•									
22	SC can be used with different types of cleaners												•								
23	SC is made from inert materials												•								
24	SC is compact													•							
25	SC is easily disassembled for cleaning														•						
26	Parts of SC are easy to replace														•						
27	SC is rugged and long-lasting															•					
28	SC doesn't require much maintenance															•					
29	SC uses off-the-shelf components																•				
30	SC does not require much physical exertion																	•			
31	SC recovers used cleaning fluid for disposal																		•		
32	SC applies scrubbing motion																			•	
33	SC checks retroreflectivity after cleaning																				•

Table 2-3: Needs-metrics

2.3. Breakdown of Target Specifications

Table 2-4 shows the target specifications that will determine whether the metrics of the sign cleaner meet the needs shown in the needs-metrics table in the previous section. These specifications have two values: a marginal value that is just acceptable but could use improvement if possible, and an ideal value that represents the need being met fully. Having marginal and ideal values allows some flexibility in the design of the tool, and may even need further iteration as the process moves forward. The choice of these values for the specifications is rationalized in the following sections.

Metric #	Need #s	Metric	Units	Marginal Value	Ideal Value
1	1,2,3,4	Coefficient of Retroreflectivity	ratio	<50	<25
2	5,6	Time to remove graffiti	s	<120	<60
3	7,8	Time to set up and break down	s	<240	<120
4	9,10,11,12	Height range of tool	m	0.6-3.6	0.6-4.3
5	13,14,15,16,17	Mass of tool	kg	14.8	<11
6	15	Noise produced by tool	dBA	92	75
7	15,18	Time of direct contact with chems	s	<600	<120
8	16,17	Radius of turn	m	<1	0
9	19	Rate over rough terrain	m/s	1.3	0.65
10	20	Time to learn how to use tool	s	<600	<300
11	21	Area of end effector	m^2	0.19-0.2	0.04-0.09
12	22,23	Compatibility of cleaner and materials	Subj.	--	--
13	24	Dimensions of tool	m	<2.5L <1.6W <0.6D Wand <2.5	<1L <1W <1D Wand <2.5
14	25,26	Time to disassemble	s	<3600	<900
15	27,28	Operating time between maintenance cycles	s	>480	>960
16	29	Cost of tool	US$	<1500	<1000
17	30	Force applied to end effector	N	37.8	37.8
18	31	Volume chem applied/Volume chem recovered	%	>90	>95
19	33	Tool applies scrubbing motion	Subj.	--	--
20	34	SC checks retroreflectivity after cleaning	Binary	no	yes

Table 2-4: Target specifications for sign cleaner

2.3.1. Coefficient of Retroreflectivity (RA)

As discussed in Section 1.6, there are federally mandated minimum maintained retroreflectivity levels for signs, the highest of which is for the white lettering on overhead signs, which must be replaced if it drops below 250. The average R_A for new white retroreflective film is around 600, so if a sign can sustain 5 cleanings before it is to be replaced, then that represents a drop in R_A of about 70 points on average per cleaning, which is acceptable. The ideal value would be a drop of 35 points or less on average, because that indicates that the sign could be cleaned 10 times, which is significantly better.

2.3.2. Time to Remove Graffiti

Current methods of graffiti removal from signs requires that after the chemical is applied, one must wait from 30 seconds to a minute for the chemical to take effect. Then, the worker must scrub the marks with a rag until the area is clean, which takes anywhere from a minute to three, depending on the thickness or age of the paint. If the sign cleaning tool is to compete with the current method in this respect, then the marginally acceptable time it takes to remove the graffiti is 120 seconds. The ideal value would be less than 60 seconds.

2.3.3. Time to Set Up and Break Down

For the sign cleaning tool, time to set up and break down refers to the amount of time between the point at which the worker pulls up to the sign in the field and the time s/he is ready to actively clean the sign, plus the amount of time between the point at which s/he is done cleaning the sign and the time s/he is in the service vehicle ready to leave. This metric could obviously vary quite widely depending on the location of the graffiti to be cleaned. If it is located on a low sign next to the road, it will obviously be much quicker and easier to clean than if it is on an overhead sign, which would most likely require a lane closure.

According to maintenance personnel, the most commonly tagged signs are the ones to which pedestrians have access. These are likely to be low- to mid-height signs, such as one- or two-post signs along freeways and around freeway entrances. They are less likely to be overhead signs; although these do get tagged, it is a much more difficult and risky endeavor, and thus does not happen as often. So for the metric, only the non-overhead signs will be considered.

Currently, in a worst case scenario, the worker cleaning the sign has to set up a ladder next to the sign and spread out an absorbent pad under the sign to catch drips before s/he can begin cleaning the sign. This setup takes roughly a couple of minutes to accomplish, and putting it all away takes another couple of minutes. Thus, the marginally acceptable value for this metric would be 240 seconds, and the ideal value would be under 120 seconds.

Note that for the tool it is assumed that it already has the cleaning fluid ready to apply, and does not count any time to fill any reservoirs with fluid. If, in the final design, the worker is required to add cleaning fluid to the tool each time it is used, then the time it takes to do this should be added to the time it takes to set up and/or break down.

2.3.4. Height Range of Tool

Maintenance personnel carry around a 1.8 m (6 ft) ladder in their vehicle, and assuming that the workers are roughly 1.8 m (6 ft) tall, this puts the upper range of reach at around 3.6 m (12 ft) before more specialized equipment, or a taller ladder, is required. The lowest edge of a two-post sign is usually set at 1.8 m (6 ft), but one-post signs, like those indicating a freeway entrance, are often much lower, down to around 0.6 m (2 ft). Thus, the marginally acceptable range for this metric would be 0.6-3.6 m (2-12 ft), with the ideal value being a little higher at 0.6-4.3 m (2-14 ft).

2.3.5. Mass of Tool

The National Institute for Occupational Safety and Health (NIOSH) devised an equation to determine the recommended maximum weight that can be lifted by a worker under certain predetermined conditions. Because these limits are dependent upon the geometry and location of the item being lifted, and the form and location of the tool is currently undefined, these values are taken to be rough approximations only, and will need to be more closely defined as the design progresses. However, if the tool is to be lifted manually be a single worker, it would need to be light enough and small enough to do so, so for the following calculations the form of the tool is assumed to be a large backpack.

The NIOSH Lifting Equation is

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM \tag{2.1}$$

where

- RWL = Recommended Weight Limit
- LC = Load constant, 23 kg
- HM = Horizontal Multiplier, 25/H, where H is the distance between the worker and the center of mass (CM) of the item
- VM = Vertical Multiplier, 1 - (0.003 |V - 75|), where V is the vertical height of the item from which it is lifted
- DM = Distance Multiplier, 0.82 + (4.5/D), where D is the vertical travel distance through which the item is lifted

- AM = Asymmetric Multiplier, 1-(0.0032A), where A is the angle between the asymmetry line and the mid-sagittal line. This is basically a measure of how much a worker must twist when picking up the item. Figure 2-1 shows how this angle is determined.
- FM = Frequency Multiplier, derived from the frequency and duration of the lifting. Because the tool is assumed to be lifted infrequently (<0.2 lifts/min) and for a short duration (<1 hour), this multiplier is set at 1.
- CM = Coupling Multiplier, derived from the quality of had-to-item coupling, or how easy it is to grasp the object. This multiplier will be set at 1, since it is assumed that the tool will be designed such that it is easy to lift (e.g. using straps or handles)

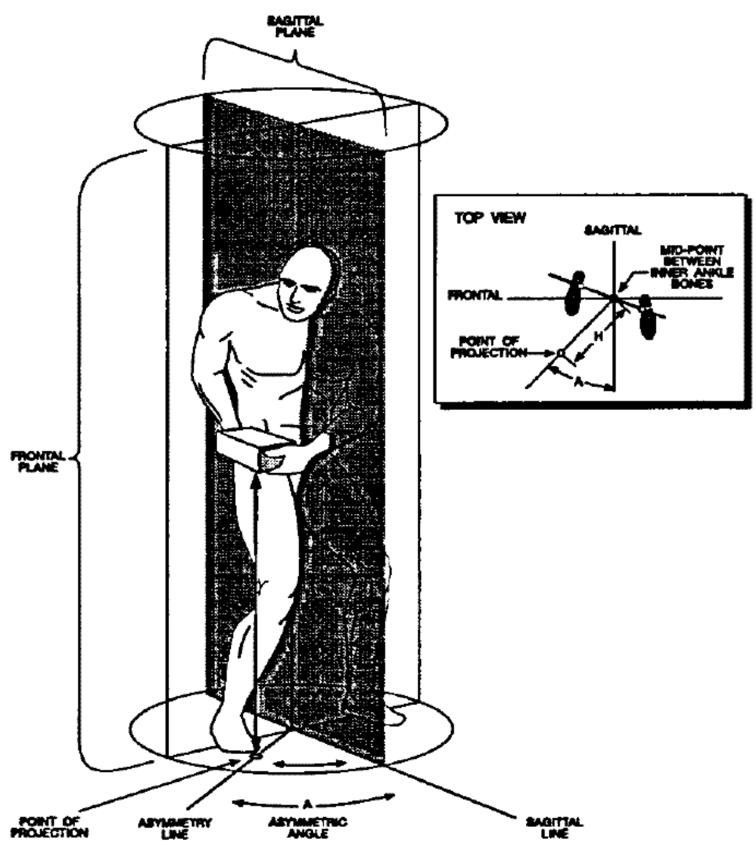

Figure 2-1: Determination of asymmetry angle [25]

Assuming that

- The tool is lifted from a height of 45 cm (location of straps/handles)
- The CM is located 30 cm away from the worker
- The tool is lifted to a height of 110 cm (roughly the height at which a backpack is worn), the distance of lift is 65 cm
- The worker can position himself in front of the tool such that the asymmetry angle is minimized to no more than 15°

then the lifting equation returns an RWL of 14.8 kg (32.6 lbm). This would be the marginally acceptable value for this metric, with an ideal metric being less than three quarters of this value, or 11 kg (24.3 lbm).

2.3.6. Noise Produced by Tool

Table 2-5 shows permissible noise exposures taken from OSHA regulations above which hearing protection must be worn. In order to keep usage of the tool as simple as possible, it is desirable that the worker not need hearing protection during operation. A worst-case scenario would have the worker cleaning graffiti for a maximum of six hours in a day, which would indicate a marginally acceptable value for this metric to be less than 92 dBA.

Duration per day (hours)	Sound Level (dBA, slow response)
8	90
6	92
4	95
3	97
2	100
1.5	102
1	105
0.5	110
0.25	115

Table 2-5: Permissible noise level exposures [26]

A more ideal value would be less than that of the actual noise level of the freeway, which at 10 meters is between 75-80 dBA [27], so the ideal value of this metric will be set at 75 dBA.

2.3.7. Time of Direct Contact with Chemicals

"Direct contact" will be defined as exposure to the possibility of bodily contact with the chemical, as well as exposure to chemical vapors or fumes. Despite most graffiti removal chemicals being formulated to be as non-toxic as possible, limiting the amount of exposure to the chemical to the minimum amount of time is desirable. Currently, the worker uses a rag to apply the chemical to the sign, resulting in a large time of direct contact. The marginally acceptable value for this metric would be exposure times slightly less than that of the current method, which would be around 120 seconds per cleaning until the chemical container is emptied. This total time is dependent on the amount of chemical used per cleaning as well as the size of the container, but is likely larger than 600 seconds (or 5 cleanings). Thus, the marginally acceptable metric will be 600 seconds. An ideal situation would be no contact at all apart from loading cleaner into the tool, which should take no more than a couple of minutes. Thus, the ideal value for this metric would be less than 120 seconds.

2.3.8. Radius of Turn

If the sign to be cleaned is a few meters away on the side of the road, the worker will take the tool out to the sign, clean it, then turn around and head back to the vehicle. This metric describes the area necessary to completely turn the tool around and move in the opposite direction of travel. Because the vegetation on roadsides can be somewhat dense, a marginally acceptable value for this metric would be one meter (3.3 ft). An ideal value for this metric would be zero meters (zero feet), meaning that the tool can be turned around in place.

2.3.9. Rate Over Rough Terrain

The average walking speed over rough terrain is 1.3 m/s (4.3 ft/s) [28]. The ideal value for this metric would be equal to that, while a marginally acceptable value would be half that, or 0.65 m/s (2.1 ft/s).

2.3.10. Time to Learn How to Use Tool

It is important that the use of the tool be as intuitive as possible, although some instruction will most likely be needed. Thus, a marginally acceptable value for the time it takes to learn to use the tool, including consumable part replacement, adding cleaner, and tool operation, should be no more than ten minutes, or 600 seconds. An ideal value for this metric would be less than five minutes, or 300 seconds.

2.3.11. Area of End Effector

The value of this metric will depend on the geometry of the end effector. The tool should be able to be used to clean smaller signs, and to spot clean on larger signs. However, if a large area of graffiti needs to be cleaned, then the end effector should be large enough that it does not take a long time to do so. Most of the signs to be cleaned are no less than 0.3 m (12 in) on their smallest side [29], so the length of a side of the end effector should be no larger than this. Thus, if the geometry is square, the area would be 0.09 m^2 (139.5 in^2); if an equilateral triangle, 0.04 m^2 (62.0 in^2). A circular geometry is not feasible since it would not be able to effectively clean the corners of the sign. However, many signs are larger than these described, so the end effector may be larger, closer to 0.46 m (18 in) per side. However, this may mean that the smaller signs will need to be cleaned by some other method, which reduces the usefulness of the tool. Thus, a marginally acceptable range for this metric would be between 0.19-0.20 m^2 (294.5-310.0 in^2), with an ideal value of 0.04-0.09 m^2 (62.0-139.5 in^2).

2.3.12. Compatibility of Cleaner and Materials

This is a subjective metric, but the materials of the tool that come into contact with the cleaning fluid should be chosen to be as non-reactive as possible to avoid corrosion, leaking or other damage to the tool.

2.3.13. Dimensions of Tool

The tool should be able to fit into a service vehicle to be taken out into the field. The bed dimensions for a standard bed Chevrolet Silverado, which is a common vehicle used by maintenance departments, are 2.5m (97.8 in) long by 1.6 m (64.7 in) wide by 0.6 m (24 in) deep. Thus, these are the marginally acceptable values for this metric. However, keeping in mind that a goal for the tool is that it must be able to be lifted by the worker, the ideal dimensions for the tool are much less, and will be less than 1 m (3.3 ft) per side. The wand portion may be longer, but should be shorter than 2.5 m (8.2 ft) when stored, so that it fits into the bed of the truck without sticking out.

2.3.14. Time to Disassemble

This metric represents the total time it would take to disassemble the tool for cleaning or servicing, and is highly dependent on the features, geometry, materials and other characteristics of the tool. As such, it may need to be further refined later in the design process. However, it should not take a worker an inordinate amount of time to service the tool, whether it is cleaning or replacing parts, and the most frequently replaced parts should be easy to service. Thus, a marginally acceptable value for this metric would be one hour, or 3600 seconds, to completely disassemble the tool for servicing, with an ideal value being less than 900 seconds.

2.3.15. Operating Time Between Maintenance Cycles

The tool should be designed in such a way that maintenance needs such as cleaning or part replacement, other than consumable parts or cleaning fluid refills, are as infrequent as possible. An acceptable value would be one maintenance cycle for two month's worth of daily use, or 480 hours. An ideal value would be greater than twice this, or over 960 hours.

2.3.16. Cost of Tool

In order to make the tool attractive to potential buyers, its cost should be kept as low as possible. This may be achieved in part by keeping the cost of its parts as low as possible, which can be done by using off-the-shelf components for motors, pumps, tanks, etc. While more marketing research should be done in order to determine a completely accurate price point, it would seem that a cost of $1500 for the tool would be marginally acceptable, while a cost of less than $1000 would be ideal.

2.3.17. Force Applied to End Effector

In order to make the use of the tool as effortless as possible, the amount of force necessary both to clean the sign and move the end effector around on the face of the sign should be minimized. Since the cleaning fluid must be recovered, it is likely that most or all of the axial force applied to the sign may come from a vacuum system which will suck the end effector onto the face of the sign. However, this may make the end effector difficult to move parallel to the face, so the axial force must be balanced with the force required to do this. A comprehensive literature search on the ergonomics and biomechanics associated with the particular configuration of the sign cleaning tool (i.e. finding the required force to move a mass on the end of a pole across a vertical plane) was fruitless. Any literature available suggested that the configuration be altered, which in this case is not possible. However, testing on the end effector (as explained later in the report) used a maximum axial force of 37.8 N (8.5 lbf), which seemed to effectively clean the surface of the sign. Therefore, pending further ergonomic tests with the sign cleaning tool (or an effective model), both the marginally acceptable and ideal values for this metric will be set at 37.8 N.

2.3.18. Ratio of Volume of Chemical Applied to Chemical Recovered

In order to maintain the retroreflective level of the sign, and to prevent chemicals from entering the environment in violation of National Pollutant Discharge Elimination System (NPDES) regulations, it is important that every effort be made to remove and capture the cleaner that is applied to the sign. Allowing for evaporation, a marginally acceptable value for this metric would be 90%, while an ideal value would be greater than 95%.

2.3.19. Tool Applies Scrubbing Motion

This is a subjective metric, but the tool should emulate the back-and-forth motion a worker uses to clean the sign, because it exposes the paint to oscillating shear forces that will help break the chemical bonds and remove the paint faster.

2.3.20. Sign Cleaner Checks Retroreflectivity After Cleaning

This is a binary metric. In order to check the retroreflectivity of the sign, a retroreflectometer must be integrated into the tool, most likely on the end effector. Due to the expense and size of this type of equipment, which arises from sensitive electronics, traceable calibrations and the necessary geometry of the meter, this may at the very least affect the price point significantly, and probably other metrics as well.

2.4. Candidate Designs

There is a wide array of choices for the design of the sign cleaner, so it is helpful to break the system up into smaller chunks to be integrated at the end. Essentially the parts of the sign cleaner are:

- The power source
- The form of the main equipment
- The form of the wand
- Cleaning fluid delivery
- Cleaning fluid recovery and disposal
- The form of the end effector
- Method of ensuring that sign is not damaged

The following sections will examine possibilities for each of these system parts and will discuss pros and cons of each.

2.4.1. Power Source

This section outlines the options for the source of the power for the sign cleaning tool. Four options are considered: a portable battery, a portable gasoline engine, a stationary gasoline engine, and a plug on the vehicle.

2.4.1.1. Portable Battery

This option uses a portable rechargeable battery for the power source, meaning one that is light enough to comfortably carry around yet has enough power to perform the required tasks. It would most likely be nickel-metal hydride or lithium-ion because these are the most readily available and power-dense types of batteries, and if possible it should be a common commercial off-the-shelf battery.

