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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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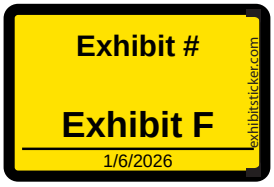
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16. ABSTRACT

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.

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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.

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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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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

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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

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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

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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

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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

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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].

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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

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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.

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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.

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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

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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.

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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

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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.

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	Removal method						
Department	Solvent	Stripper	Sac coat	Non-sac coat	Paint over	Power wash	Sandblast
Philly: PennDOT							
Pitt: PennDOT							
Milwaukee							
NYC							
Seattle							
Portland							
Reno							
LA (district 7)							
SF							
Denver							
East Bay (Dist 4)							

Key:	
	Used most frequently
	Used often
	Used occasionally
	Used rarely
	Never used
	Does not work

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.).

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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.

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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.

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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

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efficiently than the glass bead types, however they are more susceptible to damage from excess pressure deforming the structure.

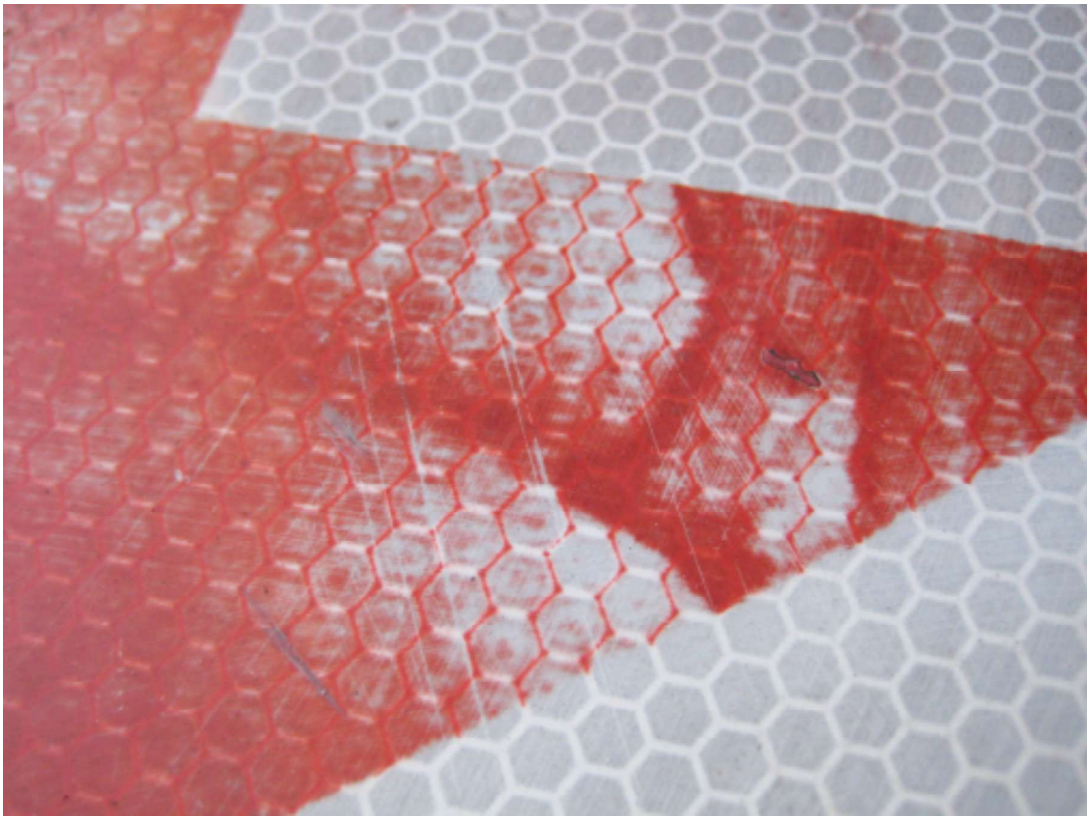


Figure 1-3: Encapsulated glass bead film