Pros of battery use include:

- Unlimited range of travel with the tool, in terms of being tethered to anything
- Less pollution
- Good energy density
- Easily replaced
- Quiet operation
- High probability that shop has compatible charger, especially if the battery geometry is identical to that used in common battery-powered tools

Cons of battery use include:

- Weight, depending on how many are needed
- Up-front cost
- Will need to be replaced eventually
- May need more than one set, depending on discharge rate and capacity

2.4.1.2. Portable Gasoline Engine

This option uses a portable gasoline-powered engine for a power source, much like that on a leaf blower. There are two different ways to use the power: using a power take-off (PTO) point, and making the entire design mechanical; or using the engine to generate electricity, and making the design electromechanical. Both have their drawbacks: a PTO would require that power be transferred all the way from the user to the face of the sign, which would be a complex endeavor at best; and power conversion to electricity is lossy, more so if the electricity is used later to run a motor.

Pros of portable gas engine use include:

- Good energy density
- Common parts and tools for maintenance and repair
- Familiarity of use
- No need to recharge or replace

Cons of portable gas engine use include:

- Heavy
- Requires more maintenance
- Pollution
- Noisy operation
- May require multiple power conversions

2.4.1.3. Stationary Gasoline Engine

This option is similar to the portable gasoline engine, except it would remain on the service vehicle. It would also most likely allow all other equipment except for the wand and cleaning head to remain on the vehicle

Pros of stationary gas engine use include:

- Power is easily sufficient
- Common parts and tools for maintenance and repair
- Familiarity of use
- No need to recharge or replace
- Reduced tool mass held by user
- Noise is distant from user

Cons of stationary gas engine use include:

- Limits range, user is tethered to vehicle
- Heavy to load in and out of vehicle
- Requires more maintenance
- Pollution
- Noisy operation
- May require multiple power conversions

2.4.1.4. Plug on Vehicle

This option uses the service vehicle as the power source. This could be as simple as a plug to provide power, or as complex as having all equipment except for the wand and cleaning head on the vehicle.

Pros of using a plug on the vehicle include:

- Reduced tool mass
- No need to develop new power source
- Power is easily sufficient
- Noise is distant from user

Cons of using a plug on the vehicle include:

- Limits range, user is tethered to vehicle
- Requires vehicle modification
- Limits which vehicle may be used

2.4.2. Form of Equipment

This section outlines the form that the equipment would take, excluding the wand and end effector. Four forms are explored: handheld, backpack, dolly and vehicle-mounted.

2.4.2.1. Handheld

This option would enclose everything into a small handheld tool, roughly the size and form of a handheld steam or vacuum cleaner, or possibly a leaf blower. Whether or not the tool would fit into this form is highly dependent on its power requirements, necessary fluid capacities, mass of components and other characteristics. However, it would be highly desirable due to its small form.

Pros of a handheld sign cleaner include:

- Lighter
- Smaller
- Highly maneuverable
- Not tethered to vehicle
- Lower cost

Cons of a handheld sign cleaner include:

- Less fluid capacity
- Less battery capacity
- Requires arm strength to hold, may be fatiguing

2.4.2.2. Backpack

This option would have all equipment mounted on a backpack chassis, much like a backpack leaf blower. This retains the freedom of movement of the handheld form, while allowing an increase in power and fluid capacity.

Pros of a backpack form include:

- Larger fluid capacity
- More power available (larger batteries, gas engine)
- Very maneuverable

- Not tethered to vehicle

Cons of a backpack form include:

- Heavier to lift and carry
- Possible noise issues from equipment located close to user's head

2.4.2.3. Dolly

This option would have all equipment mounted on a rolling chassis that the user would pull behind himself. This allows the capacities and equipment to be larger, but reduces maneuverability.

Pros of a dolly-mounted system include:

- Larger fluid capacity
- More power available
- Less fatigue to user, due to holding only hoses and wand

Cons of a dolly-mounted system include:

- Heavier
- Difficult to maneuver over rough terrain
- Difficult to reach remote spots, such as hillsides

2.4.2.4. Vehicle Mounted

For this option all equipment, except hoses and wand, would be mounted (not necessarily permanently) to the service vehicle. This allows the user to move only the hoses and wand, greatly reducing fatigue, while increasing power and capacity significantly.

Pros of a vehicle-mounted system include:

- Largest fluid capacity

- Power is easily sufficient
- Less fatigue due to only holding hoses and wand

Cons of a vehicle-mounted system include:

- Limited range (tethered to vehicle)
- Cleaner must be loaded and unloaded, or requires dedicated vehicle
- Heavy

2.4.3. Form of Wand

This section outlines the possible form that the wand would take, which is the part of the tool that the operator uses to place the end effector on the sign. Three forms are examined: static, sections and telescoping.

2.4.3.1. Static

This wand form would be a simple member of inalterable length.

Pros of a static wand include:

- Light
- Very simple design and construction
- Easy to integrate fluid/power paths
- Inexpensive

Cons of a static wand include:

- Reach is limited by length
- Difficult to reach low, high areas
- Length may make it difficult to store

2.4.3.2. Sections

This option would have separable sections that could be used to change the length of the wand. For instance, to reach a high spot, the user would add more sections, or take out sections to reach a low spot.

Pros of a sectional wand include:

- Adjustable reach
- Fairly simple design
- Fairly easy to integrate fluid/power paths
- Collapses for storage

Cons of a sectional wand include:

- Must stop to change reach
- Possibility of leakage at joints
- Multiple sections to carry, store, keep track of
- Difficult to manufacture

2.4.3.3. Telescoping

This wand would telescope to reach higher and lower sections of the sign, and would lock into place at certain intervals to prevent unwanted collapse.

Pros for a telescoping wand include:

- Reach is easily adjusted
- Collapses for storage

Cons for a telescoping wand include:

- Complex design
- Difficult to integrate power/fluid paths
- Difficult to manufacture

2.4.4. Cleaning Fluid Delivery

This section outlines the possible methods of delivering cleaning fluid to the end effector. Three options are considered: a powered pump, a manual pump, and no pump at all. The last option has the chemical being applied at the point of use by a remote trigger.

2.4.4.1. Powered Pump

This option would use power from the tool's power plant to operate a motorized pump, most likely a 360° peristaltic pump, because this type of pump has a consistent output flow for a low power input.

Pros of using a powered pump include:

- Less effort for operator
- May use thicker liquid

Cons of using a powered pump include:

- Requires power, thus a larger capacity battery or engine
- Heavier
- More expensive

2.4.4.2. Manual Pump

This option would have the worker pump the cleaning fluid by hand.

Pros of using a manual pump include:

- Cheaper
- Lighter
- Does not require power from tool

Cons of using a manual pump include:

- More work for operator
- May not work with thick liquids

- May not be able to pump to necessary height
- Risk of repetitive stress injury, such as carpal tunnel

2.4.4.3. Application at End Effector

This option does not use a pump at all, but instead alters the form of the end effector to allow integration of a container of cleaning fluid. This would most likely work only with products that come in pressurized containers, and would require some sort of remotely operated triggering mechanism.

Pros of applying the cleaner at the end effector include:

- No effort from operator
- Cheaper (no pump necessary)

Cons of applying the cleaner at the end effector include:

- Only works with certain cleaners
- Increases mass of end effector

2.4.5. Solvent Capture and Disposal

This section outlines the choices for the capture and disposal of the solvent that has been used to clean the sign. Two options are considered: a disposable absorbent pad, and a motorized vacuum sucking solvent into a tank.

2.4.5.1. Absorbent Pad

This option would use an absorbent pad, most likely attached to the end effector, which would be used to wipe the sign after cleaning, absorbing any excess cleaner. The operator would replace it when it became saturated with solvent.

Pros of using an absorbent pad include:

- Inexpensive

- Light
- Requires no power

Cons of using an absorbent pad include:

- Increased waste, likely considered hazardous
- As it becomes saturated, it is more likely to drip solvent (which is to be avoided)
- As it becomes saturated, it would smear paint and solvent on the sign

2.4.5.2. Vacuum into Tank

This option would use a motorized vacuum to apply negative pressure to the sign, which would suck any excess solvent off of the sign and deposit it into a waste tank on the tool. In order to avoid overheating the motor, there must be air passages on the end effector to allow air to flow to the face.

Pros of using a vacuum include:

- Less waste
- Applies pressure to sign, which will help clean paint
- Prevents excess solvent from dripping

Cons of using a vacuum include:

- Requires power
- May require large flow rate
- Noisy
- Heavy
- Costly

2.4.6. Form of End Effector

The methods that may be used to clean a sign are limited to chemicals and a cloth or something similar to scrub, and a laser. Since laser-based systems were developed in the early-to-mid 90s, and yet are not in use today, it is assumed that their cost and complexity is still prohibitive to their widespread adaptation. Therefore, the end effector shall consist of the former method for graffiti removal, in the form of brushes or pads scrubbing the sign.

This section examines two possible shapes for the face of the end effector: square and triangular.

2.4.6.1. Square

This option would have the face of the end effector be square. Most signs that would need cleaning are rectangular in shape

Pros of having a square end effector include:

- Fits most signs
- Larger area covered by end effector

Cons of having a square end effector include:

- May not fit irregularly shaped signs (e.g. CA state route)
- More cost
- More mass

2.4.6.2. Triangular

This option would have the face of the end effector be an equilateral triangle. This would allow it to fit more signs, though the cleaning area is reduced.

Pros of having a triangular end effector include:

- Fits irregularly shaped signs

- Lower mass
- Lower cost

Cons of having a triangular end effector include:

- Less area covered by end effector

2.4.7. Method of Ensuring Sign is Not Damaged

This section examines possible methods for ensuring that the sign has not been damaged from the cleaning. There are essentially two ways to do this: check the sign with a retroreflectometer, or be reasonably assured from previous testing that the methods of cleaning do not damage the sign.

2.4.7.1. Retroreflectometer

This option would use a retroreflectometer to check the sign's reflectivity after cleaning. While this would give instant feedback, they tend to be quite expensive (~$5000-$12,000 off-the-shelf) and heavy (2-3kg). To include one in the end effector would immediately make it more expensive, heavier and more delicate.

Pros of using a retroreflectometer include:

- Instant feedback on sign's state
- May be used solely to check a sign's reflectivity

Cons of using a retroreflectometer include:

- Very costly
- Heavy
- Delicate

2.4.7.2. Assurance from Testing

This method would use information about the signs' susceptibility to damage, gathered from the manufacturer or other knowledgeable entity. However, no one currently knows how much scrubbing or pressure a sign can take before it is damaged [21]. Therefore, this method would require tests to be run on signs using the end effector in order to assure a design that does not damage the sign. Since testing would have to be done anyway in the course of tool development, this method is likely a better choice.

Pros of using testing include:

- Less expensive
- Lighter
- More robust design
- Needs to be done anyway, to some degree

Cons of using testing include:

- More time needed to develop design
- May not accurately represent actual situations (sign conditions, user behavior, etc)

2.5. Final Design Proposal

The proposed final design is to have a backpack mounted, battery powered tool, because this allows the most freedom in terms of worker travel and choice of vehicle. The end effector would be triangular in shape because this allows irregularly shaped signs to be cleaned. It would be on the end of a telescoping wand because this gives the greatest height range while maintaining a compact form, and it would not have a retroreflectometer integrated into it due to cost and robustness considerations. The solvent would be applied by a powered pump and recovered into a tank by a vacuum. A conceptual sketch is shown in Figure 2-2.

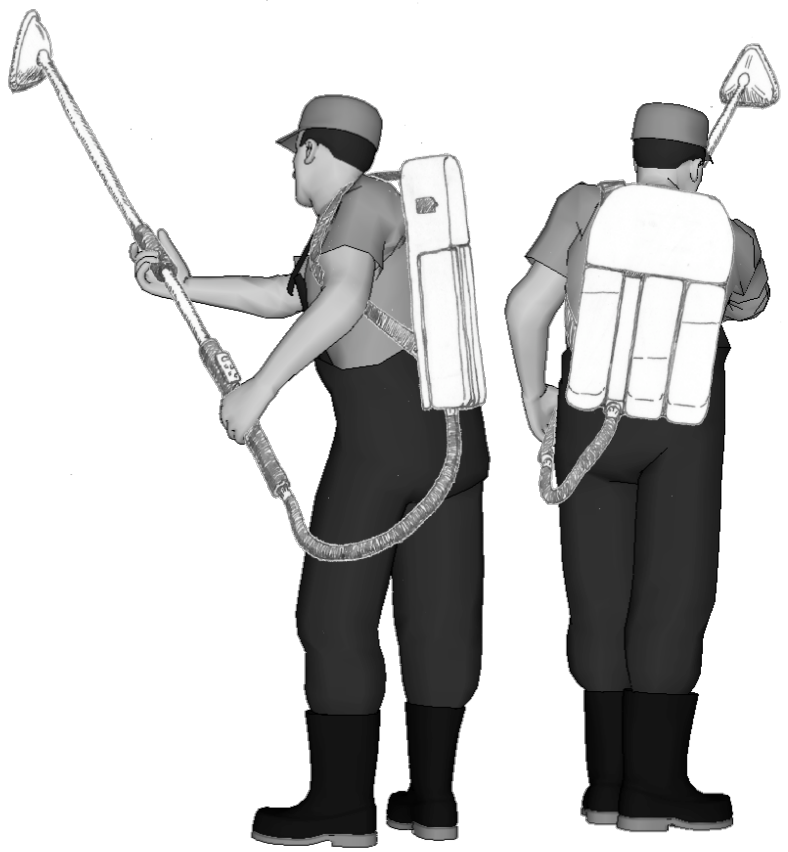

Figure 2-2: Conceptual sketch of sign cleaning tool

It should be noted that this is only an initial design proposal and will need to be developed further. For instance, the power requirements for extended operation of the vacuum system may be larger than can be feasibly supplied by battery, or the telescoping wand may increase the cost and complexity of the tool such that a static wand is a better choice. In any case, these concepts (and possibly others) should be further investigated, screened, scored and ranked, and the best one chosen.

2.6. Conclusion

This chapter began by translating customer statements about the current graffiti removal process for signs into needs for a sign cleaning tool. These needs were assigned metrics whose values would determine whether or not the need was met by the proposed design. Then, several possible aspects of the design were examined and weighed, and a final design was proposed.

Chapter 3. Development of the End Effector

3.1. Introduction

At this point in the report, the focus on development of the sign cleaning tool shifts from the overall tool to only the end effector. A critical issue revolves around the nature of the end-effector and its interaction with, and effects on, the signs. Since it is imperative that the tool not damage the sign significantly, key characteristics of the end effector must be well-developed and well-tested before the overall design of the tool continues. Accordingly, this report has been directed towards developing an understanding of this complex interaction and to delay a final concept and detailed design for a later time when the experimental results of the later chapters can be reflected in the design.

This chapter begins by presenting a basic concept of the end effector. Next, it will cover the development and execution of a 2^4 factorial experiment aimed at determining the levels of damage the sign may incur from cleaning, as well as the necessary size of the motor in the end effector. Finally, it will cover the execution of further testing aimed at gaining other information about the performance of the end effector.

3.2. Basic Concept of the End Effector

Figure 3-1 shows a rough sketch of the proposed design of the end effector. As stated previously the end effector will apply the cleaning fluid, scrub the graffiti, and remove the cleaning fluid and dissolved paint. Of these three actions, the scrubbing is most likely to damage the sign. Additionally, as stated in Section 2.4.7, it is generally unknown what levels of pressure or types of brush material will damage the sign. Finally, because it is not known what levels of friction will occur during cleaning, it is not accurately known how much torque is needed in order to accomplish the scrubbing motion. This is important because it determines the size of the motor that will be used on the end effector, which in turn determines its mass and dimensions. Thus, before other development can continue, it is first necessary to determine these characteristics of the end-effector.

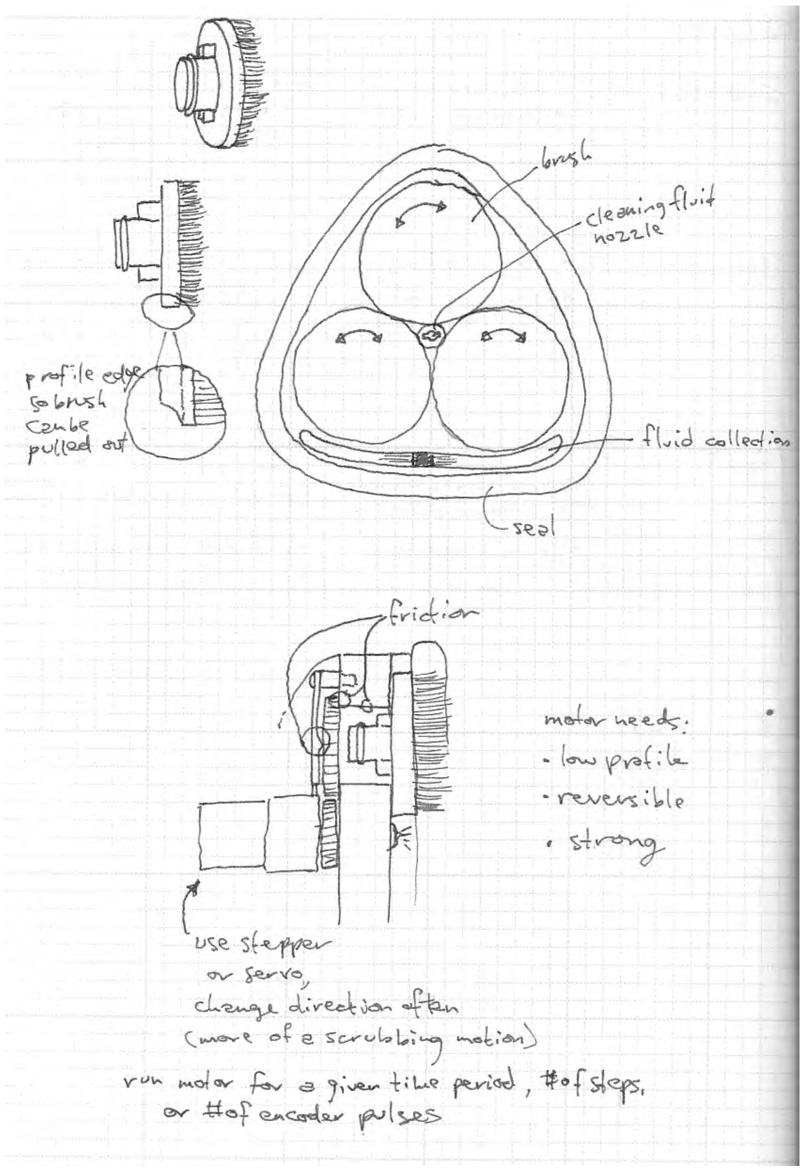

Figure 3-1: Conceptual sketch of end effector

3.3. Development and Execution of the 2^4 Factorial Experiment

In order to determine the size and speed of the motor used in the head, the amount of pressure that could be applied to the surface of the sign, and the types of brush used by the end effector, it was necessary to run tests on sign samples to determine what levels of these values, if any, caused damage to the sign and therefore should not be used. Damage to the sign is measured as a significant reduction in the coefficient of retroreflectivity, caused either by damage to the retroreflective layer or by damage to any superior layer (e.g. clouding or scratching the anti-graffiti coating). A reduction in R_A is considered significant if five "cleanings" would reduce R_A by greater than 70 per cleaning, on average.

To determine the reduction in R_A from the sign cleaner, a statistical approach was used in the form of a 2^4 factorial experiment, where each possible combination of four factors would be tested. The purpose of the test was to determine which combinations of pressure, speed, brush type and sign coating were the most likely to result in a damaged sign, as well as to develop a regression model capable of predicting the amount of damage to a sign when a given combination of these factors was used. The four factors and their levels are shown in Table 3-1.

Factor	Low level (-)	High level (+)
Axial load	7.78 N (1.75 lbf)	37.81 N (8.48 lbf)
Speed	28.5 rpm	65 rpm
Brush type	Polypropylene bristle	Scouring pad
3M 1160 film present	No	Yes

Table 3-1: Levels of factors in experiment

There are a total of 16 possible combinations of the factors, and in order to ensure statistically significant results, three replications of the test were taken, for a total of 48 data points. The run order of each replicate was randomized in order to eliminate any unaccounted-for variables (e.g. brush wear, etc.).

A secondary purpose of running the test was to measure the amount of torque generated during the tests, which would be used to determine the necessary motor size.

Because the motor driving the brushes in the final design is contained within a head mounted at the end of a long pole, it is important that the motor be strong enough to clean the sign, yet light enough to allow it to be held by the operator for the length of time necessary to clean the graffiti.

After the first group of tests was run, a second group was run, examining the effects of a polystyrene brush on the sign; then a third group examining the effects of cleaning a painted sign; then a fourth group examining the effects of multiple cleanings on both painted and unpainted signs..

3.3.1. Setup

3.3.1.1. Sample Signs

The samples under test were 15.24 cm (6 in) square panels of 6061-T6 aluminum coated with plain white 3M Series 3930 High Intensity Prismatic retroreflective sheeting (Figure 3-2). Half of the sign samples also had an additional coating of 3M 1160 Premium Protective Overlay Film (anti-graffiti coating). These materials were chosen because they are the most commonly used by Caltrans in road signage, and also because the prismatic film is the most susceptible to pressure damage from improper cleaning. White signs, as opposed to another color, were chosen due to price considerations and the fact that only reductions in R_A relative to a new sign are being measured.

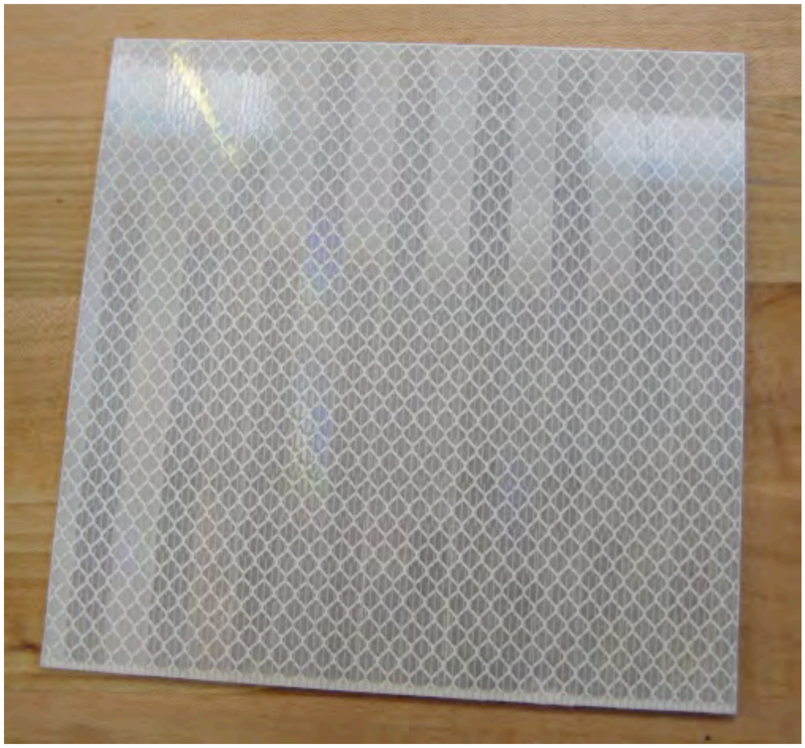

Figure 3-2: Typical sign sample used in test

3.3.1.1.1. Control Sample

In order to compare the degradation of the sign, a set of new, untouched sign samples were used as a control. Five samples of each type of sign were taken randomly from the batch of signs used in the tests. Their R_A was taken in three spots on each one, for a total of six measurements per sign: one in the center of the sign, one at the center of the top edge, and one at the center of the right-hand edge (Figure 3-3). These readings were averaged together for each sign, and then the five values for each sign were averaged together to provide one control R_A value for each type of sign (with 1160, and without 1160). The results can be seen in Table 3-2. The control values were taken only once.

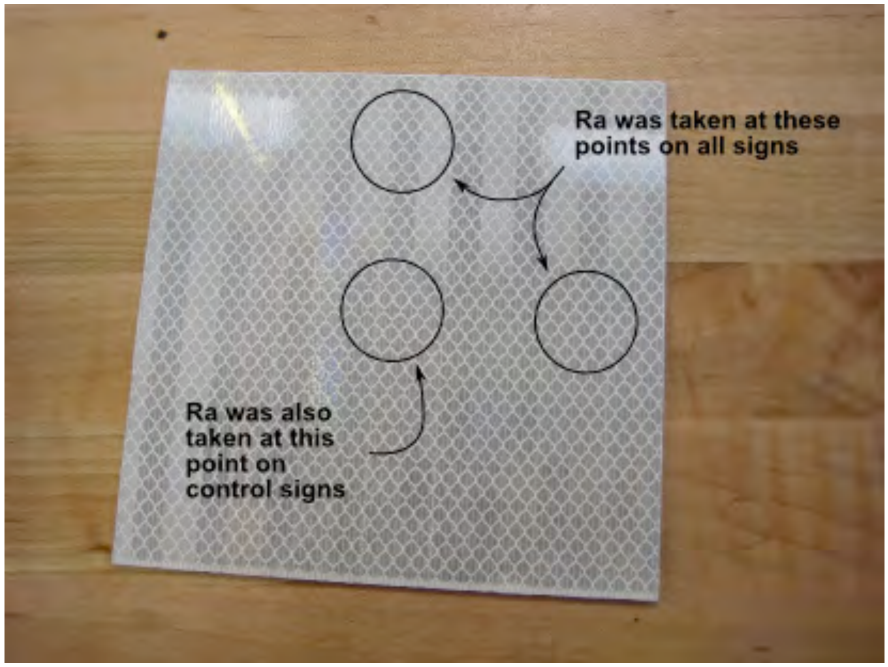

Figure 3-3: Location of test areas on sign samples

3.3.1.2. Test Fixture

The main structure for the test fixture was a Makita drill press stand, the normal function of which is to allow one to use a normal hand drill as a drill press; however, its purpose for this test was to allow different pressures to be applied to the sign surface. It had a carriage that was moved vertically by lowering and raising a handle, and masses were hung off of the handle to allow the different pressures to be applied to the sign. Figure 3-4 shows the test fixture in use.

Figure 3-4: Test fixture in use

The motor used in the test fixture was a reversible 12 VDC 100 rpm 24.9 W (1/30 hp) gearmotor, which could generate 2.26 N-m (20 in-lbs) of torque and pull 6 amps continuously at no-load conditions. This motor was chosen based on basic calculations of the interface between the brush and sign. The coefficient of friction (COF) data that most closely represented the brush-sign interface was that for polystyrene sliding on polystyrene, for which the static COF is 0.5 (kinetic unavailable) [30]. Since the static COF is generally higher than the kinetic COF and since the sign surface was to have cleaner applied to it which would act as a lubricant, this value was taken as the worst-case scenario and used in the motor-size calculations for the test stand. Because the test fixture uses flexible bristle brushes, it was assumed that axial loads would result in uniform pressure over the surface of the brush during testing. From the uniform pressure model for frictional-contact axial clutches [31], the torque resulting from a given axial force can be calculated by

$$T = \frac{Ff}{3}\frac{D^3 - d^3}{D^2 - d^2} \tag{3.1}$$

where F is the axial force, f is the COF, D is the outer diameter of the clutch, and d is the inner diameter. The brushes to be used were 12.7 cm (5 in) in diameter and covered the entire surface (d=0), and the axial load was to be no more than 9.1 kg (20 lbs) (and ended up being much less). This resulted in a maximum predicted torque of 1.89 N-m (16.7 in-lb). The motor chosen exceeded this value slightly to avoid its being anywhere near stall condition during the test.

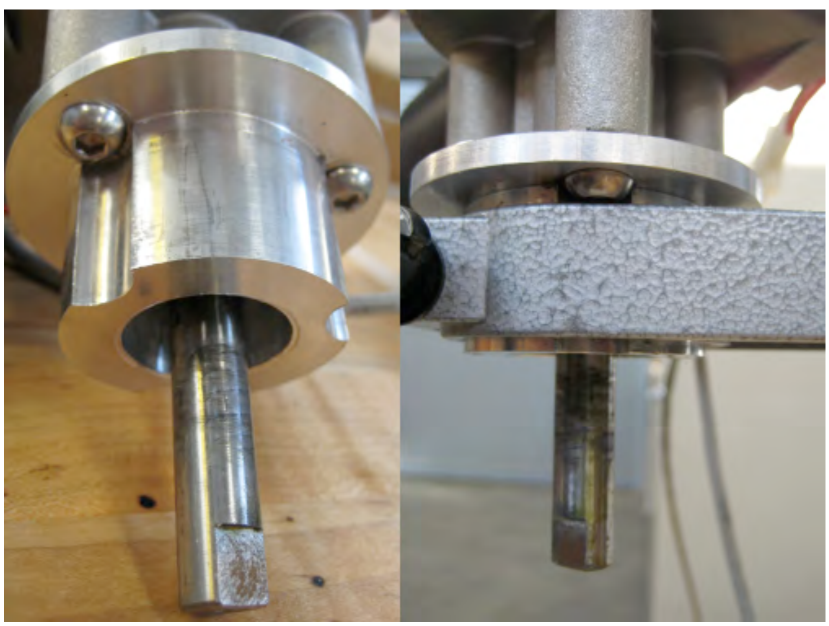

Figure 3-5: Flange motor mount. Left: bolted to motor. Right: clamped in stand.

In order to fit the motor into the carriage of the test stand, a flange mount was machined from aluminum (Figure 3-5). This flange attached to the motor mounting holes on the motor and clamped into the collar of the carriage. It also had a hole bored lengthwise through its center which allowed passage of the motor shaft. The shaft was in turn coupled to the brush by a rigid aluminum two-piece clamp-on shaft coupling, which was turned down a bit on a lathe in order to reduce the inertial load it presented to the motor (Figure 3-6).

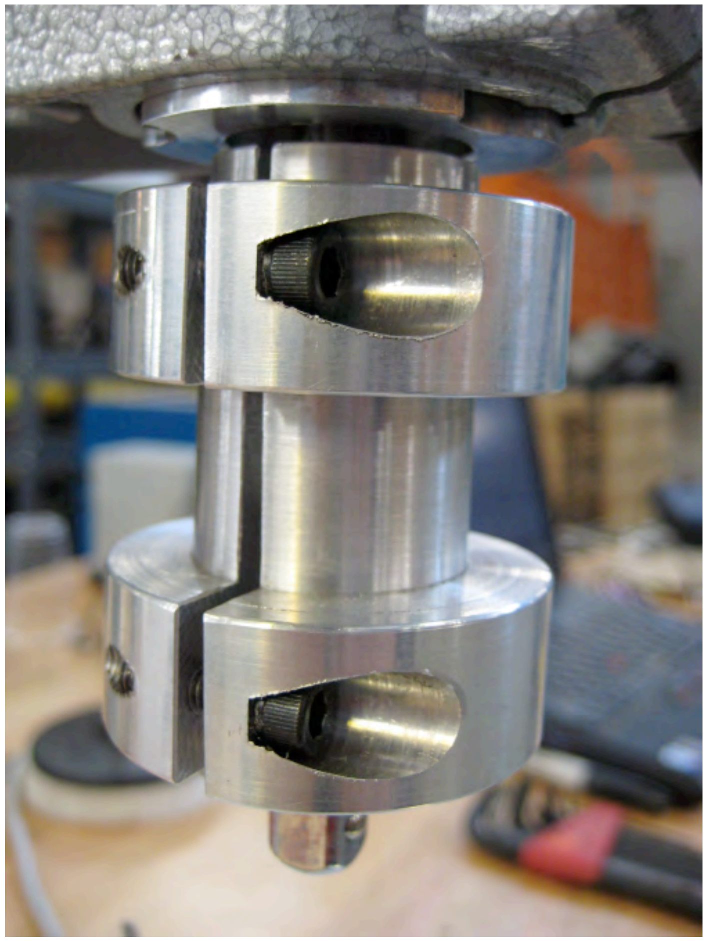

Figure 3-6: Coupling from shaft to brush

Because a few different types of brushes would be tested, it was advantageous to be able to rapidly change the brushes, as well as move them out of the way so that sign samples could be loaded and unloaded from the test bed. This was achieved by inserting a 1/4" to 3/8" socket driver adapter into the coupling, such that the 3/8" side stuck out of the bottom. Then, a 3/8" drive 5/16" hex bit socket, with the bit removed and the brush's drive shaft in its place, was attached to that, such that the brush could be rapidly moved or changed (Figure 3-7).

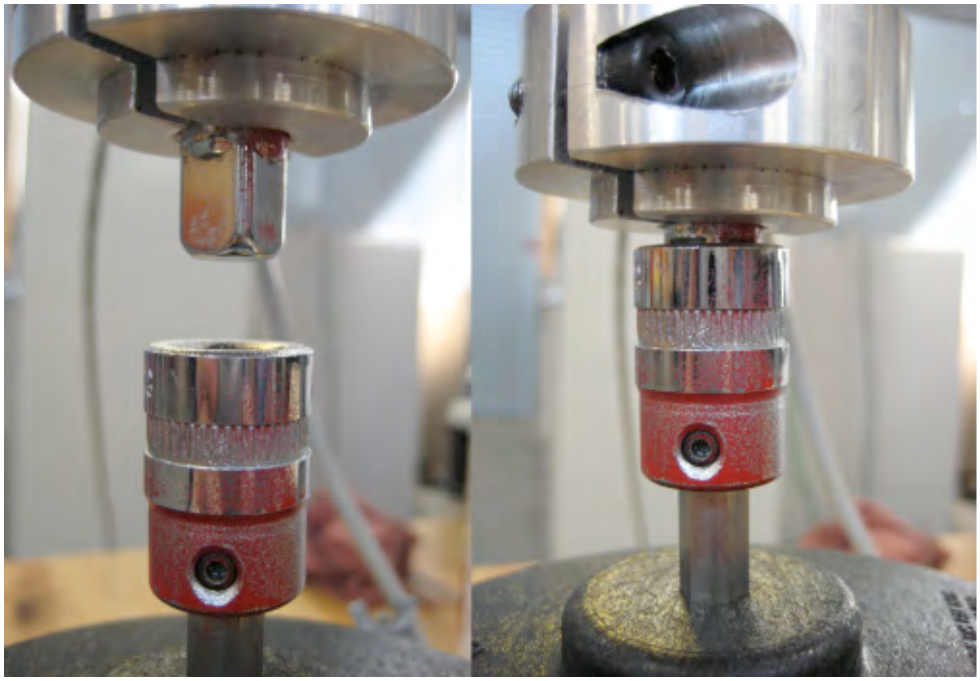

Figure 3-7: Brush connection to clamp-on coupler

The bed on which the sign samples were tested was comprised of a flat plate on which the samples were placed, and a frame that covered the sign along its edges and held it immobile for the test. This frame was attached to the plate by four dowel pins (which prevented rotational motion and allowed quick registration of the frame to the plate) and four wingnut and machine screw combinations (which provided clamping force on the sign) in slots along the upper and lower edges of the frame and plate. Slots were used rather than holes so that the signs could be quickly and easily changed; the wingnut and machine screw combinations needed only to be loosened slightly in order to be removed and the sign sample changed, rather than having to completely disassemble any hardware (Figure 3-8). The flat plate was rigidly attached to a flange-to-flange mount torque sensor, which in turn was rigidly attached to a load sensor, which in turn was rigidly attached to the bed of the Makita fixture (Figure 3-9), and the entire test stand was rigidly clamped to a table.

Figure 3-8: Detail of test bed showing frame attachment method

Figure 3-9: Torque cell and load cell affixed between test bed and stand

3.3.1.3. Brushes

Two different types of brushes were used for the first test, both manufactured by the same company (Tucel Industries, Inc.) and attached to the test fixture the same way. One was a polypropylene bristle brush (Figure 3-10, left), with bristles about 2.54 cm (1 in) in length, an inner diameter of about 6.35-7.62 cm (2.5-3 in), and an outer diameter of 12.7-13.3 cm (5-5.25 in), depending on the amount that the bristles spread out due to the load. The other was a scouring pad (Figure 3-10, right) made of an unknown material with a diameter of 12.7 cm (5 in). The pad itself was replaceable, and attached to the base by small hooks, much like hook-and-loop fasteners (Figure 3-11). These materials were chosen because of the contrast in the way each behaved when moving across the sign. When the brushes changed direction, the bristles underwent a large amount of bending while their tips remained stationary. This caused a spike in the force being applied to the sign by the brush, which subsided once the bristles began their sliding motion in the opposite direction. If a sign were to be subject to pressure damage, it is possible that a significant amount would happen at that point.