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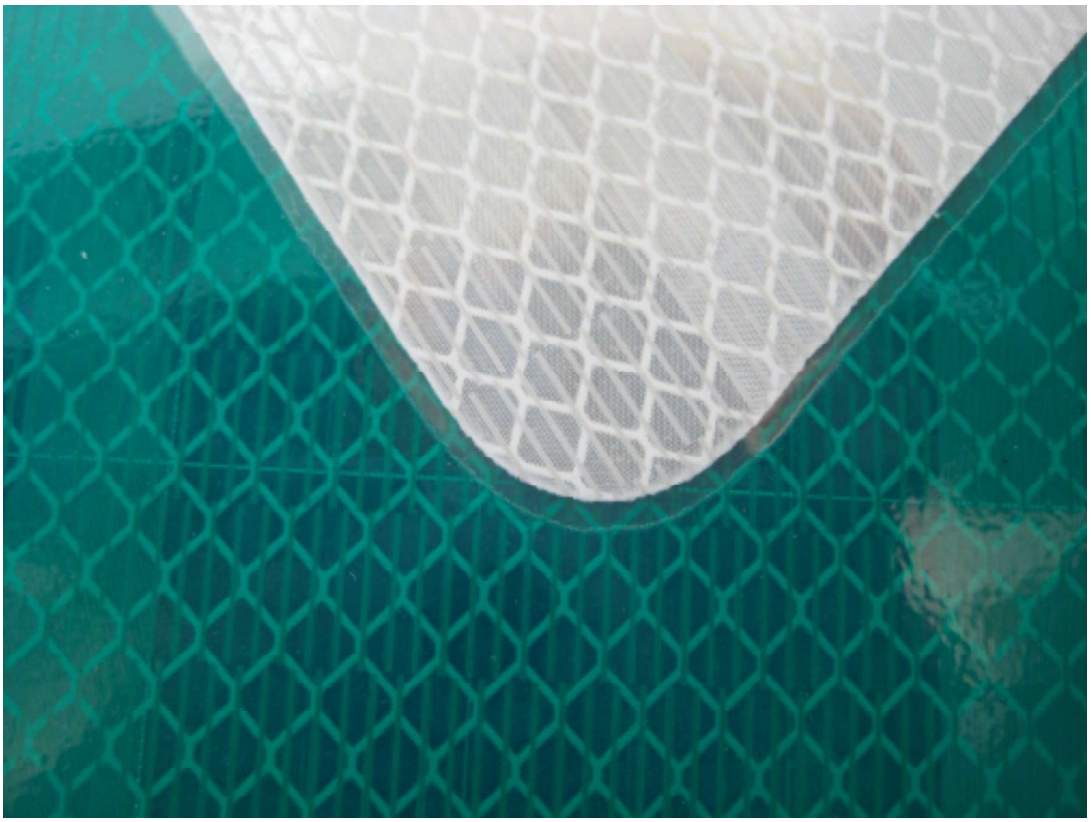


Figure 1-4: Microprismatic film, different layers of lettering and background

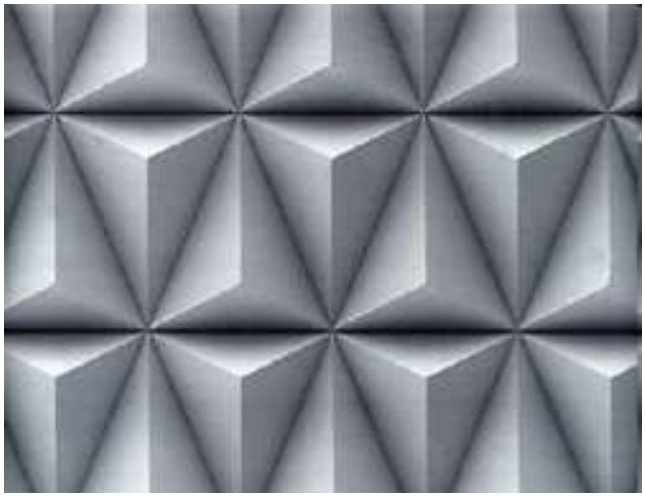


Figure 1-5: Close-up of microprismatic film

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

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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

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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).

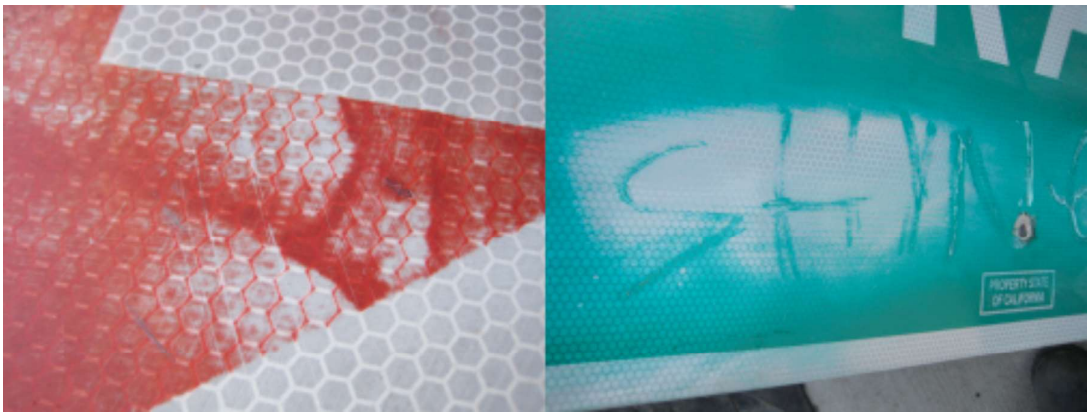


Figure 1-6: Damage to graphics from abrasion and chemicals



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

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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

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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.

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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.

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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.

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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.

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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

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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.

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	Need	Metric	unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		Coefficient of Retroreflectivity	ratio																				
		Time to remove graffiti	s																				
		Time to set up and break down	s																				
		Height range of tool	m																				
		Mass of tool	kg																				
		Noise produced by tool	dBA																				
		Time of direct contact with chems	s																				
		Radius of turn	m																				
		Rate over rough terrain	m/s																				
		Time to learn how to use tool	s																				
		Area of end effector	m^2																				
		Compatibility of cleaner and materials	Subj.																				
		Dimensions of tool	m																				
		Time to disassemble	s																				
		Operating time between maintenance cycles	s																				
		Cost of tool	US$																				
		Force applied to end effector	N																				
		Volume chem applied/Volume chem recovered	%																				
		Tool applies scrubbing motion	Subj.																				
		SC checks retroreflectivity after cleaning	Binary																				
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																						•

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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

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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

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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

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