Figure 3-10: Brushes used in tests. Left: Polypropylene; Right: Scouring Pad

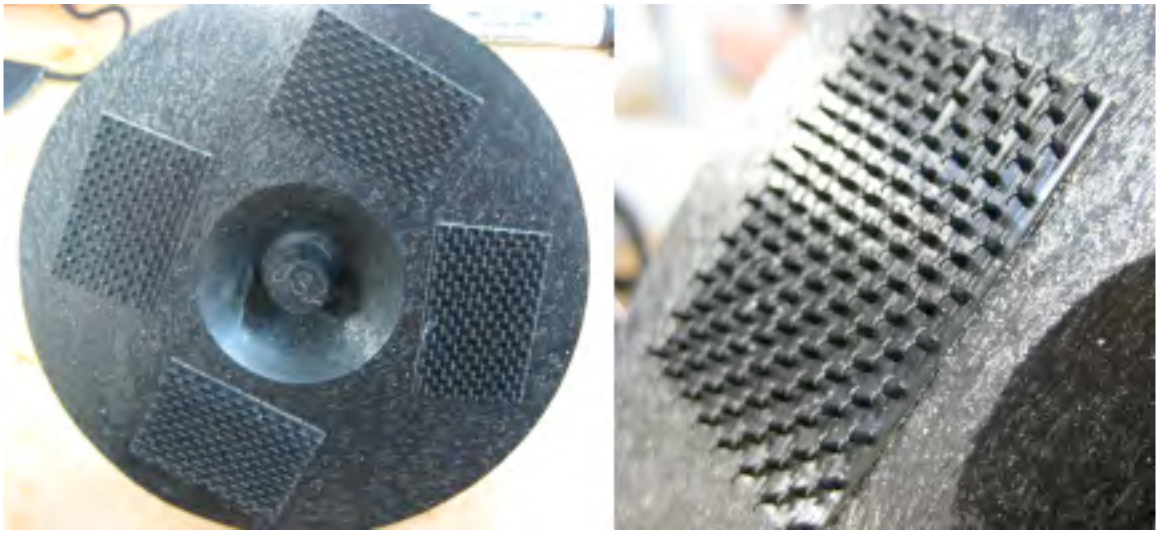

Figure 3-11: Hook-and-loop attachment for scouring pad

For the second and third tests, a polystyrene brush manufactured by Grainger, Inc. was used (Figure 3-12). This brush had an outer diameter of 13.3 cm (5.25 in) and an inner diameter of 3.81 cm (1.5 in) with 2.54 cm (1 in) bristles, and had a 0.95 cm (3/8 in) shaft that fit into the shaft coupling. This brush's bristles were softer than those of the polypropylene brush, but were still resistant to chemical damage.

Figure 3-12: Polystyrene brush

3.3.1.4. Loads Applied to Sign

In order to vary the load applied to the sign during the test, two different amounts of mass were hung statically on the handle of the test fixture for the duration of each run. These masses were 1.08 kg (2.38 lbm) for the low level, and 1.96 kg (4.32 lbm) for the high level, which resulted in axial loads at the sign surface of 7.78 N (1.75 lbf) and 37.81 N (8.5 lbf) due to the fact that the handle was a second-class lever. It should be noted that, because the brushes used covered different areas, the pressure applied to the sign varied depending on the brush being used. For the bristle brush, which had an area of 81.1 cm^2 (12.6 in^2) for the low load and 107.3 cm^2 (16.6 in^2) for the high load, the pressure was 0.96 kPa (0.14 psi) for the low level and 3.52 kPa (0.51 psi) for the high level. For the scouring pad, which had an area of 126.7 cm^2 (19.6 in^2), the pressure was 0.61 kPa (0.09 psi) for the low level and 2.98 kPa (0.43 psi) for the high level. For the polystyrene brush, which had an area of 127.5 cm^2 (19.7 in^2), the pressure was 0.61 kPa (0.09 psi) for the low level and 2.97 kPa (0.43 psi) for the high level. All of these pressures are close enough to each other that no attempt was made to correct for their differences by changing the amount of mass on the handle.

3.3.1.5. Chemicals

The chemical used for the experiment was SEI Graffiti Remover, which is on Caltrans' most recent Qualified Products List for graffiti removers [32].

3.3.1.6. Motor Control

The motion of the motor for the tests was chosen to be sinusoidally oscillatory, rather than unidirectional, for two reasons. First, oscillatory motion was chosen as a design feature because it most closely imitates the motion that a worker would use to clean a sign, which is back-and-forth scrubbing. This motion is believed to be more effective than unidirectional scrubbing because it subjects the paint film to oscillating shear forces and is thus more likely to remove the paint. Second, the reversal of the bristle brush may cause damage, which is worth investigating.

To obtain the motion, a variable frequency and amplitude signal was generated by the LabVIEW VI and sent through the digital acquisition card (DAQ) to a class D amplifier (schematic shown in Figure 3-13), which generated an amplified pulse-width modulated (PWM) signal, which was then sent to the motor. Two speeds were used for the test: ~30 rpm, and ~65 rpm, on average, for the low and high values. Neither of these was completely exact due to the changing loads that were presented to the motor from the brush type and the axial force.

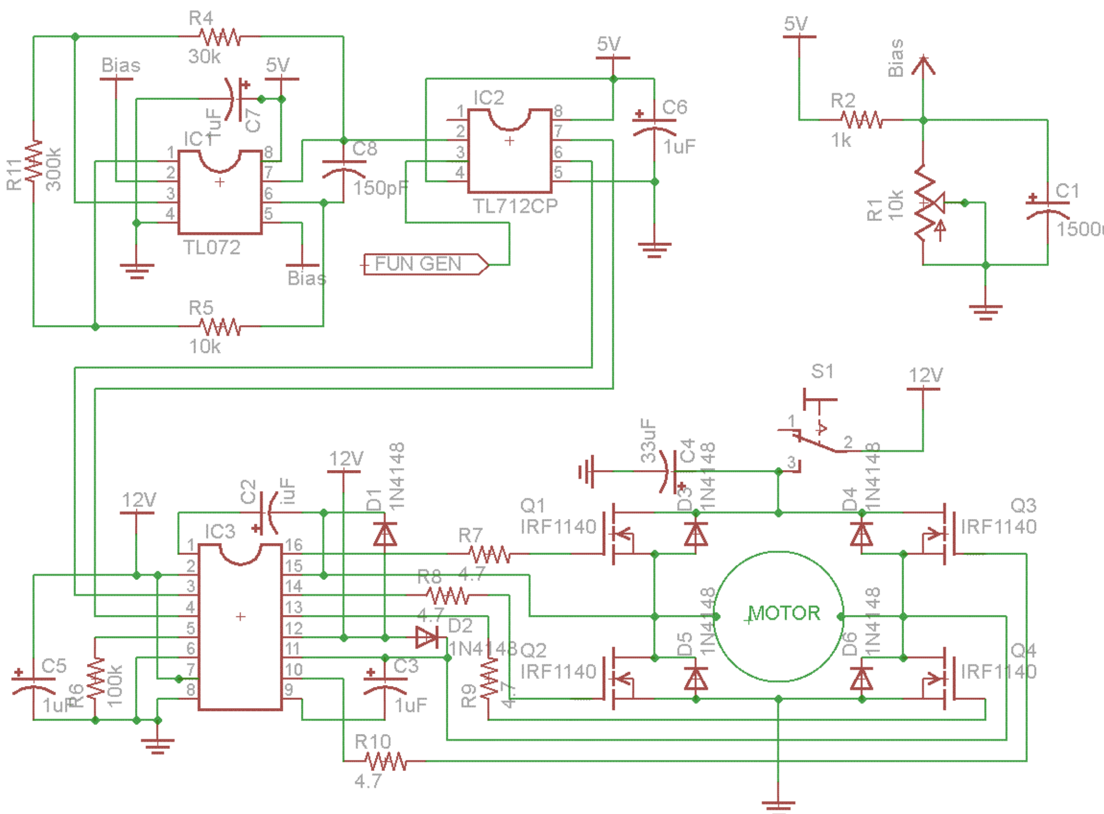

Figure 3-13: Class D PWM driver schematic

3.3.1.7. Instrumentation

Three characteristics of each test were measured: the rotational rate at which the brush moved, the amount of torque the brush exerted on the sign, and the amount of force the brush exerted on the sign. Each of these values was input to a LabVIEW virtual instrument (VI) which recorded and took long-term average values (over 40 cycles) of their characteristics.

The rotational rate was measured by a Accu-coder 755A incremental rotary encoder with an output of 2500 pulses per revolution (Figure 3-14). This encoder was attached to the output shaft of the motor by physically altering the motor's stock construction. This involved cutting a hole in the backplate of the worm gear box and adding a shaft extension that stuck out of the hole. The encoder was then attached to this shaft extension, and the body of the encoder was rigidly attached to the backplate of the worm gear box. The output of the encoder was routed to a National Instruments USB-6229 16-bit DAQ card for input to the VI.

Figure 3-14: Encoder attached to back of motor

The torque exerted on the sign was measured by a TQ-301 flange-to-flange mount torque sensor from Omega Engineering, Inc., which was comprised of a full Wheatstone bridge strain gauge circuit capable of measuring from 0 to 45 N-m (0-400 in-lb) of torque. The output of the torque sensor was 2 mV/V, and with a 10 VDC excitation, the expected full-scale output of the sensor would be 18 mV at 45 N-m of torque. This means that for this particular application, with a maximum applied torque of around 1.89 N-m (16.7 in-lb), the maximum output was roughly 0.76 mV, which was then filtered and amplified (discussed later).

The load exerted on the sign was measured by an SSM-50 surface stud-mount load cell from Transducer Techniques, which was comprised of a full Wheatstone bridge strain gauge circuit capable of measuring from 0 to 222 N (0-50 lbf). The output of the load cell was 2 mV/V, and with a 10 VDC excitation, the expected full-scale output of the sensor would be 1.76 mV at 222 N. This means that for this particular application, with a maximum applied load of around 38 N (8.5 lb), the maximum output was roughly 0.30 mV, which was then filtered and amplified.

Both the torque and load sensor outputs required filtration and amplification before being digitized by the DAQ card. Filtration was accomplished using a Sallen-Key topology, which creates an active 2nd order low-pass Butterworth filter, with the cut-off frequency set at 50 Hz in order to filter out any high-frequency noise. Due to having such a low-level output, the filter for the load cell also incorporated a gain stage of 2. The filtered signals were then sent to an instrumentation amplifier, where they were boosted by a gain of 800 (Figure 3-15). Finally, these signals were routed to the DAQ card.

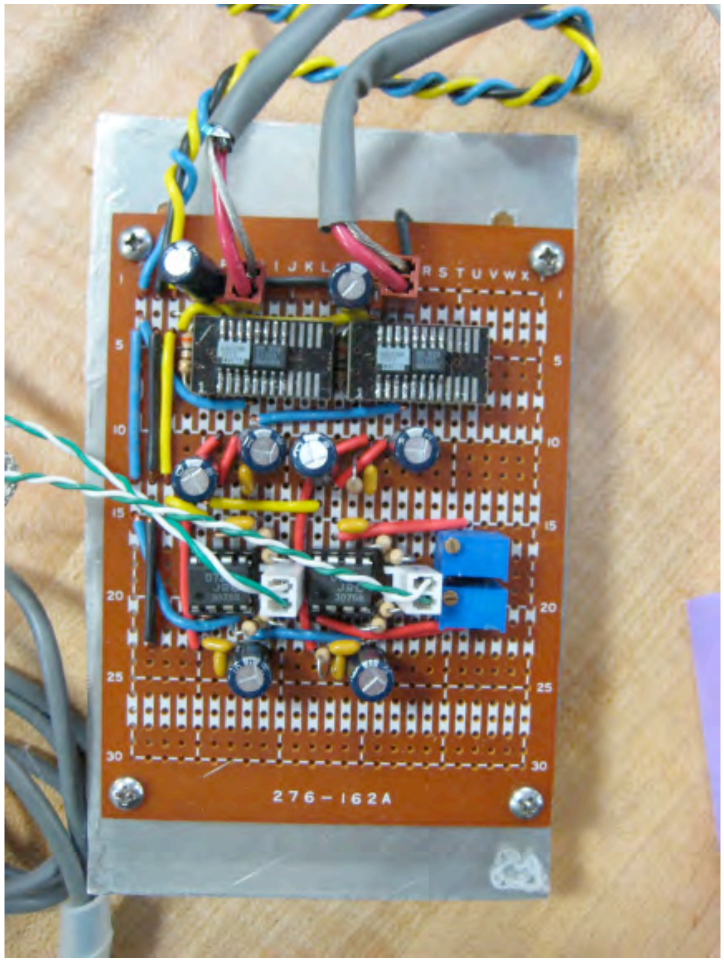

Figure 3-15: Filtration and amplification circuit for instrumentation

Because the amplification stages are not exact due to slight variances in component values of the electronics, it was necessary to calibrate the load and torque sensors. This was done through the National Instruments Measurement and Automation Explorer application using known masses for the load cell, and a calibrated torque wrench for the torque sensor.

3.3.1.8. Software

A LabVIEW virtual instrument (VI) was used to control the motor's motion, read the data from the sensors, and to parse the data into smaller, similar chunks and determine average values for several key characteristics. The code for the VI can be found in Appendix B: LabVIEW VI.

The VI was written such that the user could easily configure it to the desired speed, angular distance traveled per half-cycle, and number of cycles (defined as one complete back-and-forth rotation) to perform. The speed was set by altering the peak-to-peak amplitude of the output to the motor, and the angular distance traveled was set by altering the frequency. The number of cycles was set by entering the desired number of cycles, dividing this number by the product of the desired frequency and the loop rate (which remained constant at 50 ms), and setting the result as the number of times the acquisition loop should run.

Each sensor was polled by the VI, and a value taken. The value of the encoder at each step had the previous encoder value subtracted from it, which resulted in the change in angle (θ) between successive runs of the loop $(\Delta\theta)$. This was divided by the difference in time between each successive run, which resulted in $\Delta\theta / \Delta t$, which is the instantaneous angular speed of the motor shaft. The speed, torque and load values were then filtered and, along with time data, put into a 2-D array. This array was then passed to another loop that divided each element into successive half-cycles. Each half-cycle was examined for four specific key values: for the torque, the mean value of each half-cycle was taken; for the speed, the max of each half-cycle was taken; and for the load, both the mean load and the max load for each half-cycle were taken. Each was used to build a 1-D array of each value, so that at the end of the loop there were four arrays of the mean torque, mean and max loads, and max speed, with one value taken from each half-cycle.

Finally, the mean values of each array, along with their widths and standard deviations, were taken and written to a measurement file.

3.3.1.9. Test Procedure

The test began by first opening the VI and turning on the DAQ. Doing these steps first prevented the motor from turning itself on. Next, the power to the sensors and instrumentation amplifiers was turned on, followed by the motor signal amplifier and motor power. All equipment was left on for roughly 10 minutes before beginning the test in order to allow everything to come to steady-state, if needed.

Next, the chart displaying the factor levels corresponding to the run number was consulted for the proper configuration. For example, if run 10 was to be performed, then the proper configuration was high speed, low mass, bristle brush, and 1160 film present. The proper sign type was then loaded onto the test bed, and the graffiti remover chemical was applied to the sign. Next, the proper brush was attached to the motor and the proper speed was set in the VI. Finally, the proper amount of mass was added to the cord attached to the handle of the test fixture. The test was not begun until a minute or so after the graffiti removing chemicals were applied to the sign in order to allow most of the carrier solvent to evaporate (the chemical would take on a dull appearance). This was done in order to ensure that there was no solvent acting as an additional lubricant between the brush and sign interface, which would show up as an increasing (and thus inaccurate) level of torque for the duration of the run. Once the solvent evaporated sufficiently, the brush was lowered onto the sign, and the run was started.

After each run was completed, data from the measurement file was copied into an Excel spreadsheet, and the sign was removed from the test bed, given an initial wipe-down with a dry paper towel to remove excess chemical, and then (in accordance with the chemical manufacturer's instructions) rinsed off with water and wiped dry. Finally, each sign was labeled with the replication number, date, run number, factor levels and number of cycles.

Once all replicates of the test were run, the resulting coefficients of retroreflectivity (R_A) were measured for each sign, to be later compared against control values. The R_A values were taken using a Model 920L field retroreflectometer manufactured by Advanced Retro Technology, Inc. First, the retroreflectometer was calibrated using two different materials of known R_A, by using the two knobs on the end of the retroreflectometer (Figure 3-16). The first material was a flat black felt surface with an R_A of zero, by which the retroreflectometer was zeroed out. The other material was a small piece of encapsulated glass bead retroreflective film with a known R_A of 308.

Figure 3-16: Retroreflectometer; Detail of calibration knobs and readout

Once the retroreflectometer was calibrated, the R_A values of the control samples were taken. The standard method for taking the readings, as dictated by the manufacturer, was to take a measurement at roughly 0° orientation, another at the same spot but with the retroreflectometer rotated roughly 90°, and then to average these two measurements. This average value counts as one reading.

A similar method was used to obtain the R_A for the signs under test, with the exception of the reading at the center of the sign. This was not taken because of the different geometries of the brushes; the scouring pad contacted the center of the sign, while the bristle brush did not. Thus the two points read were located at the center top of the sign and the center right of the sign (Figure 3-3), and the R_A value for the sign was taken as the average between the two. The results were then recorded in an Excel spreadsheet and statistical analysis was performed on them.

3.4. Results

This section covers the results of the testing performed on the signs. First, the control values of the untouched signs will be given. These values were used as the baseline from which a drop in R_A is calculated for the 2^4 factorial experiment. Then, the results from this experiment will be examined, and the effects and interactions of the factors will be revealed. These aspects will then be used to create a rough regression model, which will suggest the direction that further experimentation should take.

3.4.1. Control Values

Table 3-2 shows the values obtained from the control samples. For the signs with the 1160 film, the control R_A is 626.0 ± 11.0, and for the signs without the 1160 film the R_A is 578 ± 25.9. Note that there is a fairly large amount of variation in the values, even on the same sign. It is believed that the reason for this variation is that the orientation of the corner-cube retroreflective structures in the reflective layer alternate between 0° and 90° in 1 cm stripes. These stripes can be clearly seen in Figure 3-2. Since the area of the lens of the retroreflectometer is only 5.1 cm^2, it is likely that with each reading it will overlap these stripes differently, which will affect the reading. However, the method of averaging across all of the readings makes the final values less sensitive to these variations.

w/ 1160	0 deg	90 deg	avg	0 deg	90 deg	avg	0 deg	90 deg	avg		
con1	625.6	608.4	617.0	626.4	621.1	623.8	629.8	623.0	626.4		
con2	614.6	600.6	607.6	622.2	606.4	614.3	638.3	626.2	632.3		
con3	634.0	640.8	637.4	630.8	640.0	635.4	650.9	642.4	646.7		
con4	641.3	625.4	633.4	637.7	628.7	633.2	620.4	599.8	610.1		
con5	631.2	606.2	618.7	630.8	614.8	622.8	648.1	614.1	631.1	grand mean	std dev
										626.0	11.0

w/o 1160	0 deg	90 deg	avg	0 deg	90 deg	avg	0 deg	90 deg	avg		
con1	586.2	585.0	585.6	536.5	540.2	538.4	577.3	570.7	574.0		
con2	584.2	568.3	576.3	638.4	616.1	627.3	573.4	557.5	565.5		
con3	567.1	561.0	564.1	586.8	591.5	589.2	579.2	573.1	576.2		
con4	599.9	605.0	602.5	588.3	581.4	584.9	607.3	598.8	603.1		
con5	550.4	543.2	546.8	611.4	600.3	605.9	539.8	531.3	535.6	grand mean	std dev
										578.3	25.9

Table 3-2: Control values used in factorial experiment

3.4.2. Results of 2^4 Factorial Experiment — Retroreflectivity

Table 3-3 shows the contrast coefficients used in determining the effects and interactions of the factors under study, along with the raw and averaged drops in R_A from each run. The amount by which the R_A was reduced was calculated by subtracting the average R_A of the sign after cleaning from the average R_A indicated by the control value for that type of sign. For this reason, it appears that some of the values actually increased when cleaned, but what most likely happened is that the initial R_A of the sign was higher than the average value and the sign was damaged very little by the cleaning. The averaged values were used to estimate the effects and interactions of the factors.

																Drop in R_A			
Key:	1	2	3	4	12	13	14	23	24	34	123	124	134	234	1234	R1	R2	R3	AVG
1: Axial Load	-	-	-	-	+	+	+	+	+	+	-	-	-	-	+	-106.7	-206.1	-148.9	-153.9
2: Speed	+	-	-	-	-	-	-	+	+	+	+	+	+	-	-	-133.4	-263.6	-161.7	-186.2
3: Brush Type	-	+	-	-	-	+	+	-	-	+	+	+	-	+	-	-83.8	-141.8	-131.8	-119.1
4: 1160 Film	+	+	-	-	+	-	-	-	-	+	-	-	+	+	+	-165.1	-264.8	-228.9	-219.6
	-	-	+	-	+	-	+	-	+	-	+	-	+	+	-	-39.1	23.3	-40.8	-18.9
	+	-	+	-	-	+	-	-	+	-	-	+	-	+	+	-19.1	-21.3	-81.9	-40.8
	-	+	+	-	-	-	+	+	-	-	-	+	+	-	+	-58.1	-72.0	27.9	-34.1
	+	+	+	-	+	+	-	+	-	-	+	-	-	-	-	-31.6	-20.8	-44.2	-32.2
	-	-	-	+	+	+	-	+	-	-	-	+	+	+	-	-371.6	-356.7	-423.5	-383.9
	+	-	-	+	-	-	+	+	-	-	+	-	-	+	+	-391.0	-481.2	-391.0	-421.1
	-	+	-	+	-	+	-	-	+	-	+	-	+	-	+	-356.5	-385.0	-454.5	-398.7
	+	+	-	+	+	-	+	-	+	-	-	+	-	-	-	-431.4	-440.9	-409.4	-427.2
	-	-	+	+	+	-	-	-	-	+	+	+	-	-	+	-62.5	-73.0	-80.1	-71.9
	+	-	+	+	-	+	+	-	-	+	-	-	+	-	-	-51.9	-26.2	-98.2	-58.8
	-	+	+	+	-	-	-	+	+	+	-	-	-	+	-	-176.9	-199.3	-63.3	-146.5
	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-180.9	-32.4	-68.5	-93.9
Divisor	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8			Grand mean	-175.4

Table 3-3: Contrast coefficients, raw and averaged data for R_A

In order to show that the data are distributed normally, thus making this analysis relevant, the residuals were calculated and used to generate a normal probability plot. The residuals are calculated by

$$\bar{y} - y \tag{3.2}$$

which is the difference between the actual data point and the grand mean over all data points. Figure 3-17 shows the plot. Although the data are somewhat spread out, they appear to be normally distributed, and so the following analysis methods are most likely relevant.

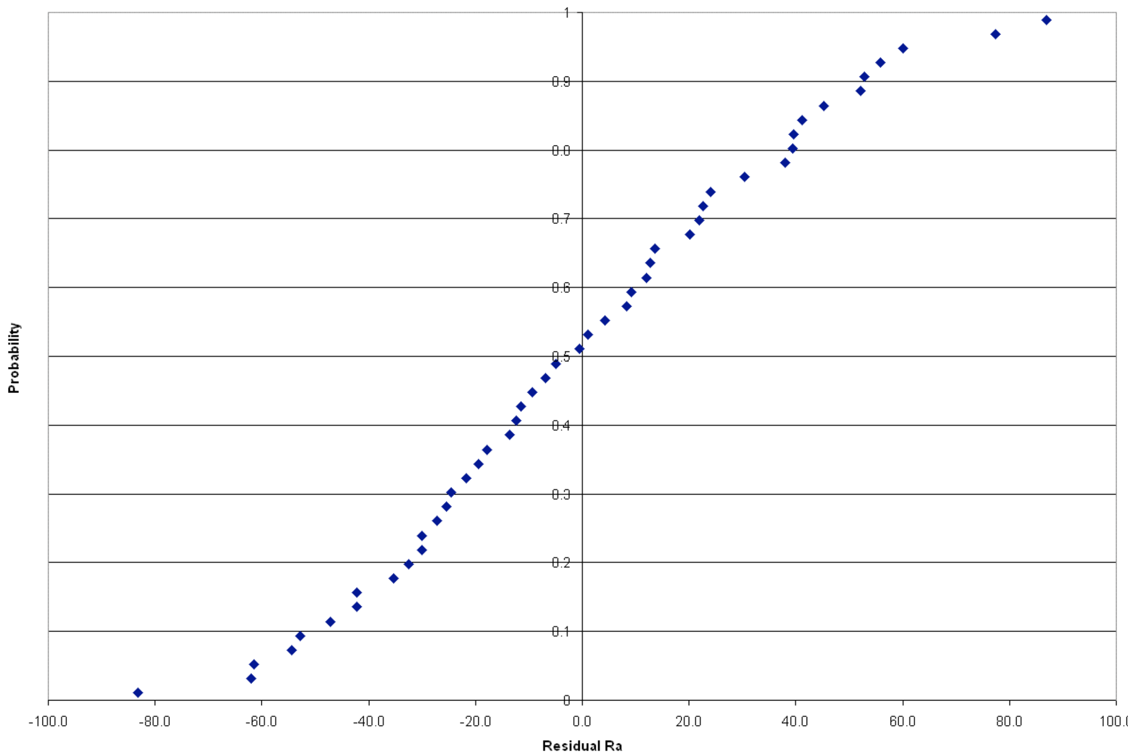

Figure 3-17: Probability plot of residuals for R_A data

The effects and interactions of the factors were calculated by multiplying the average R_A's for a given run by the signs indicated in the column of the factor of interest. Then these values were summed and divided by the divisor shown in that column. This results in the difference between the two averages of the "positive" values and the "negative" values (for more clarification on the calculations see Appendix C: Sample Statistical Calculations). For instance, to calculate the interactions between factors 1 and 2, the values in the AVG column are multiplied by the signs in the 12 column, then summed and divided by 8 (Table 3-3). The values obtained from this process are shown in Table 3-4 along with the standard error. These values were ordered and put into a normal probability plot (Figure 3-18), where it becomes apparent that the effects from 3, 4 and 34 (in bold) are likely to be significant because they lie well off the "error line" and are almost certainly not due to noise. Recall that factors 3 and 4 are the brush type and the presence of the 1160 protective film. Thus, it would appear that any drop in R_A is dependent on these two factors and to a lesser extent their interaction with one another.

Factor	Estimated E&I ± SE
1	-19.1 ± 27.4
2	-17.0 ± 27.4
3	**226.6 ± 27.4**
4	**-149.6 ± 27.4**
12	0.5 ± 27.4
13	30.5 ± 27.4
14	19.1 ± 27.4
23	-12.1 ± 27.4
24	-15.7 ± 27.4
34	**88.4 ± 27.4**
123	15.4 ± 27.4
124	11.5 ± 27.4
134	2.3 ± 27.4
234	-10.1 ± 27.4
1234	-7.6 ± 27.4

Table 3-4: Calculated effects and interactions, and standard errors

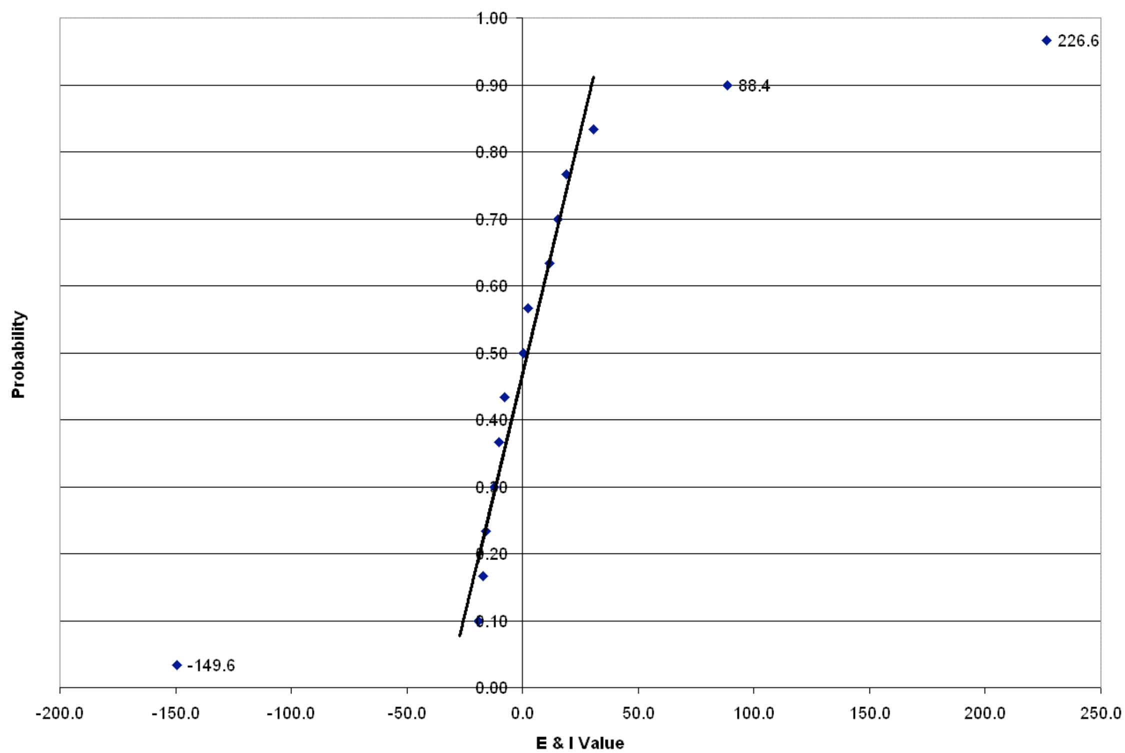

Figure 3-18: Probability plot of ordered effects and interactions

Knowing the factors that influence the amount of damage caused to the sign, a fitted model can be created from the calculated effects, as follows:

$$\hat{y} = -175.4 + \left(\frac{226.6}{2}\right)x_3 - \left(\frac{149.6}{2}\right)x_4 + \left(\frac{88.4}{2}\right)x_3x_4 \tag{3.3}$$

where x_3 and x_4 take the value -1 or +1 according to the columns of signs in Table 3-3. Using this model, the reduction in R_A can be predicted as shown in Table 3-5, which would indicate that, in order to avoid substantial damage, the use of the bristle brush should be avoided on signs with the 1160 protective film. On inspection of those sign samples that had the 1160 film and were cleaned with the bristle brush, it appeared that the reason for the drop in R_A was indeed due to the bristles' scratching the film.

x_3	x_4	Predicted Drop in R_A
-	-	-169.7
+	-	-31.5
-	+	-407.7
+	+	-92.8

Table 3-5: Predicted reduction in R_A from fitted model

Also of importance is the fact that neither the axial force applied to the sign nor the speed at which the brush rotated had any apparent effect on the R_A. This is useful because it allows further testing to use a high load and high speed without worry of damage, so long as they are kept within the ranges used in the test. Additionally, all damage appears to have been caused only to the films that overlay the retroreflective structure, and not to the structure itself. This would seem to indicate that the microprismatic structure is more robust than had been thought, or is sufficiently protected from harm by the overlying layers.

3.4.3. Results of 2^4 Factorial Experiment — Torque

Table 3-6 shows the raw and averaged torque values from each run in the experiment.

Run	T1	T2	T3	Avg T
1	0.16	0.19	0.19	0.18
2	0.38	0.45	0.44	0.42
3	0.18	0.17	0.18	0.18
4	0.45	0.50	0.48	0.48
5	0.26	0.29	0.24	0.26
6	0.55	0.60	0.54	0.56
7	0.27	0.28	0.28	0.27
8	0.60	0.67	0.67	0.65
9	0.13	0.19	0.18	0.16
10	0.41	0.47	0.45	0.44
11	0.18	0.18	0.19	0.18
12	0.45	0.45	0.47	0.46
13	0.31	0.32	0.37	0.33
14	0.87	0.97	0.74	0.86
15	0.25	0.34	0.39	0.33
16	0.71	0.97	1.06	0.91
			Grand Mean	0.42

Table 3-6: Raw and averaged torque values, in N-m

However, if the residuals are calculated and plotted in a fashion similar to Figure 3-17, the result is Figure 3-19. Note that the residuals do not appear to be distributed normally about the mean, which indicates that further investigation of the effects and interactions of the factors may not be accurate. However, it should be enough, looking at the raw data, to notice that the highest levels of torque appear in the runs which used the scouring pad on the 1160 film at high load (runs 14 and 16). The next highest levels of torque appear in the runs which used the scouring pad without the 1160 film at high load (runs 6 and 8). This may be enough information to suggest a motor size, given a particular brush choice and axial load.

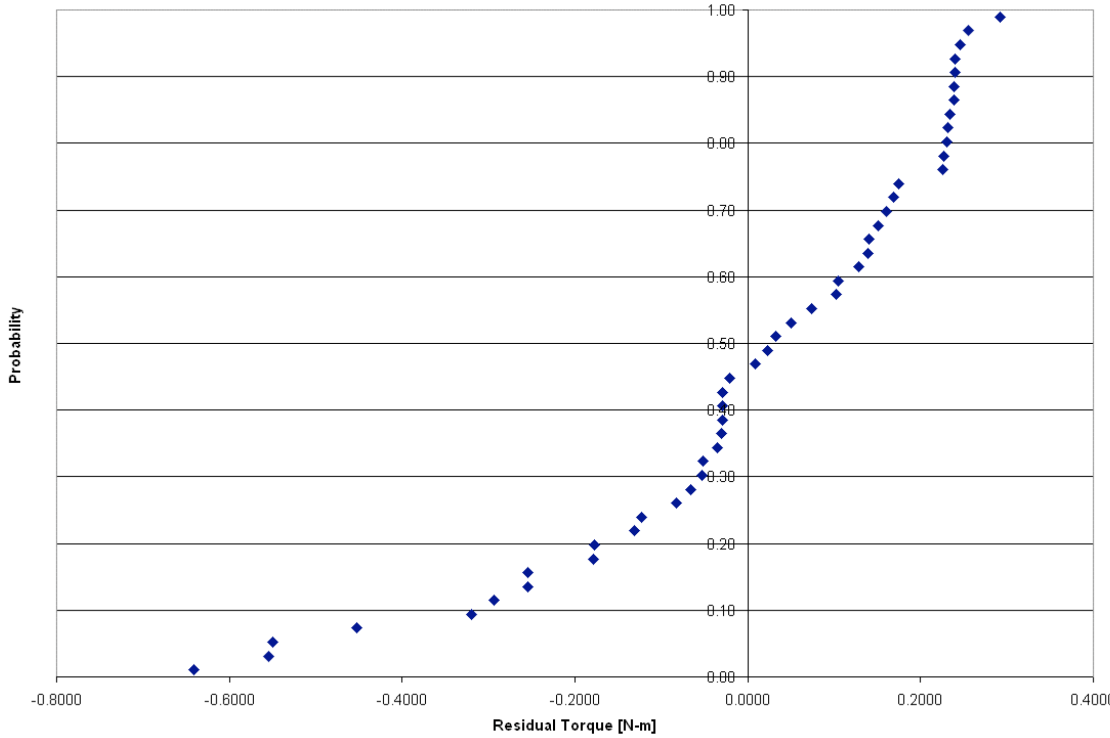

Figure 3-19: Probability plot of torque residuals

3.4.4. Further Testing

Because the results of the factorial experiment seemed to indicate that degradation of a sign's reflectivity is not affected by the load or speed of the cleaning implement, all further testing used high levels for both of these values. However, the brush type and presence of the 1160 film were still varied. First, a test using a polystyrene brush was conducted. Next, both the polystyrene brush and scouring pad were used to clean painted signs. Then, multiple cleanings on the same sign were investigated, followed by multiple cleanings on painted signs.

3.4.4.1. Polystyrene Brush

This test was run similarly to the factorial experiment; however, it only used one type of brush, so the only variable was the presence of the 1160 film. The polystyrene brush used had softer bristles than the polypropylene brush, and it was believed that it might produce less damage to the sign. Table 3-7 shows the results from the test.

		Drop in Ra		
Run	1160	R1	R2	AVG
1	-	-7.42	-62.87	-35.1
2	+	-275	-225.6	-250

Table 3-7: Results from polystyrene brush test

From these results it would appear that, as in the factorial experiment, the use of the brush on the 1160 film seems to cause a significant amount of damage to the sign, which seemed on visual inspection to be due to scratching on the protective film.

3.4.4.2. Painted Signs — Single Run

For this test, the sign samples were painted with a layer of flat black spray paint such that the film on the surface of the sign was no longer visible and allowed to cure for 48 hours. The variables for the test were the brush type (polystyrene and scouring pad) and the presence of the 1160 film. This resulted in 4 runs, which were duplicated once. The tests ran for 40 cycles, just as they had in the previous experiments, and the cleaning fluid was applied in the same manner. Table 3-8 shows the results from this test.

	Brush	1160?	Drop in Ra		
Run	1	2	R1	R2	Avg Y
1	-	-	-89.0	-65.6	-77.3
2	+	-	-57.0	-48.5	-52.8
3	-	+	-263.0	-164.6	-213.8
4	+	+	-23.3	-121.3	-72.3

Table 3-8: Results of single run test on painted signs

Again it would appear that the most damage to the sign was caused by the use of the brush on the signs with the 1160 film. However, there was quite a bit of difference between the duplicate runs with the film present (runs 3&4). Upon inspection of the signs, this appeared to be caused by a layer of residue on the sign left over from the cleaning fluid, which could not be removed even with vigorous rubbing. This residue can be seen in Figure 3-20 as a mottled appearance in the cleaned area. Initially this was thought to be due to the paint adhering to signs with the 1160 film better than to those without, but further testing revealed that this was probably not the case. Instead, it was probably due to a lack of sufficient cleaner being used to remove the paint. Also, it appeared partway through the test that the paint seemed to be removed from the sign before the 40 cycles had passed, meaning that the runs could be of a much shorter duration. Thus, for future tests, the number of cycles was reduced from 40 to 20.

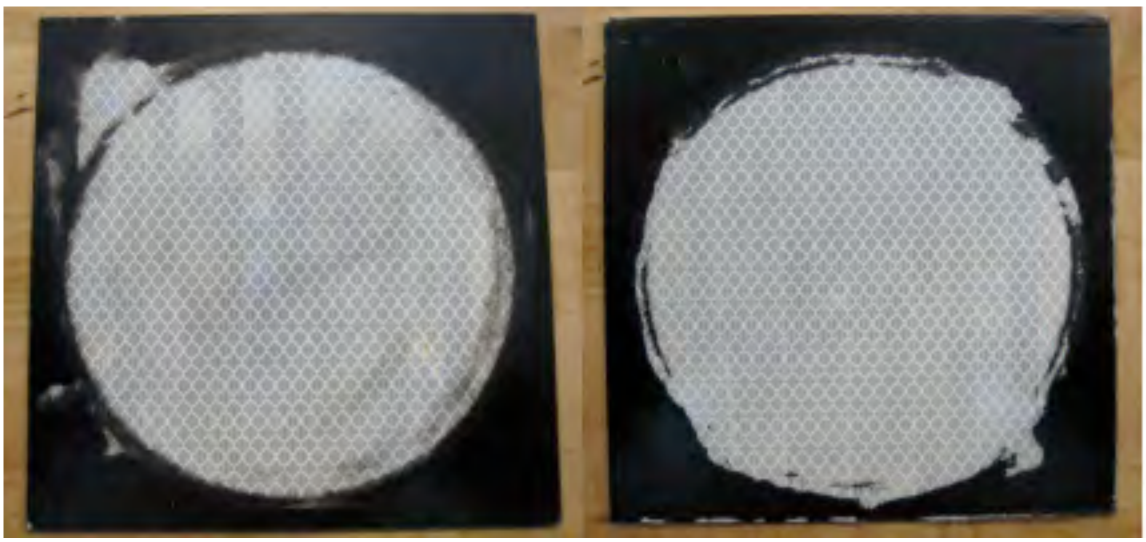

Figure 3-20: Comparison of cleaned signs; Left with 1160, Right without.

3.4.4.3. Multiple Cleanings on One Unpainted Sign

For this test six signs—three with 1160 film, and three without—were subjected to a total of five cleanings each. Only the scouring pad was used, as by this point it had become apparent that bristle brushes tended to damage the sign more. Additionally, a brand-new scouring pad was used in order to determine if pad wear had an effect on the outcome. The decision to do this was based on the perception that a new pad felt much rougher than a used one. Figure 3-21 shows the change in R_A for the signs without the 1160 film, and Figure 3-22 shows the change for those signs with the film.

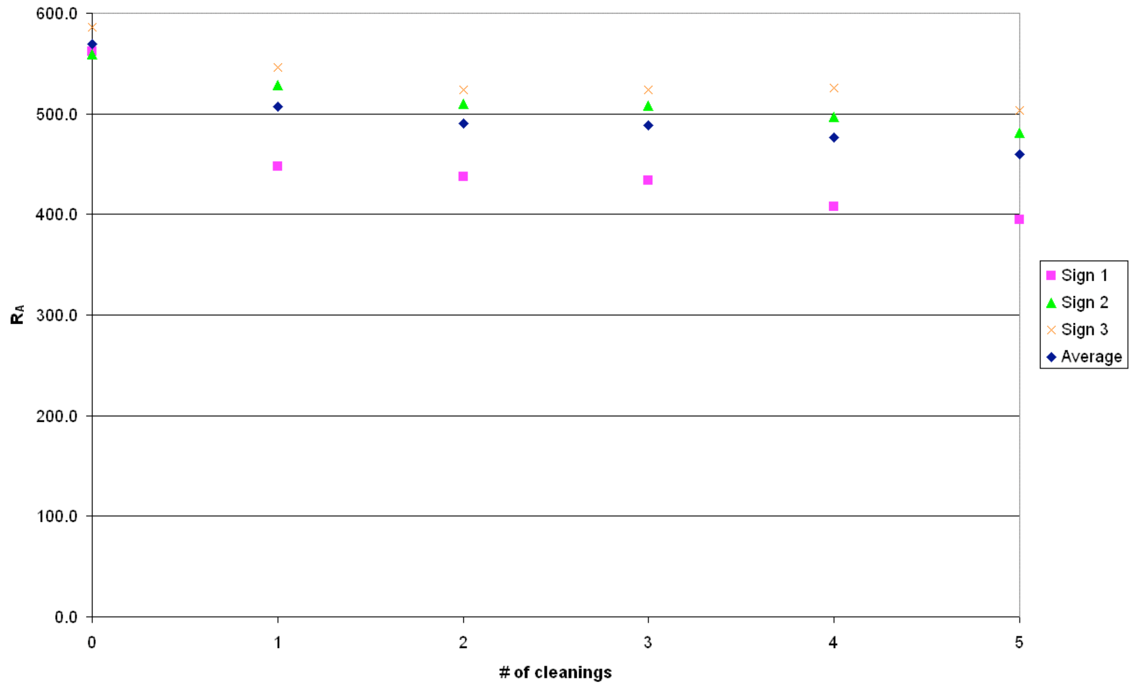

Figure 3-21: Results from multiple runs w/o 1160 film

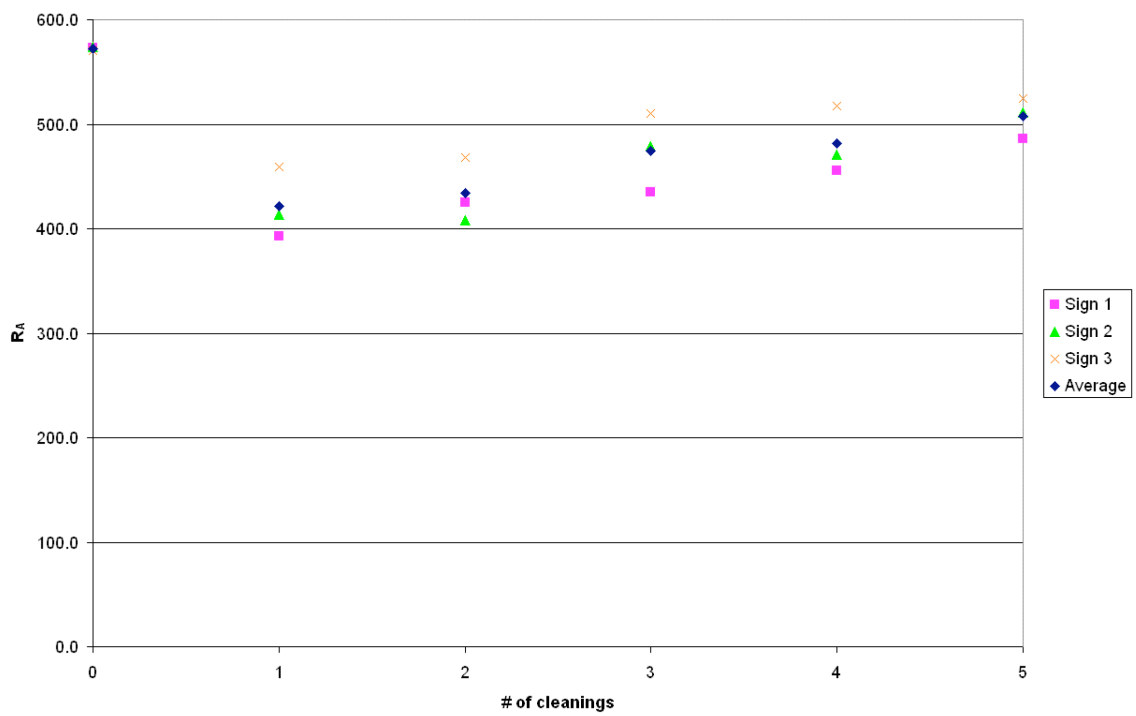

Figure 3-22: Results from multiple runs with 1160 film

These results were somewhat surprising. With the results from the factorial experiment, it was thought that the R_A would degrade steadily over several cleanings. Instead, what happened is the reduction in RA leveled off, and in the case of the signs with the 1160 film actually began to improve dramatically. Visual inspection of the signs after the initial tests showed a fair amount of scratching on the surface from the new pad, but over time the samples began to regain a shiny surface again. It is thought that the reason for these results was probably a combination of pad wear and the characteristics of the cleaner. After the first few uses, the surface of the pad took on a noticeably softer feel which seemed to reduce its abrasive qualities. Additionally, once the SEI Graffiti Remover was applied and the solvent allowed to evaporate, the cleaner that was left behind had a waxy consistency which may have aided in "polishing" the sign. At any rate, it appeared that it was possible to clean the signs multiple times without significant damage, as the R_A levels never approached the minimum levels mandated by the FHWA.

3.4.4.4. Multiple Cleanings on One Painted Sign

For the last test in the series, attempts were made to simulate a situation likely to be faced by maintenance workers: cleaning a sign that has been painted multiple times. The paint used was the same flat black spray paint used in the single-run test, was applied the same way and allowed to cure for at least 48 hours each time. Due to time constraints, only four cleanings were possible. Again, both signs with and without the 1160 film were tested, and the tests were run for 20 cycles. The pad used was the same one from the previous test, indicating that initial damage should not be a problem. Figure 3-23 shows the results from the signs without the 1160 film, and Figure 3-24 shows the results from those with the film.

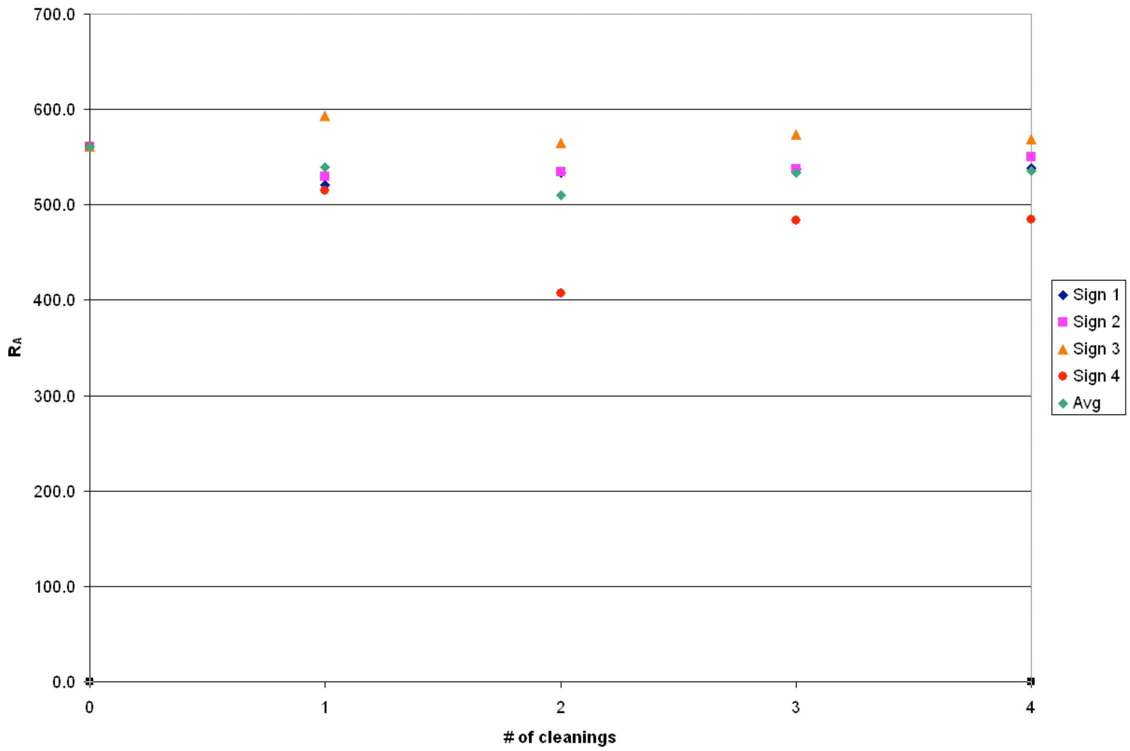

Figure 3-23: Multiple cleanings on painted signs w/o 1160

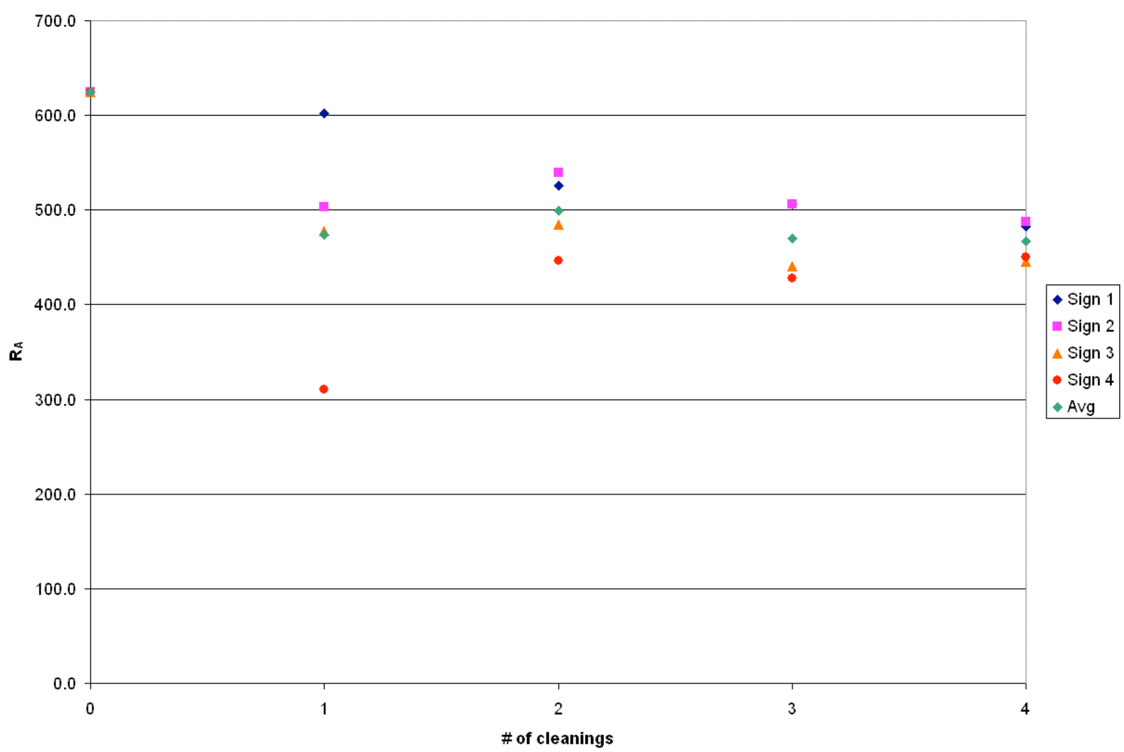

Figure 3-24: Multiple cleanings on painted signs with 1160

While these results are not as dramatic as those from the previous test since none of the signs improved over several cleanings, it is notable that the R_A never really got close to the FHWA minimum levels. This indicates that it is probably possible to use the proposed design of a motorized pad and chemicals to clean a sign.

3.5. Conclusion

This chapter began by describing the concept of the end effector of the sign cleaning tool, and illustrated the need to determine the behavior between it and the sign surface. Next, a 2^4 factorial experiment to determine the effects and interactions of certain factors on the R_A of the sign was developed, and its setup and procedure described. Then the results of the experiment were revealed, indicating a direction for further testing and development. Finally, more tests using both a different brush and multiple cleanings were described, and their results explained.

Chapter 4. Conclusions and Recommendations

4.1. Introduction

This chapter will use the results of the tests in the previous chapter to make recommendations about the end effector of the sign cleaning tool. First, the feasibility of the proposed design for the end effector will be discussed. Then, the torque data will be examined, and a recommendation made. Next, some recommendations about the use of cleaning fluid will be made. Finally, some recommendations for further testing will be made, with the purpose of more closely simulating actual sign conditions.

4.2. Feasibility of Proposed Design of the End Effector

From the tests performed on the signs, it appears that using an end effector with a soft scouring pad and oscillating motion is a feasible idea, as far as damage to a sign is concerned. The feature of having a disposable pad that attaches to a permanent base by a hook-and-loop structure is a bonus because it reduces the amount of waste and cost associated with the tool, and also allows both sides of the pad to be used, effectively doubling its life and further reducing waste and cost. The concern of having a new pad damage the sign, as indicated in the test in Section 3.4.4.3, is not a major concern because the amount of damage was relatively low and did not cause the reflectivity to approach the minimum FHWA mandated levels. However, that test used a new pad on a new sign; if it is determined that there is a concern of a new pad causing too much damage to a sign whose R_A is already reduced, then it may be necessary to "pre-wear" the pad on a scrap sign before it is actually used to clean.

4.3. Recommendations from Torque Data

The maximum levels of torque recorded were around 1 N-m (8.85 in-lb) for the scouring pad at high load on the 1160 film. Since this configuration most closely resembles that of the tool as designed, this value for the torque should be used when selecting a motor. However, note that this value is for only one pad, and the proposed design uses three pads, which results in a total torque requirement of 3 N-m (26.6 in-lb). Depending on the final configuration of the drive system for the pads, this is an achievable value.

4.4. Amount of Cleaning Fluid Used

It became apparent over the course of the paint-removal tests that a large amount of cleaner could be used, since this seemed to improve the amount of paint removed. However, to use the cleaner only once could be too costly, since it tends to be expensive and must be disposed of properly as hazardous waste. Therefore, the idea of circulating and filtering the paint particles from the cleaning fluid should be investigated. Alternatively, the fluid recovered from the surface could later be allowed to sit and the paint solids allowed to settle at the bottom. Then, the cleaning fluid could be decanted off the top and used again, and the sludge of particles at the bottom removed for disposal. However, this results in more contact with the fluid by the worker, as well as increasing the risk for spills.

4.5. Opportunity for Further Testing

More tests could be performed to more closely simulate the conditions a sign would face on the roadside. Caltrans has developed a test, CT684 [33], which is used to determine the effectiveness of graffiti removal products for inclusion in the Qualified Products List. It consists of reflective sign panels which are inked with different colors, and half of which are also coated with a protective film like the 1160. These samples are then painted and artificially weathered by being placed under a xenon arc lamp for a certain number of hours, occasionally being sprayed with water. Performing tests on samples such as these using the test fixture from the previous experiments would determine with even greater accuracy whether the end effector is a feasible design.

4.6. Conclusion

This report began the initial stages of development of a tool that could be used to clean graffiti off of signs. Research was done into the current best practices of graffiti removal, both by performing extensive literature searches and by interviewing persons who work in the field of graffiti removal. It was determined that, with the exception of signs, most methods of graffiti removal are well established and well developed. It was learned that signs present a particular problem due to their surfaces being sensitive to damage, as well as their awkward location for cleaning. As a result, most removal from signs is done by hand by maintenance personnel, which can expose them to hazards in the form of falls or stress injuries. Thus, a need was identified, and work began on a product that would fulfill that need.

The development of the tool began by interviewing maintenance personnel who often have to clean signs about their current methods, likes and dislikes. These statements were translated into a set of needs, which formed the basis for the function of the tool. A set of metrics was also developed by which certain aspects of the tool could be judged successful. Then, a set of target specifications was elicited, which would determine qualitatively the level of success of the metrics. Finally, several possible key aspects of the tool were discussed along with their pros and cons, and a final design was proposed.

At this point, the report switched from an overall development of the tool to a more specific development of the end effector of the tool. This was due to the unknown interaction between the end effector and the sign surface, which is arguably the most critical aspect of the design. A factorial experiment was developed to test the effects of load, speed, brush type and sign surface material on the retroreflectivity levels of the sign. The setup and procedure for this experiment was described, and then the results of both the experiment and further tests were revealed. It was determined that in order not to damage the surfaces of all types of sign, a soft scouring pad should be used. Further tests showed that this pad was also effective at removing paint, even over several painting cycles, without damaging the sign beyond an unacceptable level.

Finally, the recommendations based on these results were made, along with suggestions regarding cleaning fluid use and even further testing. From the research done in this report, it appears that a tool for cleaning signs is both feasible and desirable, and will enhance the speed and comfort related to removing graffiti from signs along the roadways.

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Appendix A: Results of Interviews

The following is a copy of the questionnaire used for the interviews, followed by the results of the interviews.

Name:__________________
Position:___________________

Graffiti Removal Methods Questionnaire

1. What does your department currently do for graffiti removal from the following?
   - Unpainted concrete
   - Painted concrete
   - Murals
   - Retroreflective signage
   - Galvanized steel
   - Painted metal

2. How does each of these methods work well, and why does your department use that method as opposed to another? For example, why paint instead of pressure wash or sandblast? Is it cost, speed, effectiveness?

3. What are the drawbacks or limitations of each of these methods? How do they not work well?

4. Is there anything you have tried that didn't work at all?

5. Is there anything you have tried that worked well but was too slow or expensive?

6. How much graffiti do you remove in your jurisdiction?

7. Contact info for other people in other departments?

Results of Interviews

PennDOT District 6-0 Roadside Specialist Supervisor
Interview date: 8/28/8
Reports that 80% of their removal method is overpainting, due to low cost and speed.
Surfaces:
- Unpainted concrete: High pressure wash, or paint over
- Painted concrete: Same
- Murals: N/A
- Retroreflective signage: High pressure wash
- Galvanized steel: Paint

- Painted metal: Paint

Benefits of methods, reason for using one over another: There is a high potential for lead paint to exist on structures from which graffiti is removed. Testing can be time consuming, so overpainting is the best choice. It is also less harmful to the environment.

Drawbacks of methods: Aesthetics of overpainting can be unsightly, pressure washing may leave ghosting.

Method tried that didn't work? Tried anti-graffiti coatings, both sac and non-sac. Both were cost prohibitive/ ineffective

Method that worked, but too slow or expensive?

Amount of graffiti removed? 240-250 yd^2/day

Highway Maintenance Engineer, Wisconsin DOT, SE district
Interview date: 8/28/8
Surfaces:

- Unpainted concrete: Paint over
- Painted concrete: Same
- Murals: N/A
- Retroreflective signage: Solvent-based cleaner
- Galvanized steel: Paint over
- Painted metal: Paint over

Benefits of methods, reason for using one over another: Uses overpainting due to time and convenience. Paint is color-matched at a paint store.

Drawbacks of methods: Expensive to purchase and match paint

Method tried that didn't work?

Method that worked, but too slow or expensive? Non-sac coating, too time-consuming

Amount of graffiti removed? Unknown

Maintenance Resident Engineer, Queens/Manhattan counties, New York
Surfaces:

- Unpainted concrete: Paint over old concrete, for new concrete (or new surfaces) they use a sacrificial coating, a hot wax that is spray applied. When tagged, it is power washed with hot water, then reapplied
- Painted concrete: Paint over
- Murals: N/A
- Retroreflective signage: Solvent-based cleaner

- Galvanized steel: Solvent
- Painted metal: Solvent

Benefits of methods, reason for using one over another: Sac coating is very easy to use and is quite effective. Painting is cheap and easy.

Drawbacks of methods: Sac coating must be immediately reapplied

Method tried that didn't work? Non-sac coating was only good for 3-4 removals before it started peeling off with power wash. It is also difficult to reapply the coating over previously coated surfaces because it doesn't stick

Method that worked, but too slow or expensive? Solvents are slow

Amount of graffiti removed? Unknown

Head of Graffiti Rangers, Seattle, WA
Surfaces:

- Unpainted concrete: Pressure wash or sandblast
- Painted concrete: Repaint, either with prematched city, county, state color scheme, or matched paint
- Murals: N/A
- Retroreflective signage: N/A (different jurisdiction)
- Galvanized steel: Solvents, from citrus based to paint strippers
- Painted metal: Repaint

Benefits of methods, reason for using one over another: Uses a wide range of methods, so each is used because it works the best. Choices made by trial and error, working from weakest method toward strongest.

Drawbacks of methods: None

Method tried that didn't work? Lots of chemicals don't work. Non-sac coating didn't work.

Method that worked, but too slow or expensive? Lots of chemicals are too slow

Amount of graffiti removed? In 2007, 336000 ft^2, 106000 tags removed

Graffiti Abatement Coordinator, Portland OR
Surfaces:

- Unpainted concrete: Pressure wash or paint with recycled paint that is close in color to concrete
- Painted concrete: Repaint with recycled paint, or with customer-supplied paint

- Murals: Contracts out—non-profits pressure wash or repaint mural, for-profit company (Goodbye Graffiti) uses their methods. Once, a non-sac coating was applied over a mural that worked well.
- Retroreflective signage: State highway jurisdiction; David Smith (ODOT) reports using chemicals on signs and aluminum colored paint on the backs of signs. Says that removal from uncoated silkscreened signs (e.g. stop) is a problem, since solvents remove screened graphics as well.
- Galvanized steel: Solvents
- Painted metal: Solvents

Benefits of methods, reason for using one over another: Repainting is cheap, generally they try for the best process they can find

Drawbacks of methods: With powerwashing, the unit has to hook up to water, so if there's no water close by, crew can't powerwash. Lots of graffiti on unpainted wooden fences, and powerwashing quickly degrades the fence. Reds and blues don't come out with PW (ghosting)

Method tried that didn't work? Tried sandblasting on one soft brick surface—destroyed the surface. If it's a historic building, they just contract with Goodbye Graffiti.

Method that worked, but too slow or expensive?

Amount of graffiti removed? Unknown, but reports indicate that incidents are increasing. Not sure if it's due to more graffiti, or just more awareness.

Community Service Officer, Graffiti Enforcement, Reno NV
Surfaces:

- Unpainted Concrete: Pressure wash or paint over with grey
- Painted concrete: Paint over. No matching, they use spray equipment with long hoses, so color changes are not possible, other than the 4 basic colors they have.
- Murals: Don't touch murals, it is up to the owner to touch it up.
- Retroreflective signage: Don't touch signs, that is the street department's jurisdiction. Believes they may be changing to signs with anti-graff coatings
- Galvanized steel: solvent wipes
- Painted metal: solvent wipes, or owner's responsibility to repaint to their color

Benefits of methods, reason for using one over another: Depends on surface—best method chosen for that particular surface. Ex: Can't use strong power wash surface of old fence, it gets destroyed. Needs to be painted or replaced. Can't sandblast porous surface, it etches the paint into the surface.

Drawbacks of methods: Sometimes removal is incomplete. Ex: Power wash on old fence doesn't get it off, must replace.

Method tried that didn't work? None, because they get rid of it, even if they have to replace the surface it is on (e.g. fence, sign)

Method that worked, but too slow or expensive? Coatings are expensive, but owners may use them if they wish (maintenance becomes their job). Many solvents are too slow/don't work.

Amount of graffiti removed? 1300 incidents/mo

District 7 Graffiti Coordinator, Caltrans
Surfaces:

- Unpainted Concrete: Paint over, unless it is around waterways, storm control, then it is left up
- Painted concrete: A chemical is sprayed on, which causes non-tar-based paints to blister up. It is then removed, and fresh paint is applied.
- Murals: Up to the artist to remove, generally using conservation methods. If graffiti is not removed, mural is removed and painted out
- Retroreflective signage: Since signs are coated with 3M film, solvent removers are used (wipes)
- Galvanized steel: Solvent removal
- Painted metal: Solvent removal

Benefits of methods, reason for using one over another: Use what works, especially in a given area. If a location is perpetually and heavily hit, painting is fastest and easiest, since they know they'll be back. Don't sandblast, because it can only be done once (degrades the surface badly)

Drawbacks of methods: Lots of paints can be hard to go over, especially if additives have been put in (e.g. silicone, graphite), so overpainting is sometimes ineffective without complete removal

Method tried that didn't work? Most citrus-based chemicals don't work, even if they do say they are reformulated. Physical barriers, are effective deterrents for a short while, but are eventually overcome (bent, broken)

Method that worked, but too slow or expensive? Farrow system—low pressure blast mix of ash, pumice and hot water. Worked, but too expensive.

Amount of graffiti removed? 3 million ft^2, \$5.5 million per year

Civil Engineer, PennDOT district 11
Surfaces:

- Unpainted Concrete: Sandblast in high-visibility areas, frequently targeted areas get painted

- Painted concrete: Paint over, attempts to match with samples from Home Depot that are 2 shades darker than what is present. Does not use technical procedure
- Murals: don't touch (responsibility of owner)
- Retroreflective signage: Solvents, sometimes paint backs
- Galvanized steel:
- Painted metal:

Benefits of methods, reason for using one over another: Paint is simple to apply, quick, no mess. Can be done with one man, as opposed to sandblasting.

Drawbacks of methods: Difficult to blend paint on concrete. Sandblasting machine sometimes clogs, needs replacements

Method tried that didn't work? None, has never tried coatings

Method that worked, but too slow or expensive? none

Amount of graffiti removed? 160 hours painting, 300 hours blasting, both over 3 years

Operations Supervisor, Graffiti Removal Unit, SF DPW, San Francisco, CA
Surfaces:

- Unpainted Concrete: Use chemical remover, Heritage: apply and let sit, then power wash it off. Reapply if necessary.
- Painted concrete: Paint over. They have a van with a power washer, paint sprayer and computerized matching system
- Murals: Not allowed to touch them. Finds that most taggers respect the murals.
- Retroreflective signage: Solvent removers
- Galvanized steel: Solvents
- Painted metal: Paint over

Benefits of methods, reason for using one over another: Painting is fast and pretty effective, Heritage works on a wide range of surfaces and is also effective. Power washing is slow and time consuming, many methods (e.g. blasting) require extensive training, but painting does not.

Drawbacks of methods: Painting looks pretty crappy on awnings of businesses, since they are often custom colors and designs. None of the methods of removal work on acid-etched windows (which they don't deal with anyway—they are the owner's responsibility)

Method tried that didn't work? None really, except for awnings and glass. Tried non-sac coatings, but they started to wear off after a few removals.

Method that worked, but too slow or expensive? Heritage is expensive, but it works, so they use it.

Amount of graffiti removed? Roughly 700 incidents a month. Roving crews are assigned to a certain area, and try to be proactive in removal.

Program Coordinator, Denver Partners Against Graffiti, Denver CO
Surfaces:

- Unpainted Concrete: Gel stripper and power wash
- Painted concrete: Paint over with nearest matching color (they have 7 standard colors)
- Murals: Contact owner or artist to try and repaint or remove. They don't do it.
- Retroreflective signage: Soy-based solvent
- Galvanized steel: Soy, maybe stripper with PW if needed
- Painted metal: repaint

Benefits of methods, reason for using one over another: Cheap and work fairly well. Blasting would damage surface

Drawbacks of methods: Soy-based solvent removes graphics from older, non-coated signs. Sometimes people will try to do removal themselves, and graffiti ghosts, which is difficult to remove (e.g. black paint on blond brick)

Method tried that didn't work? They have chemical products shopped to them that often don't work

Method that worked, but too slow or expensive? No, haven't tried any kind of coatings

Amount of graffiti removed? 2.5M ft^2 last year, moving towards ~4M this year

Caltrans Maintenance Supervisor, District 4, Unit 712 (east bay)
Surfaces:

- Unpainted Concrete: Paint over. Uses recycled paint, have 10 colors but uses 4-5 often. Tried to get a color matching system, but it fell through. For overhead work: guy in a cherry picker with spray equipment.
- Painted concrete: Paint over
- Murals: Don't touch
- Retroreflective signage: Don't touch (sometimes paint backs)
- Galvanized steel: Paint
- Painted metal: Paint

Benefits of methods, reason for using one over another: Painting is cheap, fast and effective. Growing evergreen ivy on wall works well; only two incidents in ~25 years of taggers removing vegetation.

Drawbacks of methods: Getting to the surfaces (dangerous shoulder work), protecting pretty sound walls, cost of crew operation

Method tried that didn't work? Sacrificial coatings violated NPDES.

Method that worked, but too slow or expensive? Soda blasting took forever to use. Hot pressure washing has very high maintenance costs, along with burn danger to operator.

Amount of graffiti removed? Unknown, as he is head of crew, not in an office.

Eradication Component Supervisor, San Jose Anti-Graffiti Program, San Jose, CA
Surfaces:

- Unpainted Concrete: Power wash
- Painted concrete: Paint over—have a flatbed truck with power washer and 4 paint sprayers (standard scheme for city)
- Murals: don't touch
- Retroreflective signage: Graffiti wipes (Omega), weaker than solvent they use
- Galvanized steel: Solvent followed by P/W
- Painted metal: Paint over

Benefits of methods, reason for using one over another: Easy, convenient

Drawbacks of methods: Some ghosting on very porous masonry

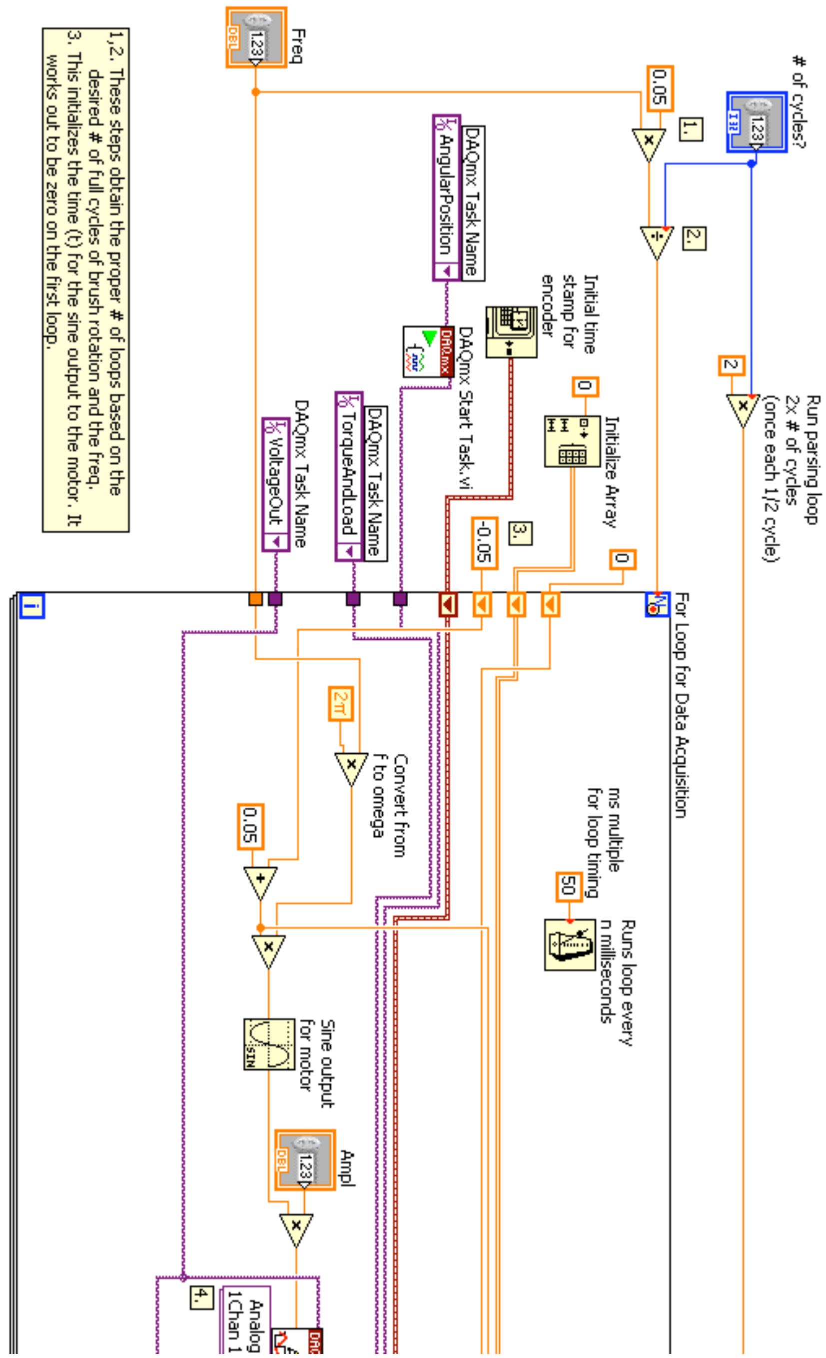
Method tried that didn't work? None known. Current system in place for 10 years

Method that worked, but too slow or expensive? Non-sacrificial coatings—worked but turned white ("Drew alkali out of the masonry"), wore down after several cleanings

Amount of graffiti removed? 1990: 72000 tags. 2006: 2600 tags. Credits swift removal policies with steady decrease (within 24(gang) to 48(other) hours). 2007: 13000 tags

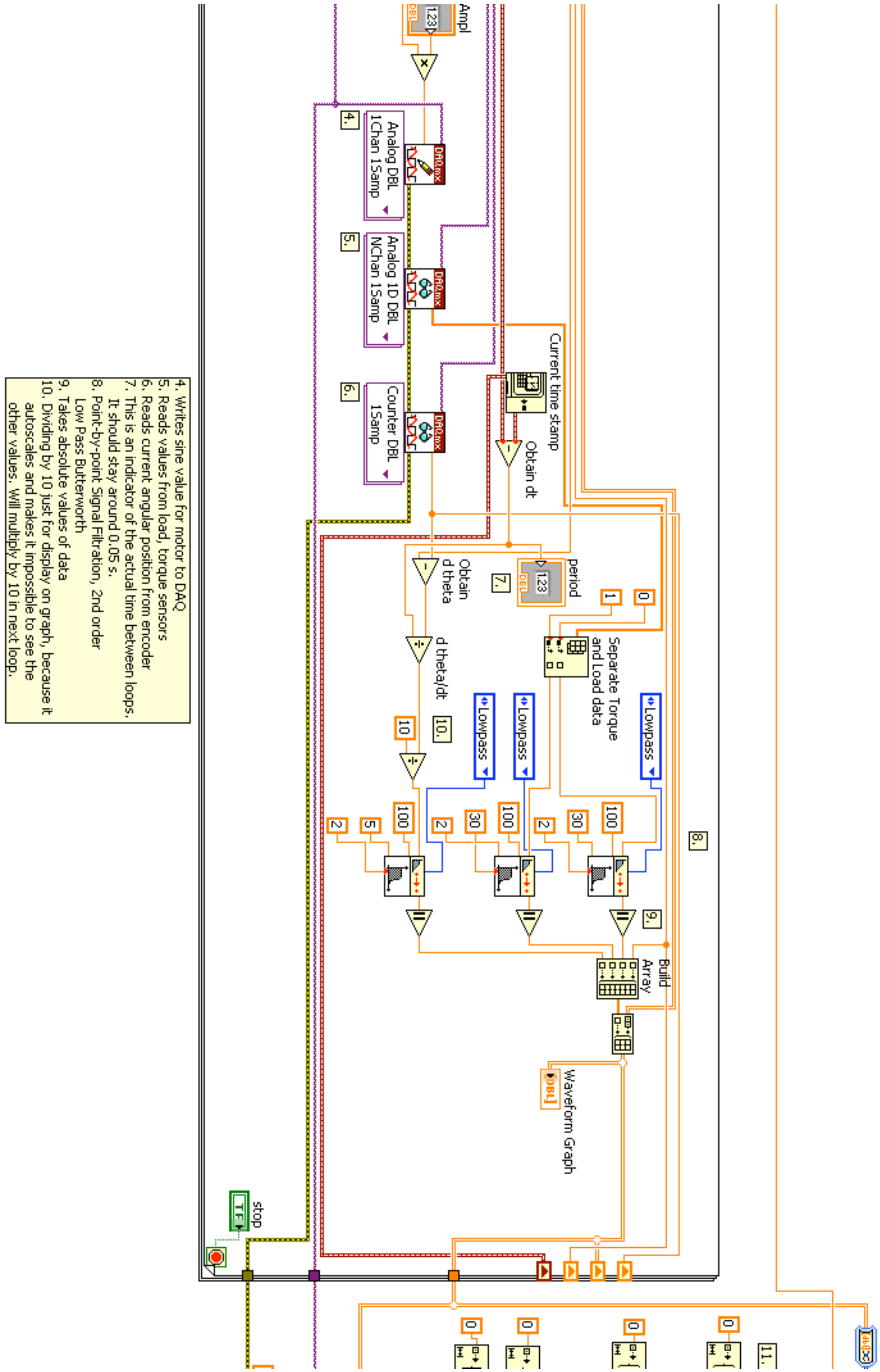
Appendix B: LabVIEW VI

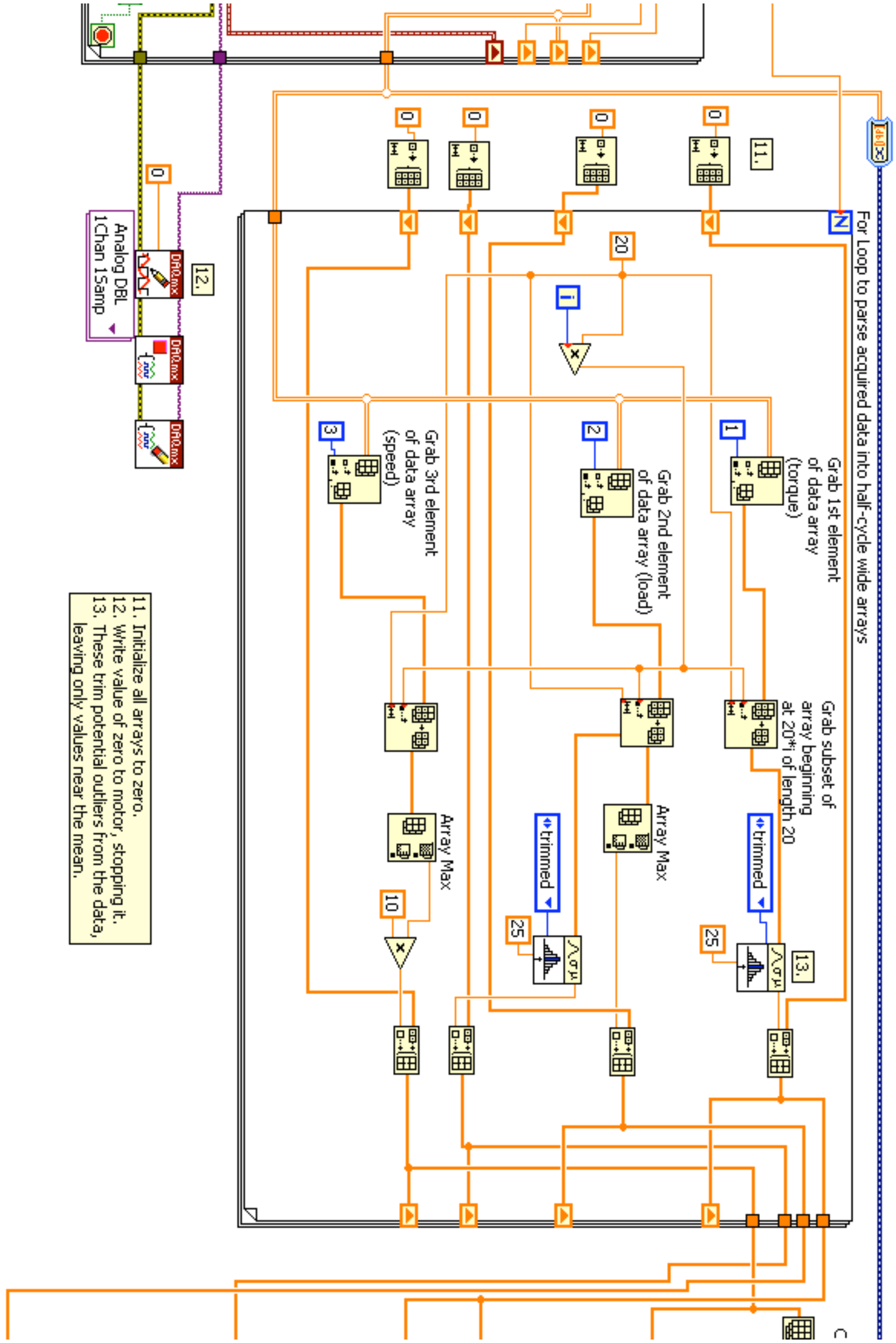
The following images show the LabVIEW Virtual Instrument that was written for the factorial experiment. The images should be tiled from left to right to obtain an image of the entire program. The final image shows the front panel of the VI.

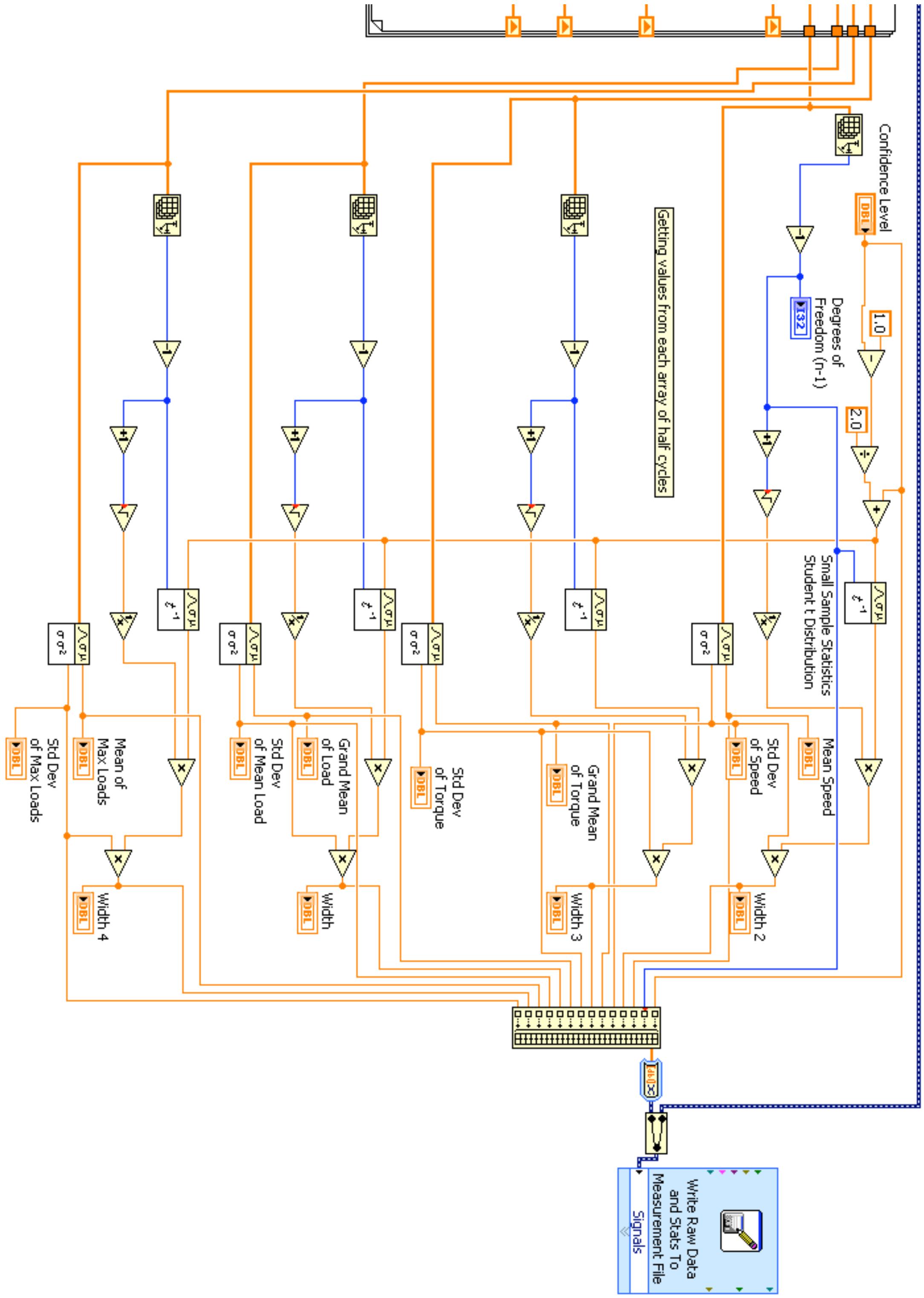


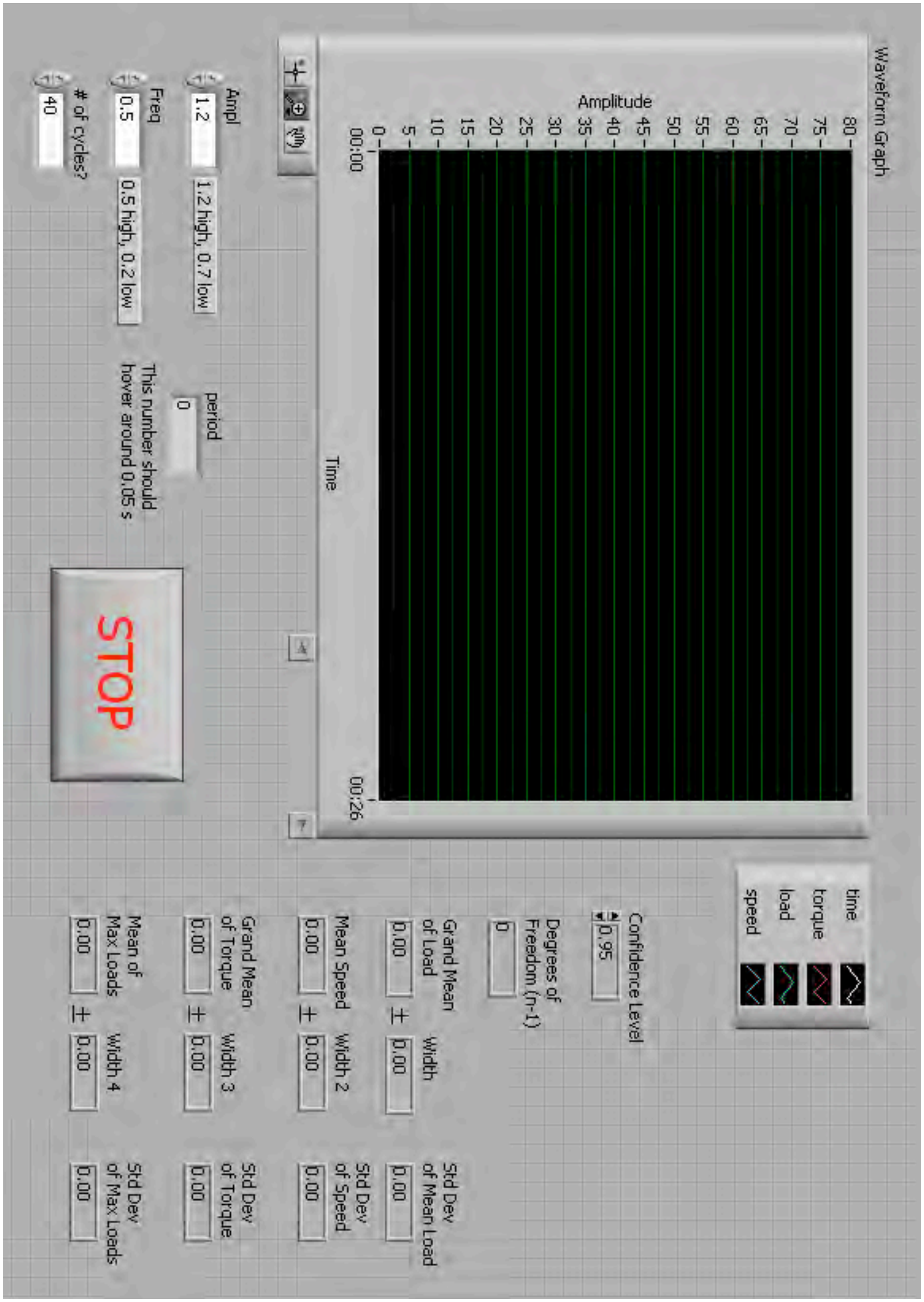
# of cycles?
Freq
0.05
1.
2.
2
Run parsing loop 2x # of cycles (once each 1/2 cycle)
DAQmx Task Name
AngularPosition
Initial time stamp for encoder
0
Initialize Array
DAQmx Start Task.vi
DAQmx Task Name
TorqueAndLoad
DAQmx Task Name
VoltageOut
3.
-0.05
0
1,2. These steps obtain the proper # of loops based on the desired # of full cycles of brush rotation and the freq.
3. This initializes the time (t) for the sine output to the motor. It works out to be zero on the first loop.
For Loop for Data Acquisition
ms multiple for loop timing
50
Runs loop every n milliseconds
Convert from f to omega
0.05
Sine output for motor
Ampl
4.

Figure 0-1


Ampl
Analog DBL 1Chan 1Samp
Analog 1D DBL NChan 1Samp
Counter DBL 1Samp
Current time stamp
Obtain dt
period
Obtain d theta
d theta/dt
Separate Torque and Load data
Lowpass
Build Array
Waveform Graph
stop
4. Writes sine value for motor to DAQ
5. Reads values from load, torque sensors
6. Reads current angular position from encoder
7. This is an indicator of the actual time between loops.
It should stay around 0.05 s.
8. Point-by-point Signal Filtration, 2nd order
Low Pass Butterworth
9. Takes absolute values of data
10. Dividing by 10 just for display on graph, because it
autoscales and makes it impossible to see the
other values. Will multiply by 10 in next loop.


For Loop to parse acquired data into half-cycle wide arrays
Grab 1st element of data array (torque)
Grab 2nd element of data array (load)
Grab 3rd element of data array (speed)
Grab subset of array beginning at 20*i of length 20
Array Max
Array Max
trimmed
trimmed
Analog DBL 1Chan 1Samp
11. Initialize all arrays to zero.
12. Write value of zero to motor, stopping it.
13. These trim potential outliers from the data, leaving only values near the mean.


Confidence Level
1.0
2.0
Degrees of Freedom (n-1)
Getting values from each array of half cycles
Small Sample Statistics Student t Distribution
Mean Speed
Std Dev of Speed
Width 2
Grand Mean of Torque
Width 3
Std Dev of Torque
Grand Mean of Load
Std Dev of Mean Load
Width
Mean of Max Loads
Std Dev of Max Loads
Width 4
Write Raw Data and Stats To Measurement File
Signals


Waveform Graph
Amplitude
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
00:00
00:26
Time
time
torque
load
speed
Ampl
1.2
1.2 high, 0.7 low
Freq
0.5
0.5 high, 0.2 low
# of cycles?
40
period
0
This number should hover around 0.05 s
STOP
Confidence Level
0.95
Degrees of Freedom (n-1)
0
Grand Mean of Load
0.00
±
Width
0.00
Std Dev of Mean Load
0.00
Mean Speed
0.00
±
Width 2
0.00
Std Dev of Speed
0.00
Grand Mean of Torque
0.00
±
Width 3
0.00
Std Dev of Torque
0.00
Mean of Max Loads
0.00
±
Width 4
0.00
Std Dev of Max Loads
0.00

Appendix C: Sample Statistical Calculations

This appendix highlights the methods used to obtain the statistical results of the factorial experiment. These methods are taken from [34].

Effects

The effects are basically calculated by finding the difference between the two averages

$$\bar{y}_{+} - \bar{y}_{-} \tag{C.1}$$

as follows: Given a column from the table of contrasts, e.g. column 12, the signs (+ - - + + - - + + - - + + - - +) are multiplied by the average values of the reduction in RA. This is then summed and divided by half the number of values, since half of the values are "positive" and half are "negative." The result is the effect.

Standard Error of Effects

The standard error of effects is a measure of the overall confidence interval for the data from the replicates of each run. It begins by estimating the variance at each *i*th set of conditions, by

$$s_i^2 = \frac{(\max - \min)^2}{2} \tag{C.2}$$

Then a pooled estimate of the experimental run variance from g factor combinations at n degrees of freedom for each replicate would be

$$s^2 = \frac{s_1^2 + s_2^2 + \ldots + s_g^2}{n} \tag{C.3}$$

Because each estimated effect is a difference between three averages of 16 observations, the variance of an effect is given as

$$V(\text{effect}) = \left(\frac{1}{16} + \frac{1}{16} + \frac{1}{16}\right)s^2 \tag{C.4}$$

Its square root is the standard error of an effect, SE(effect).